Prepared in cooperation with the National Park Service, U.S. Fish and Wildlife Service, Arizona Game and Fish Department, and the Western Area Power Administration

Brown Trout in the Lees Ferry Reach of the Colorado River—Evaluation of Causal Hypotheses and Potential Interventions

Open-File Report 2018–1069

U.S. Department of the Interior
U.S. Geological Survey

Cover image: Brown trout, rainbow trout, and humpback chub. Photographs by Craig Ellsworth, Morgan Ford, Amy S. Martin, and Melissa Trammell.

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The work documented in this report arose from a motion at the February 2017 meeting of the Glen Canyon Dam Adaptive Management Work Group, which asked for a workshop to be held to investigate the causes and implications of brown trout expansion in the Lees Ferry reach of the Colorado River. A workshop was held in September 2017 in Phoenix, Arizona. The steering committee for the workshop also provided guidance to establish the scope of work for this report. The steering committee consisted of: Rob Billerbeck of the National Park Service; Chris Cantrell of the Arizona Game and Fish Department; Shane Capron and Craig Ellsworth of the Western Area Power Administration; Katrina Grantz and Marianne Crawford of the Bureau of Reclamation; Jessica Gwinn of the U.S. Fish and Wildlife Service; Scott VanderKooi and Michael Runge of the U.S. Geological Survey; and David Braun of Sound Science, LLC. An initial whitepaper outlining the brown trout issue was written in September 2017 and served as inspiration and raw material for this report. In addition to the authors of this report and the members of the steering committee, the contributing authors of the whitepaper included Robert Schelly of the National Park Service; Dave Rogowski of the Arizona Game and Fish Department; David Ward, Mike Yard, Kimberly Dibble, and Jim Peterson of the U.S. Geological Survey; Barry Nehring of the Colorado Division of Wildlife; and Josh Korman of Ecometric Research, Inc.

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Abbreviations

AGFD	Arizona Game and Fish Department
AMWG	Adaptive Management Work Group
BO	Biological opinion
CFMP	Comprehensive Fisheries Management Plan
CPUE	Catch per unit effort
DFC	Desired Future Condition
ESA	Endangered Species Act of 1973, as amended
FEIS	Final environmental impact statement
FONSI	Finding of no significant impact
GCD	Glen Canyon Dam
GCDAMP	Glen Canyon Dam Adaptive Management Program
GCMRC	Grand Canyon Monitoring and Research Center
GCNP	Grand Canyon National Park
GCNRA	Glen Canyon National Recreation Area
HBC	Humpback chub (*Gila cypha*)
HFE	High-flow experiment
LCR	Little Colorado River
LTEMP	Long-term Experimental and Monitoring Plan
NEPA	National Environmental Policy Act
NO	Natal Origins study
NPS	National Park Service
PIT	Passive integrated transponder
RM	River mile
ROD	Record of decision
TL	Total length (of a fish)
TMF	Trout-management Flow
TMM	Trout Movement Model
USBR	U.S. Bureau of Reclamation
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WAPA	Western Area Power Administration

Brown Trout in Lees Ferry—Evaluation of Causal Hypotheses and Potential Interventions

By Michael C. Runge,[1] Charles B. Yackulic,[1] Lucas S. Bair,[1] Theodore A. Kennedy,[1] Richard A. Valdez,[2] Craig Ellsworth,[3] Jeffrey L. Kershner,[1] R. Scott Rogers,[4] Melissa A. Trammell,[5] and Kirk L. Young[6]

Abstract

Over the period 2014–2016, the number of nonnative brown trout (*Salmo trutta*) captured during routine monitoring in the Lees Ferry reach of the Colorado River, downstream of Glen Canyon Dam, began increasing. Management agencies and stakeholders have questioned whether the increase in brown trout in the Lees Ferry reach represents a threat to the endangered humpback chub (*Gila cypha*), to the rainbow trout (*Oncorhynchus mykiss*) sport fishery, or to other resources of concern. In this report, we evaluate the evidence for the expansion of brown trout in the Lees Ferry reach, consider a range of causal hypotheses for this expansion, examine the likely efficacy of several potential management interventions to reduce brown trout, and analyze the effects of those interventions on other resources of concern.

The brown trout population at Lees Ferry historically consisted of a small number of large fish supported by low levels of immigration from downstream reaches. This population is now showing signs of sustained successful reproduction and is on the cusp of recruiting locally hatched fish into the spawning class, based on analysis with a new integrated population model. The proximate causes of this change in status are a large pulse of immigration in the fall of 2014 and higher reproductive rates in 2015–2017. The ultimate causes of this change are not clear. The pulse of immigrants from downstream reaches in fall 2014 may have been induced by three sequential high-flow releases from the dam in November of 2012–2014, but may also have been the result of a unique set of circumstances unrelated to dam operations. The increase in reproduction may have been the result of any number of changes, including an Allee effect, warmer water temperatures, a decrease in competition from rainbow trout, or fall high-flow releases. Correlations over space and time among predictor variables do not allow us to make a clear inference about the cause of the changes. Under a null causal model, and without any changes to management, we predict there is a 36-percent chance the brown trout population at Lees Ferry will not show sustained growth, and will remain around a mean size of 5,800 adults, near its current size; in contrast, we predict there is a 64-percent chance that the population has a positive intrinsic growth rate and will increase 3–10 fold over the next 20 years. A humpback chub population

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model linked to the brown trout model suggests an increase of brown trout of this magnitude could lead to declines in the minimum adult humpback chub population over the same time period. Forecasts of rainbow trout abundance, however, suggest that increased abundance of brown trout in the Lees Ferry reach does not pose a threat to the rainbow trout fishery there.

There are interventions that may be effective in moderating the growth of the brown trout population in the Lees Ferry reach of the Colorado River. Across causal hypotheses, we predict that removal strategies (for example, a concerted electrofishing effort or an incentivized take program targeted at large brown trout) could reduce brown trout abundance by approximately 50 percent relative to status quo management. Reductions in the frequency or a change in the seasonal timing of high-flow releases from Glen Canyon Dam could be even more effective, but only under the causal hypotheses that involve effects of such releases on immigration or reproduction. Brown trout management flows—dam releases designed to strand young fish at a vulnerable stage—may be able to reduce brown trout abundance to some degree, but are not forecast to be the most effective strategy under any causal hypothesis.

We predict that the alternative management interventions would have effects on other resource goals as well, and the pattern of these effects differs across causal hypotheses. The removal strategies would incur direct costs (on the order of $7 million over 20 years) and the mechanical removal strategy is unethical from the perspective of several tribes. The strategies that involve reducing the frequency of high-flow releases from Glen Canyon Dam would decrease the ability to transport and store sediment in the ecosystem, potentially undermining goals associated with sandbar building, recreation, and riparian vegetation, but would increase hydropower revenue. Trout management flows would reduce hydropower revenue. From the standpoint of humpback chub, the alternative strategies largely follow the effect on brown trout; when brown trout abundance is reduced, predation pressure decreases, and humpback chub viability is predicted to increase, but the variation in predicted chub viability is not large across strategies or causal hypotheses.

To design a response to brown trout, management agencies will need to navigate both the tradeoffs among resources goals and the uncertainty in the causes of the brown trout expansion. Continued monitoring, possibly coupled with new research or experimental management actions that better inform demographic and ecological dynamics, can help to reduce the causal uncertainty.

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 U.S. Bureau of Reclamation (USBR). 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. 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, and comprises three canyons: Glen Canyon, which stretches upstream from Lees Ferry; Marble Canyon, between Lees Ferry and the Little Colorado River (LCR); and Grand Canyon proper, from the LCR to Lake Mead. This report focuses on the Lees Ferry reach, the 15.5-mile stretch of the Colorado River in Glen Canyon between the Glen Canyon Dam and Lees Ferry, but this reach can only be understood within the larger geographical context.

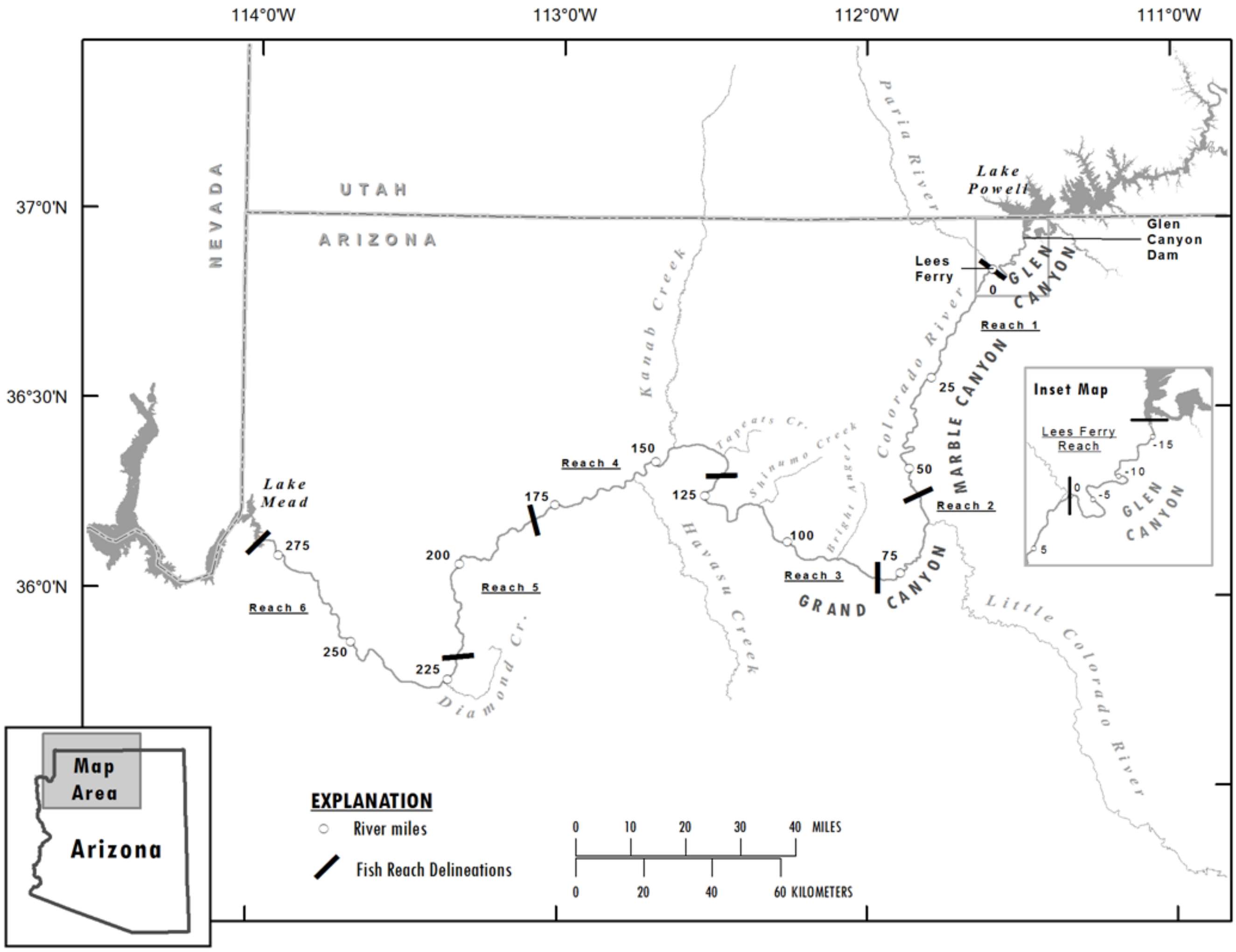

Figure 1. Map of the Colorado River through Glen, Marble, and Grand Canyons, identifying Glen Canyon Dam, Lees Ferry, Lake Mead, and six fish reaches. River miles starting at Lees Ferry are marked at 25-mile intervals. The fish reaches are segments designated by the Arizona Game and Fish Department for the purpose of reporting fish distribution. Map from Tom Gushue, U.S. Geological Survey.

There are many valuable natural resources in the GCDAMP project area, and management of these resources requires a deft consideration of the tradeoffs among them (Schmidt and others, 1998). These resources include: native fish species, like the humpback chub (*Gila cypha*); a unique riverine ecosystem influenced by the dynamic movement of sediment; other native flora and fauna; a rainbow trout (*Oncorhynchus mykiss*) fishery; world-famous recreational opportunities; hydropower generation and capacity; water storage and delivery; and a vast, breathtaking wilderness. This area is the current or ancestral home to a number of American Indian Tribes, to whom it provides economic, cultural, and spiritual benefits. In 2016, USBR and the National Park Service (NPS), in cooperation with many other agencies and tribes, completed a long-term planning project concerning the operation of Glen Canyon Dam and related activities. The Long-term Experimental and Management Plan (LTEMP) seeks to achieve as much benefit across the many resource goals as possible, while navigating some of the difficult tradeoffs. A central set of tradeoffs involves the interaction between native and nonnative fish in the Colorado River, especially between humpback chub, valued as a native, endemic fish, and rainbow trout, valued as a recreational and economic resource. Both of these fish are affected in complex ways by the operations of Glen Canyon Dam, by environmental variables, and by interactions with other aquatic species.

The brown trout (*Salmo trutta*) is one of two nonnative, cold-water fish species found in the Colorado River downstream of Glen Canyon Dam. Recent apparent increases in abundance of brown trout in the Lees Ferry reach have raised concerns about their potential effects on the endangered humpback chub and the Lees Ferry rainbow trout fishery. Management of these fish species is part of the larger enterprise of environmental management downstream of Glen Canyon Dam, authority for which is shared among a number of federal, state, and tribal agencies, including NPS, USBR, the U.S. Fish and Wildlife Service (USFWS), the Arizona Game and Fish Department (AGFD), the Hopi Tribe, the Hualapai Tribe, the Navajo Nation, the Pueblo of Zuni, the San Juan Southern Paiute Tribe, and the Southern Paiute Consortium.

Brown trout have been collected in low numbers for several decades in the Lees Ferry reach, but over the period 2014–2016, as part of their fish monitoring program, the AGFD detected an increase in the catch per unit effort (CPUE) of brown trout (fig. 2), concurrent with observations of increased spawning behavior during a mark-recapture study (Korman and others, 2016).

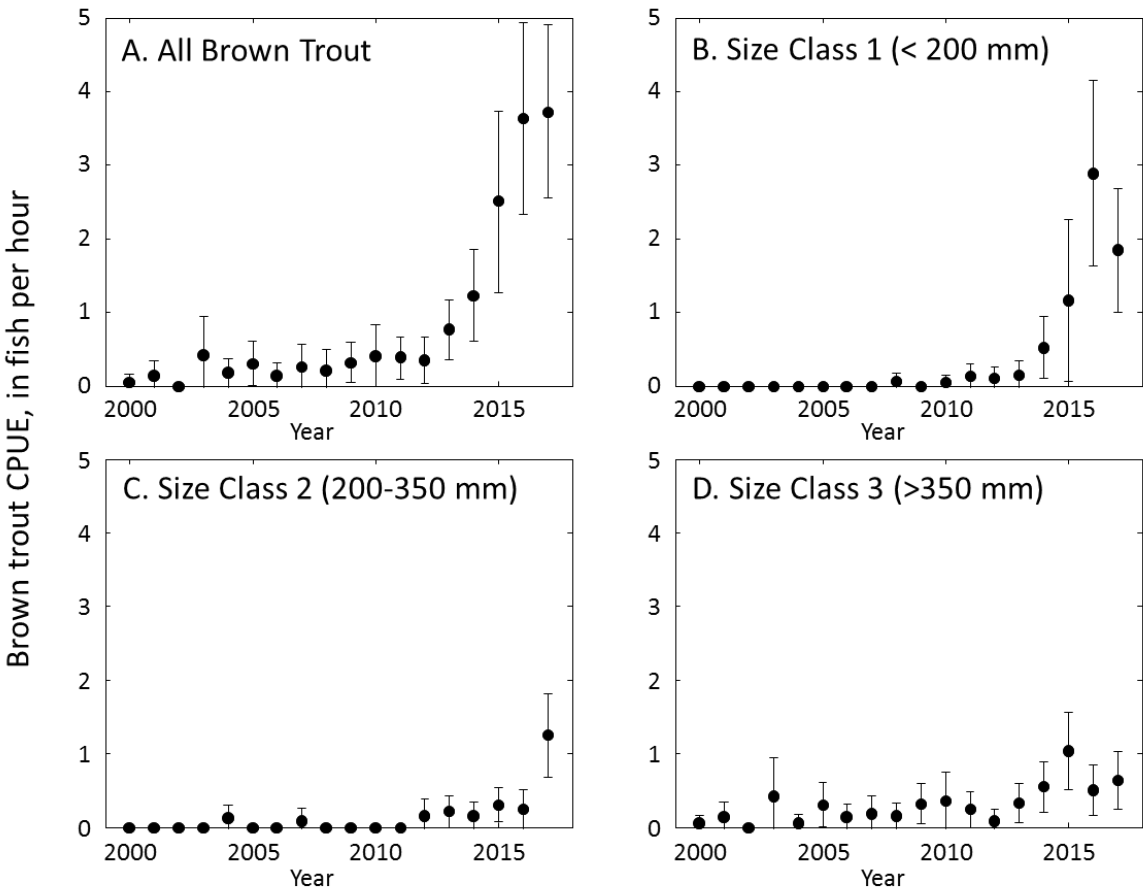

Figure 2. Brown trout average yearly electrofishing catch per unit effort (CPUE) in the Lees Ferry reach of the Colorado River, 2001—2017. The closed circles show the mean value; the error bars show the 95-percent confidence intervals. *A*, All brown trout; *B*, Size class 1 fish (length <200 millimeters [mm]); *C*, Size class 2 fish (length 200–350 mm); and *D*, Size class 3 fish (length >350 mm). Data from Arizona Game and Fish Department.

There is a complex set of relations among brown trout, rainbow trout, and humpback chub. Humpback chub are a native fish found in the Colorado River downstream of Glen Canyon Dam and listed as endangered under the Endangered Species Act (ESA). Both brown trout and rainbow trout have been identified as a threat to humpback chub, because of predation and competition for habitat. Brown trout are known to prey on juvenile and adult humpback chub (Yard and others, 2011), so their presence downstream of Lees Ferry has been a management concern for several decades. Field and laboratory studies demonstrate that brown trout are more piscivorous on native fish, including humpback chub, than rainbow trout (Yard and others, 2011; Ward and Morton-Starner, 2015). Brown trout also prey on and compete with rainbow trout, so their presence in the Lees Ferry reach raises concerns about the rainbow trout fishery.

In February 2017, the GCDAMP Adaptive Management Work Group (AMWG), a group convened under the Federal Advisory Committee Act to advise the Secretary of the Interior on aspects related to operations of Glen Canyon Dam, passed a motion to recommend that the Secretary direct NPS and the U.S. Geological Survey's Grand Canyon Monitoring and Research Center (GCMRC), and request AGFD, to convene a workshop to evaluate the causes of the brown trout increase, possible risks to the rainbow trout fishery and to the recovery of humpback chub, pros and cons of different management options, and research needed to inform decisions regarding management of brown trout in the Lees Ferry reach. That workshop was held in September 2017 (http://gcdamp.com/index.php?title=Brown_Trout). Following the workshop, NPS, USBR, GRMRC, AGFD, the Western Area Power Administration (WAPA), and USFWS convened a science panel, consisting of the authors of this report, to explore the topic in greater depth.

Many of the management activities associated with Glen Canyon Dam are described in the 2016 Glen Canyon Dam LTEMP Final Environmental Impact Statement (FEIS) (U.S. Department of the Interior, 2016a) and its associated Record of Decision (ROD; U.S. Department of the Interior, 2016b). Three types of actions that are possibly relevant to management of brown trout are described in the LTEMP; high-flow experiments (HFEs), trout-management flows (TMFs), and mechanical removal of trout. High-flow experiments are water releases through the hydropower generators and the bypass tubes of the dam, designed to redistribute sediment from the river channel to higher elevation sites on the margins of the river. These HFEs may last from 1 to 250 hours, depending on water volume, sediment availability, and the type of HFE. The HFEs are used to redistribute sediment accumulated on the river bed downstream of the dam onto high-elevation beaches along the river corridor. The LTEMP specifies the conditions under which fall (November) and spring (April) HFEs are triggered, with spring HFEs prohibited until 2020. (For an interactive tool to visualize discharge, sediment, and other variables downstream of the dam, see https://www.gcmrc.gov/discharge_qw_sediment/stations/GCDAMP). Trout-management flows are dam operations designed to reduce rainbow trout recruitment, by stranding fry- and fingerling-sized trout (<6 months old), to reduce the threat to humpback chub. The TMFs described in the LTEMP are focused on periods when rainbow trout young-of-the-year are thought to be most vulnerable to stranding-induced mortality (May–August), and this may not be the same period when brown trout young are vulnerable to stranding. Mechanical removal consists of using a variety of methods, particularly electrofishing from a boat, to reduce trout densities (rainbow or brown) to a level that is consistent with management goals designed to allow for the recovery of the humpback chub.

The evaluation of management options related to brown trout described in this report takes place against the backdrop of many existing management activities and plans, as well as the National Environmental Policy Act (NEPA) and ESA Section 7 compliance that accompanies them. Recent NEPA and ESA processes provide existing compliance and guidance on nonnative fish management actions downstream of Glen Canyon Dam, including; the 2016 LTEMP FEIS (U.S. Department of the

Interior, 2016a), the corresponding ROD (U.S. Department of the Interior, 2016b), several USFWS Biological Opinions (BO; U.S. Fish and Wildlife Service, 2008, 2011, 2016), and the NPS 2013 Comprehensive Fisheries Management Plan (CFMP; National Park Service, 2013a). The LTEMP ROD provided a set of goals and objectives for the future guidance of the GCDAMP and those objective statements are the guidance for how management options are evaluated in this report.

Status of Brown Trout at Lees Ferry

Brown trout were introduced to various tributaries of the Colorado River between 1926 and 1934, and became established over time, particularly at some sites downstream of Marble Canyon (fig. 1). Since 2000, there has been a low CPUE of adult brown trout in the Lees Ferry reach (fig. 2*D*), with even lower CPUE of small- and intermediate-size fish (figs. 2*B* and 2*C*). In 2014 and 2015, increases in the catch of large brown trout were observed, presumably as a result of immigration from downstream locations. These increases in spawning-sized fish were followed by increases in the catch of young-of-the-year fish, likely as a result of reproduction in the Lees Ferry reach. Finally, in 2017, an increase in the catch of intermediate-size fish was observed. If another jump in the catch of large brown trout is seen in 2018 in the Lees Ferry reach, this will suggest that the population is now recruiting into the spawning class through local reproduction.

The establishment of a self-sustaining breeding population of brown trout in the Lees Ferry reach could have two direct effects and a number of indirect effects on resources of concern in the Colorado River ecosystem. The direct effects concern rainbow trout in the Lees Ferry reach and humpback chub residing near the Little Colorado River (LCR). Indirect effects concern any resources that would be affected by actions taken to manage brown trout.

Purposes

The observation of increased numbers of brown trout in the Lees Ferry reach raises many questions. The purpose of this paper is to evaluate these questions.

- Has a brown trout population become established in the Lees Ferry reach?
- Does such a population threaten any resources of concern?
- Why might such a change have occurred, and is it the unintended effect of other management actions?
- What possible approaches could be taken to ameliorate the effects of brown trout, and how might these approaches affect other resources of concern?
- In short, will brown trout at Lees Ferry, or any attempts to management them, threaten the current balance among multiple natural resources in the Colorado River ecosystem downstream of Glen Canyon Dam?

Management of the operations of Glen Canyon Dam and related activities in the Colorado River ecosystem affects many resources of concern, including hydropower generation, water delivery, sediment dynamics, riparian vegetation, the rainbow trout fishery, humpback chub, other native aquatic and terrestrial wildlife, and recreation. Further, there are many aspects of the natural world and human interaction with it that are highly valued by American Indian Tribes with cultural, historical, and economic ties to Grand Canyon and the Colorado River. The thoughtful and deliberate management of all these resources requires careful attention to the multifaceted effects of any action taken.

The paper is organized as follows.

- First, we provide background on brown trout in the Colorado River.

- Second, we articulate and evaluate alternative mechanistic hypotheses for the increase of brown trout in the Lees Ferry reach.
- Third, we present a set of management objectives and associated performance metrics to form the basis of further evaluation.
- Fourth, we propose six management strategies aimed at reducing brown trout in the Lees Ferry reach.
- Fifth, we describe the methods for evaluating the effects of such management strategies on the management objectives.
- Sixth, we present results examining the effects of the management strategies, first on brown trout and then on other resources, including humpback chub, rainbow trout, sediment, hydropower generation, other management costs, long-term economic value of the Lees Ferry fishery, and tribal values.
- Finally, we discuss the role of research and monitoring in reducing the uncertainty that makes decision making difficult.

Scientific Background

The brown trout is a cold-water fish species that inhabits streams, river, and lakes, and is capable of migrating to and from salt water. The original distribution of the brown trout was Europe, North Africa, and Western Asia, but it has been introduced into suitable habitats around the world. The species was first imported to the United States from Germany in 1883 and stocked in the Pere Marquette River, Michigan, by the U.S. Fish Commission (Mather, 1889; Courtenay and others, 1984). Since then, the species has been stocked in virtually every state of the country, including Arizona and in Grand Canyon.

The Colorado River through Grand Canyon (fig. 1) was historically warm, turbid, and unsuitable for trout. The Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) was native to upper basin tributaries and as far south as the headwaters of the San Juan and Escalante Rivers, but there were no trout native to tributaries of the Grand Canyon (Behnke and Tomelleri, 2002). The Apache trout (*O. apache*) and the Gila trout (*O. gilae*) are native to tributaries of the Gila River of the lower Colorado River basin, downstream of the Grand Canyon region.

Historical Stocking of Trout in the Grand Canyon Region

After Grand Canyon was established as a National Park in 1919, the NPS began stocking fish into tributaries to provide recreational fishing opportunities for park visitors. Several trout species were introduced, including rainbow trout into Bright Angel Creek (1923, 1924, 1932–42, 1947, 1950, 1958, and 1964), Tapeats Creek (1923 and 1940), Havasu Creek (1931, 1944, 1948, and 1954), Clear Creek (1940), and Phantom Creek (1942). Brook trout (*Salvelinus fontinalis*) were introduced into Bright Angel Creek (1920), Havasu Creek (1927), and Clear Creek (1928, 1931, and 1934). Brown trout were introduced into Shinumo Creek (1926 and 1930), Garden Creek (a tributary of Pipe Creek, 1930), and Bright Angel Creek (1930 and 1934; Brooks, 1931; Carothers and Minckley, 1981). The last stocking of brown trout in Grand Canyon was in Bright Angel Creek in December of 1934. Brook trout evidently did not persist; rainbow trout and brown trout successfully reproduced, but remained confined to tributaries until about 1976.

With completion of Glen Canyon Dam in 1963 and the filling of Lake Powell, hypolimnetic dam releases provided a cold, clear, and productive environment for trout in the tail water. The AGFD, in cooperation with NPS, began to stock cold-water species in the Lees Ferry reach to establish a recreational fishery. Rainbow trout were stocked in this reach in 1964–1998 (Reger and others, 1989), along with kokanee salmon (*O. nerka*) in 1967 (Stone and Rathbun, 1968), coho salmon (*O. kisutch*) in 1971 (Carothers and Minckley, 1981), brook trout in 1977–78, 1980–83, and 1985–87 (Carothers and Minckley, 1981; McKinney and Persons, 1999), and cutthroat trout (*O. clarki*) in 1979 (McCall, 1980). There is no record of brown trout having been stocked in the Lees Ferry reach or elsewhere in the mainstem Colorado River through Glen, Marble, or Grand canyons.

Annual stocking of rainbow trout in the Lees Ferry reach continued from 1964 to 1998 and the fish survived successfully, but highly fluctuating dam releases precluded most natural reproduction (McKinney and others, 2001). In 1991, dam operating criteria were modified, including increased minimum flows and reduced daily variability in discharge associated with hydropower production. Following these changes in dam operations, rainbow trout began to reproduce and recruit naturally, and stocking the species in the Lees Ferry reach ceased in 1998 (McKinney and others, 2001; Makinster and others, 2011). Since 1998, the Lees Ferry rainbow trout fishery has been maintained through natural reproduction (Makinster and others, 2011). Except for localized spawning in and near the confluence of some downstream tributaries (for example, Nankoweap, Clear, Bright Angel, Shinumo, Tapeats, Deer, and Havasu Creeks), most rainbow trout reproduction in the mainstem Colorado River downstream of Glen Canyon Dam occurs within the Lees Ferry reach.

Reproduction by brown trout in the GCDAMP project area occurs primarily in Bright Angel Creek, although the presence of gravid adults and young in the mainstem indicate limited but successful mainstem spawning (Valdez and Ryel, 1995; Rogowski and others, 2017a). Electrofishing surveys of Shinumo, Deer, Tapeats, Kanab, and Havasu Creeks in February–March of 2004 and 2005 yielded low numbers of 2, 0, 3, 1, and 0 brown trout, respectively; notably, one male brown trout in Tapeats Creek was expressing milt and in spawning condition (Leibfried and others, 2006). Removal of nonnative fish by the NPS from Shinumo Creek (upstream of the barrier falls) in 2009 and Havasu Creek in 2011, in advance of humpback chub translocations yielded no brown trout from either tributary (Healy and others, 2011; Omana-Smith and others, 2011). Hence, the numbers of brown trout in tributaries, except for Bright Angel Creek, appear to remain low.

History of Known Brown Trout Distribution, Abundances, and Movement

Distribution and abundance of brown trout in the Colorado River through the Grand Canyon have changed over time, as indicated by system-wide surveys. The first surveys of fishes in the Colorado River and tributaries from Lees Ferry (river mile [RM] 0[7]) to Diamond Creek (RM 226) in 1968 (Miller and Smith, 1972) and in 1970–1976 (Suttkus and others, 1976) reported no brown trout from either the mainstem or lower reaches of tributaries. During 1977–1979, Carothers and Minckley (1981) reported low catch rates of brown trout in the mainstem from the LCR (RM 61) to downstream of Shinumo Creek (RM 109) and found brown trout only in Phantom Creek (tributary of Bright Angel Creek) and Shinumo Creek. From 1984 to 1986, Maddux and others (1987) reported no brown trout from the Lees Ferry reach, very low catch rates downstream to the LCR, highest catch rates of adults and subadults from the LCR to Bright Angel Creek (RM 88), and moderate catch rates of adults and subadults from Bright Angel Creek to National Canyon (RM 167). An AGFD survey of the Lees Ferry reach from 1984–1988 indicated less than 1 percent of the electrofishing catch was brown trout in 1986 (Reger and others, 1989). Studies during 1990–1993 showed catches of brown trout primarily

[7]The use of river miles (RM) has a historical precedent and provides a reproducible method for describing locations along the Colorado River below Glen Canyon Dam. Lees Ferry is the starting point, river mile 0, with mileage upstream indicated with negative values (–) and mileage downstream with positive values (+).

downstream of the LCR, with highest catch rates in and near the confluence of Bright Angel Creek, Shinumo Creek, and Tapeats Creek (RM 134) (fig. 3; Valdez and Ryel, 1995). Surveys from Diamond Creek to Pearce Ferry (RM 280) in 1992–94 (Valdez, 1994; Valdez and others, 1995) reported no brown trout from that reach at a time when Lake Mead was at high elevation and much of the reach was inundated by the lake and the river channel filled with stored sediments.

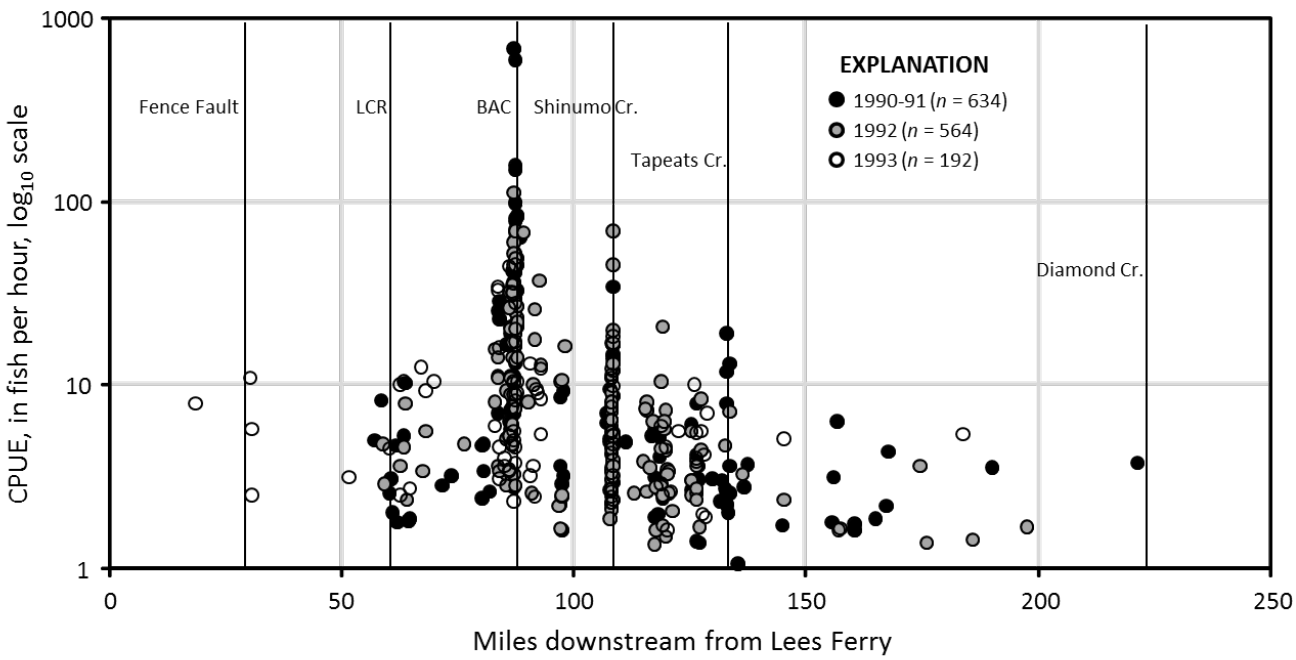

Figure 3. Catch per unit effort (CPUE) of brown trout in number of fish captured per hour of electrofishing in the mainstem Colorado River from Lees Ferry (River mile [RM] 0) to Diamond Creek (RM 226), 1990–1993. Key sites, tributaries, and their locations in river miles downstream from Lees Ferry include Fence Fault (RM 30.3), the Little Colorado River (LCR; RM 61.5), Bright Angel Creek (BAC; RM 87.7), Shinumo Creek (RM 108.6), and Tapeats Creek (RM 133.8). Data collected by BioWest, Inc. as reported in Valdez and Ryel (1995), and stored at the Grand Canyon Monitoring and Research Center, Flagstaff, AZ.

These surveys may not be directly comparable because of different gear types and sampling strategies, but they provide a perspective of distribution and abundance of brown trout prior to 2000. Evidently, brown trout were not present in detectable numbers in the mainstem prior to about 1976, but were detected afterward, primarily near the mouths of Bright Angel and Shinumo Creeks, as river temperature cooled and brown trout were able to use the mainstem. Beginning in 1984, numbers of adults and subadults began to increase in the mainstem from Bright Angel Creek to National Canyon, although they remained rare in the Lees Ferry reach. During the 1990s, brown trout began to be captured near mouths of the major cold-water tributaries, including Bright Angel, Shinumo, and Tapeats Creeks, although the numbers within the latter two tributaries were very low in 2004–2005 and 2009.

Electrofishing surveys by AGFD from Lees Ferry to Pearce Ferry starting in 2000 (Makinster and others, 2010; Rogowski and others, 2017b) found that mean CPUE of brown trout by reach declined from 2000 to 2006 and subsequently increased to different levels in various reaches (fig. 4). Whereas only one brown trout was captured in the most downstream reach (downstream of RM 220) during 1990-93, brown trout were caught in this reach in all years starting in 2007. We note that this change coincided with a decline in elevation of Lake Mead, which resulted in this reach becoming more riverine. Thus, increased brown trout catch could be because of an increase in abundance related to more favorable conditions in this re-emerging river segment. Alternatively, increased catches may be the result of a greater susceptibility to capture because of lower water volumes in this no longer impounded reach.

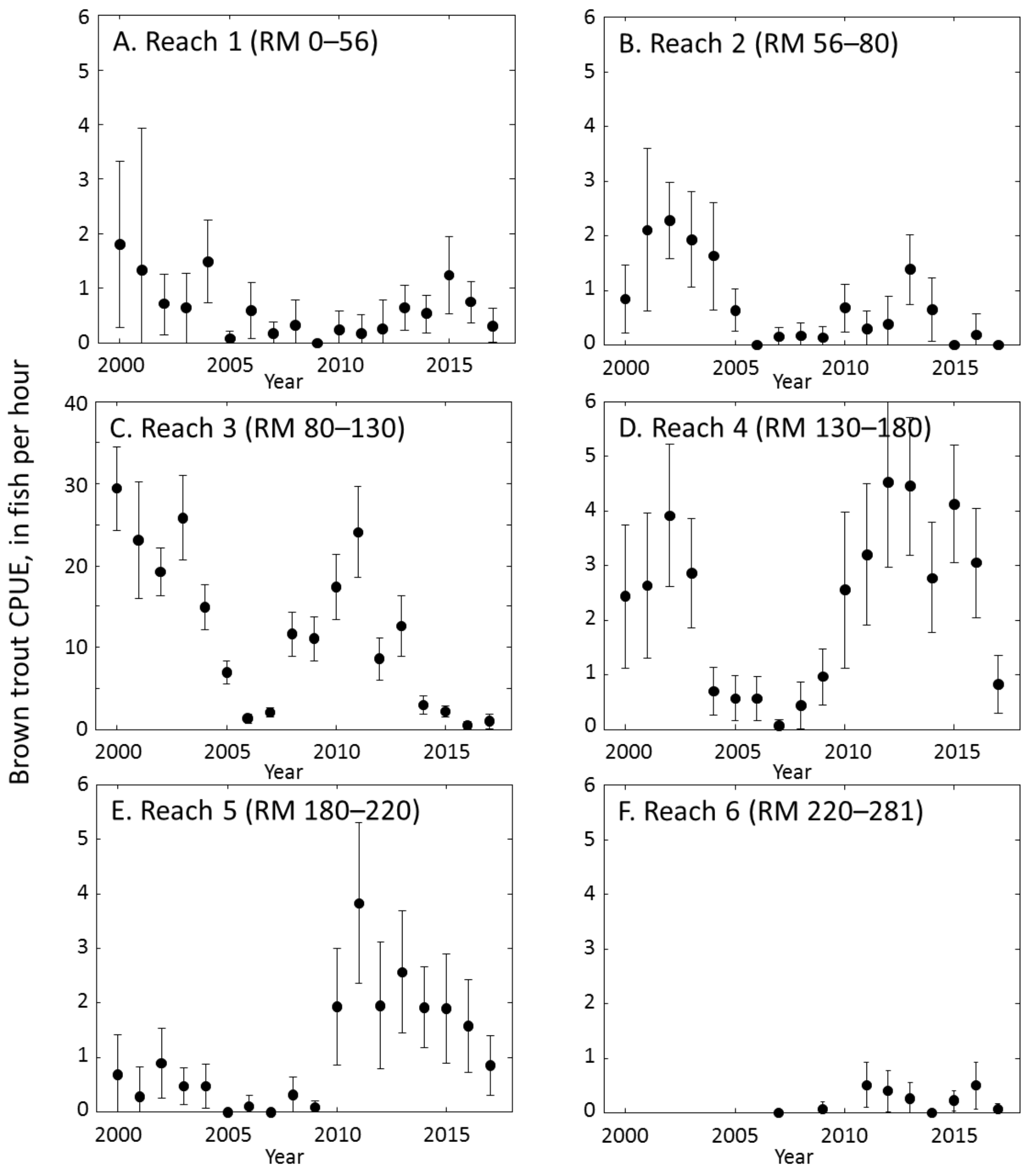

Figure 4. Mean catch per unit effort (CPUE) of brown trout captured during electrofishing surveys on the Colorado River between Lees Ferry and Pearce Ferry for reaches 1–6 (plots A–F), 2000–2017. Reach locations are provided in river miles (RM) downstream of Lees Ferry (RM 0), see fig. 1. Most surveys occurred during the spring (April–June). The closed circles show the mean value; error bars represent 95-percent confidence intervals; note change in y-axis scales. Reach 6 (F) was sampled 2004–2006 and in 2010, but data were not included because of high turbidity, and no sampling occurred in 2008 for Reach 6. Data from Arizona Game and Fish Department.

Electrofishing in the Lees Ferry reach indicates that few brown trout were present prior to 2001. Recent increases in brown trout recruitment in 2014–2015 have occurred in the Lees Ferry reach (Stewart and Winters, 2016) and the total catch rate has increased more than ten-fold, from 0.35 fish per hour (fish/hr) in 2012 to 3.73 fish/hr in 2017 (fig. 2). Brown trout were observed spawning near the 4-mile bar in Glen Canyon (approximately 4 river miles upstream of Lees Ferry) as part of winter sampling in 2014-15 and 2015-16 (Korman and others, 2016; Yackulic and others, 2018a).

Size classes of brown trout captured in the Lees Ferry reach show low numbers of fish of various sizes from 1996 through 2012 (fig. 2). In 2013 and 2014, some increases in numbers are seen in fish 200 millimeters (mm) total length (TL) or larger. The lack of smaller fish in earlier years suggests the observed fish either evaded detection while being reared or moved into the Lees Ferry reach from elsewhere. In 2015 and 2016, distinct length modes began to appear for fish <100 mm TL, indicating substantial and detectable local reproduction, but with an apparent lack of subsequent age modes and the continued low abundance of larger adults. The substantial increase in size class 2 (200–350 mm TL) fish in 2017, combined with recaptures of fish >200 mm that were <200 mm when marked, suggests that fish are indeed surviving past the first year.

Some brown trout in the mainstem Colorado River migrate to Bright Angel Creek to spawn. About 60 brown trout have been recaptured in Bright Angel Creek, either in a weir operated by NPS or by electrofishing, that were originally tagged in other parts of the Colorado River as far as 85 miles away (Leibfried and others, 2005; Sponholtz and others, 2010; Bureau of Reclamation, 2011; B. Healy, NPS, written commun., March 5, 2018). Small numbers of brown trout are also found in other locations within Grand Canyon, including the vicinity of the LCR confluence and in the Lees Ferry reach. An indication of the relative abundance of brown and rainbow trout in the vicinity of the LCR is provided by the numbers captured by electrofishing during trout removal efforts. Of 23,207 nonnative fish captured as part of removal efforts from 2003 to 2006, 19,020 were rainbow trout and 479 were brown trout (Coggins and others, 2011). All rainbow and brown trout captured during these efforts were removed from the river.

Threat to Humpback Chub and Rainbow Trout

The brown trout poses a threat to humpback chub and rainbow trout in the GCDAMP project area as a predator and competitor for food and space. The brown trout is a known predator of fish in many river systems (Young and others, 2010; Budy and others, 2013). In Glen, Marble, and Grand Canyons, it is considered a more serious predator than rainbow trout because of a higher incidence of piscivory and a greater tolerance to warm water temperature and high turbidity (Valdez and Ryel, 1995; Marsh and Douglas, 1997; Yard and others, 2011). Laboratory trials confirm these findings and indicate that brown trout remain effective predators of juvenile humpback chub at temperatures as high as 20°C (Ward and Morton-Starner, 2015) and are less affected than rainbow trout in their ability to capture juvenile humpback chub as turbidity levels increase (Ward and others, 2016). Increased numbers of brown trout in Grand Canyon could pose a substantial threat to native fishes, including the humpback chub.

Brown trout also pose a threat to rainbow trout in the Lees Ferry reach. Brown trout have been reported in small numbers in this reach, but the sudden increase of adults in 2014 and evidence of successful reproduction in 2015 indicate a potential threat to the rainbow trout fishery. The effect of this increase on rainbow trout is uncertain and is one of the topics addressed in this paper.

Brown Trout Management Activities

Two major projects have removed large numbers of brown trout from Grand Canyon in an attempt to evaluate the efficacy of nonnative fish removals to benefit native fishes: (1) mainstem electrofishing in the vicinity of the LCR, and (2) installation and operation of a fish weir to trap fish moving to and from Bright Angel Creek, combined with mechanical removal of brown trout from Bright Angel Creek using backpack electrofishing.

During 2003–2006, over 23,000 nonnative fish, including rainbow trout (19,020; 82 percent) and brown trout (479; 2 percent), were removed from a 9.4-mile reach of the Colorado River near the LCR confluence (Coggins and others, 2011). Concurrent with mechanical removal, mark-recapture studies within a control reach of river 20 miles upstream of the removal reach demonstrated a system-wide decline in both rainbow trout and brown trout that was unrelated to the fish removal effort. During this same period, a rapid shift in fish community composition was observed in the LCR reach (the mainstem Colorado River upstream and downstream of the LCR; see reach 2 in fig. 1), from one dominated by cold-water salmonids (>90 percent), to one dominated by native fishes and the nonnative fathead minnow (*Pimephales promelas*) (>90 percent). Thus, our understanding of the efficacy of mechanical removal was confounded by an external systemic decline, particularly in 2005–2006 (Coggins and others, 2011). Another removal effort took place in 2009, with around 2,500 nonnative fishes removed from the LCR reach (Makinster and Avery, 2010). Subsequent electrofishing in the LCR reach showed that the number of rainbow trout and brown trout was higher after 2008 (fig. 4; Makinster and others, 2010), but the catch rate declined for rainbow trout and brown trout after 2014. The average catch per trip (based only on the first two passes of electrofishing to standardize across years) for rainbow trout was 209, 294, 460, 67, 18, and 56 between 2012 and 2017, and 2, 10, 5, 2, 0.3, and 2 for brown trout over the same period (C.J. Yackulic, GCMRC, written commun., April 3, 2018).

A second effort to control nonnative fish, specifically brown trout, was implemented in 2002 in Bright Angel Creek. As recently as the 1970s, rainbow trout dominated the fish community in Bright Angel Creek and brown trout were rare (Minckley, 1978), despite this tributary having been stocked with brown trout, twice in 1930 and once in 1934. After the 1990s, however, brown trout became a predominant component of the fish community in the creek, and a corresponding decline in native fish such as speckled dace (*Rhinichthys osculus*) was observed (Otis, 1994). Bright Angel Creek is now a principal spawning site for brown trout, and an aggregation is found in the Colorado River near the confluence with Bright Angel Creek (fig. 3; Valdez and Ryel, 1995; Makinster and others, 2010).

In an attempt to restore the native fish community of Bright Angel Creek and to reduce the threat of predation to humpback chub in the Colorado River, a program of mechanical removal of nonnative trout from Bright Angel Creek was implemented. From November 2002 to January 2003, a weir was operated near the creek mouth, which resulted in the capture of over 400 brown trout as part of an initial feasibility study (Leibfried and others, 2005; fig. 5). In 2006, the Bright Angel Creek Trout Reduction Project Environmental Assessment (EA) and Finding of No Significant Impact (FONSI; National Park Service, 2006) identified goals and a strategy for reducing numbers of brown trout. This project was initiated in cooperation with the USFWS in 2006–2007 (National Park Service, 2006; Sponholtz and others, 2010) following the feasibility study. This effort was resumed in 2010 (Omana-Smith and others, 2012) following the 2008 and 2011 Biological Opinions on Operation of Glen Canyon Dam (U.S. Fish and Wildlife Service, 2008 and 2011) that identified conservation measures to conduct trout reduction in Bright Angel Creek and to establish multiple self-sustaining populations of humpback chub in Grand Canyon tributaries (Valdez and others, 2000).

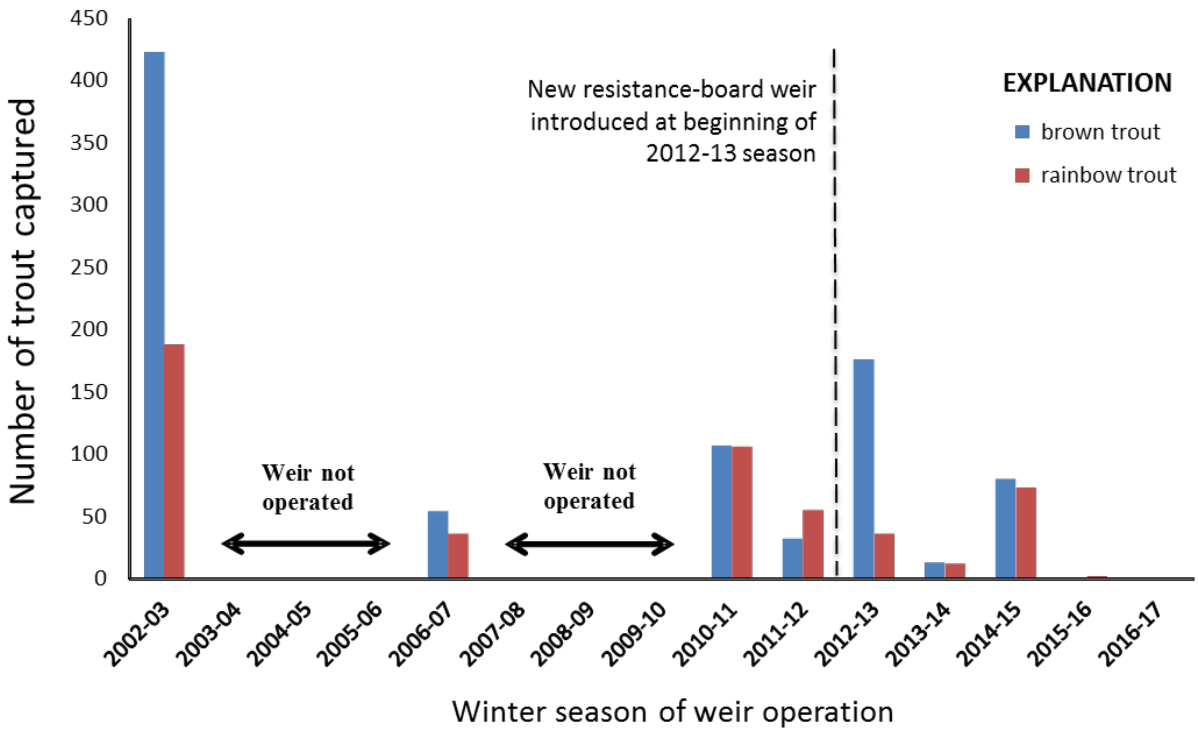

Figure 5. Numbers of brown trout and rainbow trout captured in a fish weir located near the mouth of Bright Angel Creek (BAC), 2002–2017. The weir was operated October through February. Any brown trout captured were removed and put to beneficial use; rainbow trout were not removed in the early years. R. Schelly, National Park Service, written commun., January 10, 2018.

Current operations under the Bright Angel Creek trout control project were established through the NPS Comprehensive Fisheries Management Plan (CFMP; National Park Service, 2013a). From 2010–2012 trout reduction efforts included installation and operation of a weir and backpack electrofishing in the lower 2900 meters (m) of the creek (confluence to Phantom Creek; Omana-Smith and others, 2012). Beginning in fall of 2012, removal efforts were expanded to encompass the entire length of Bright Angel Creek (~16 kilometers [km]) and Roaring Springs (~1.5 km).

The operation of the weir was extended from October through February to capture greater temporal variability in the trout spawn (Omana-Smith and others, 2012; National Park Service, 2013b). Electrofishing removal efforts, led by NPS and GCMRC, also occurred in the mainstem Colorado River in the Bright Angel Creek inflow in 2013 to 2016 (C. Nelson, USGS, oral commun., January 27, 2016). The brown trout removal effort in Bright Angel Creek proper has continued annually from 2010 to 2017 (Schelly and others, 2017). Across the most recent five seasons of removal, encompassing the entire Bright Angel Creek drainage, brown trout captures have declined steadily and considerably from 12,467 fish per year in 2012–13 to 4,902 in 2016–17, despite a similar level of effort each year. This decline has been most pronounced in age-2 and larger fish, with cohorts of age-1 fish produced in the previous season remaining fairly stable from year to year (fig. 6). A large cohort of age-0 fish was apparent in the winter of 2013–2014, perhaps a result of compensatory survival following removal of larger brown trout. Similar relative declines were seen in rainbow trout, which were also removed, while native fish abundance and upstream extent increased, particularly in speckled dace (B. Healy, NPS, written commun., March 5, 2018).

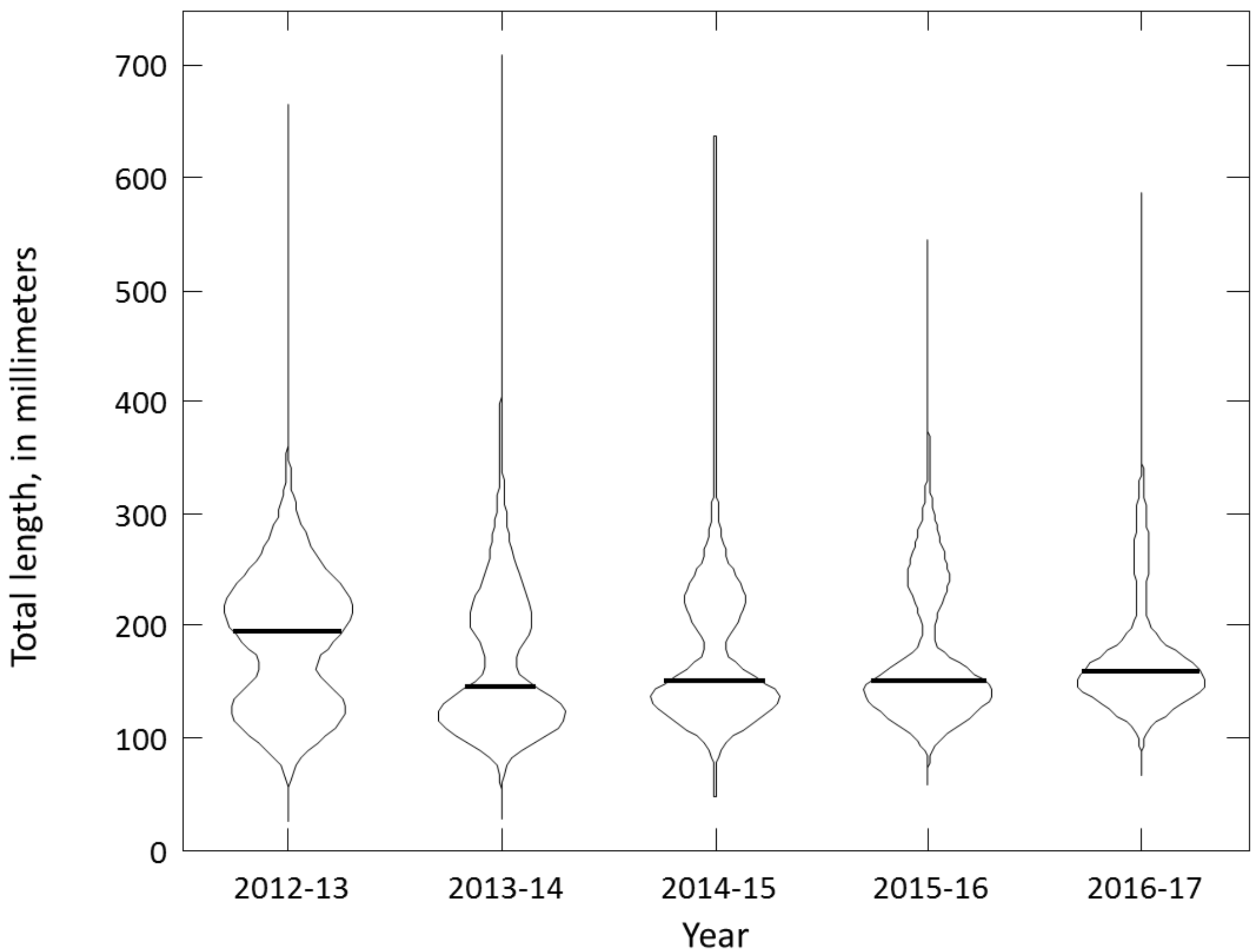

Figure 6. Violin plot of the distribution of total length of brown trout removed from Bright Angel Creek during five years (removals occur October through February) of backpack electrofishing. The width of each "violin" is proportional to the number of fish caught at each length. The solid lines show the median length of the fish removed. R. Schelly, National Park Service, written commun., January 10, 2018.

Current Brown Trout Research and Monitoring

In addition to work by NPS mentioned above, most brown trout research and monitoring in Glen, Marble, and Grand Canyons is being conducted as part of other ongoing studies by the GCMRC and its cooperators with support from the GCDAMP. These studies include long-term monitoring of the Lees Ferry trout fishery and the fish community in Grand Canyon by the AGFD, as well as research by GCMRC directed at understanding the population dynamics and movement of rainbow trout in the Lees Ferry reach. Prior to 2017, brown trout captured during ongoing mark-recapture studies of rainbow trout were marked with passive integrated transponder (PIT) tags and released. In 2017, the NPS directed GCMRC and AGFD to euthanize any brown trout captured during research and monitoring trips, after measuring and scanning for PIT tags.

The NPS, in collaboration with BioWest, Inc. and GCMRC, also began a pilot-level telemetry study in 2017. Ten brown trout captured in the Lees Ferry reach were surgically implanted with dual sonic/radio tags and released. The objectives of this work are to gather information regarding daily and seasonal movements of brown trout within the Lees Ferry reach and downstream, to identify locations of spawning aggregations, and to quantify time spent in habitats where these fish might be vulnerable (shallow, nearshore) or invulnerable (deep, mid-channel) to capture. Results will be used to inform managers concerning potential control strategies for brown trout in the Lees Ferry reach.

Hypotheses for the Increase of Brown Trout in the Lees Ferry Reach

Motivating Observations

There have been five consecutive annual increases in brown trout catch rates in the Lees Ferry reach from 2012 to 2017 (fig. 2). From 2001 to 2012 mean brown trout catch rates were low, averaging 0.26 fish/hr. In 2012, brown trout catch rate was around 0.35 fish/hr but by 2017 catch rates increased to 3.7 fish/hr (Rogowski and others, 2017b). Catch rates are a proxy for population abundance, so an increase in catch rates of this magnitude reflects a possible 10-fold increase in numbers of brown trout in the Lees Ferry reach. Catch rates by size class (figs. 2*B*, 2*C*, and 2*D*) show that the increase in numbers of brown trout in 2013–2014 was for a range of adult sizes, whereas increases in 2015–2016 were primarily driven by large numbers of young-of-year brown trout and, to a lesser extent, increases in adults, indicating that successful reproduction had taken place.

Brown trout spawn late in the calendar year, with the majority of Northern Hemisphere populations spawning between October and December (Elliott, 1994). Thus, young-of-year brown trout that began showing up in the catch in 2015 were probably spawned at the end of 2014. These trends of increasing adult numbers starting around 2013 or 2014, followed by multiple successful recruitment events starting in fall of 2014, are also evident in mark-recapture data that were first collected starting in 2012 (M.D. Yard, USGS, oral commun., August 20, 2017). Although brown trout numbers in the Lees Ferry reach have been increasing since 2013, the relative abundance of brown trout in the Lees Ferry reach remains relatively low at about 6 percent of the total trout catch in 2016 (Rogowski and others, 2017b).

This recent trend of rapidly growing Lees Ferry brown trout numbers has occurred against the backdrop of changing environmental conditions, including rapidly declining rainbow trout numbers (fig. 7). Specifically, catch rates for rainbow trout in Lees Ferry peaked in 2012 at about 464 fish/hr, but by 2016, after four consecutive years of decline, catch rates had decreased by 80 percent (to 99 fish/hr; Rogowski and others, 2017b). Mark-recapture studies in Lees Ferry show similar declining trends for rainbow trout (Korman and others, 2017). Mark-recapture studies also identified the cause of the rainbow trout decline as low availability of preferred aquatic insect prey (midges and blackflies), which led to poor condition and low adult survival (Yard and others, 2016; Kennedy, 2017; Korman and others, 2017). Concurrently with these changes in fish and invertebrate communities, mean September-January water temperatures increased over the period 1991–2017 (fig. 8).

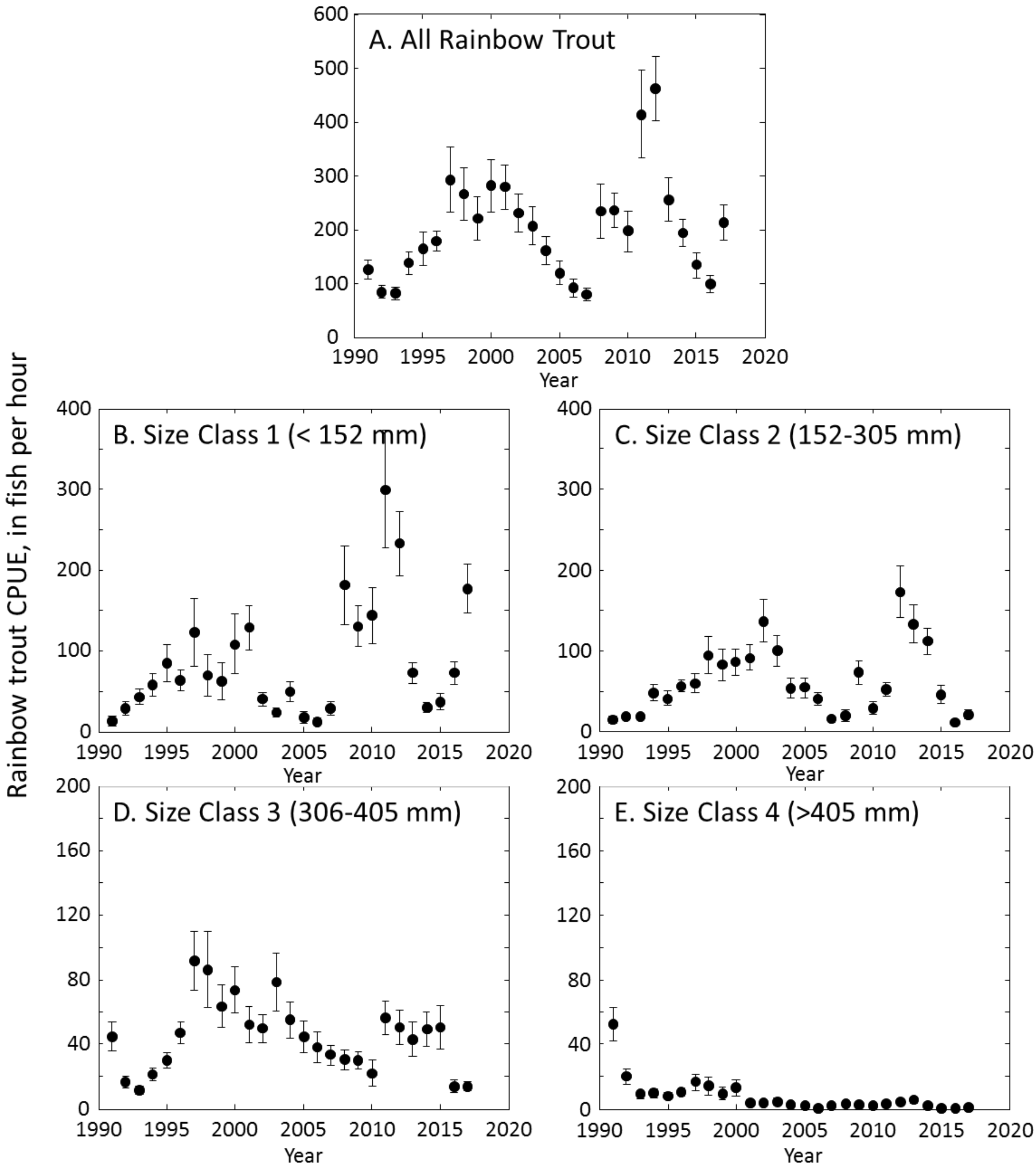

Figure 7. Rainbow trout average yearly electrofishing catch per unit effort (CPUE), in fish per hour, in the Lees Ferry reach of the Colorado River, 2001–2017. The closed circles show the mean value; the error bars show the 95-percent confidence intervals. *A*, All fish; *B*, Size class 1 fish (length <152 millimeters [mm]); *C*, Size class 2 fish (length 152–305 mm); *D*, Size class 3 fish (length 306–405 mm); *E*, Size class 4 fish (length >405 mm). Data from Arizona Game and Fish Department.

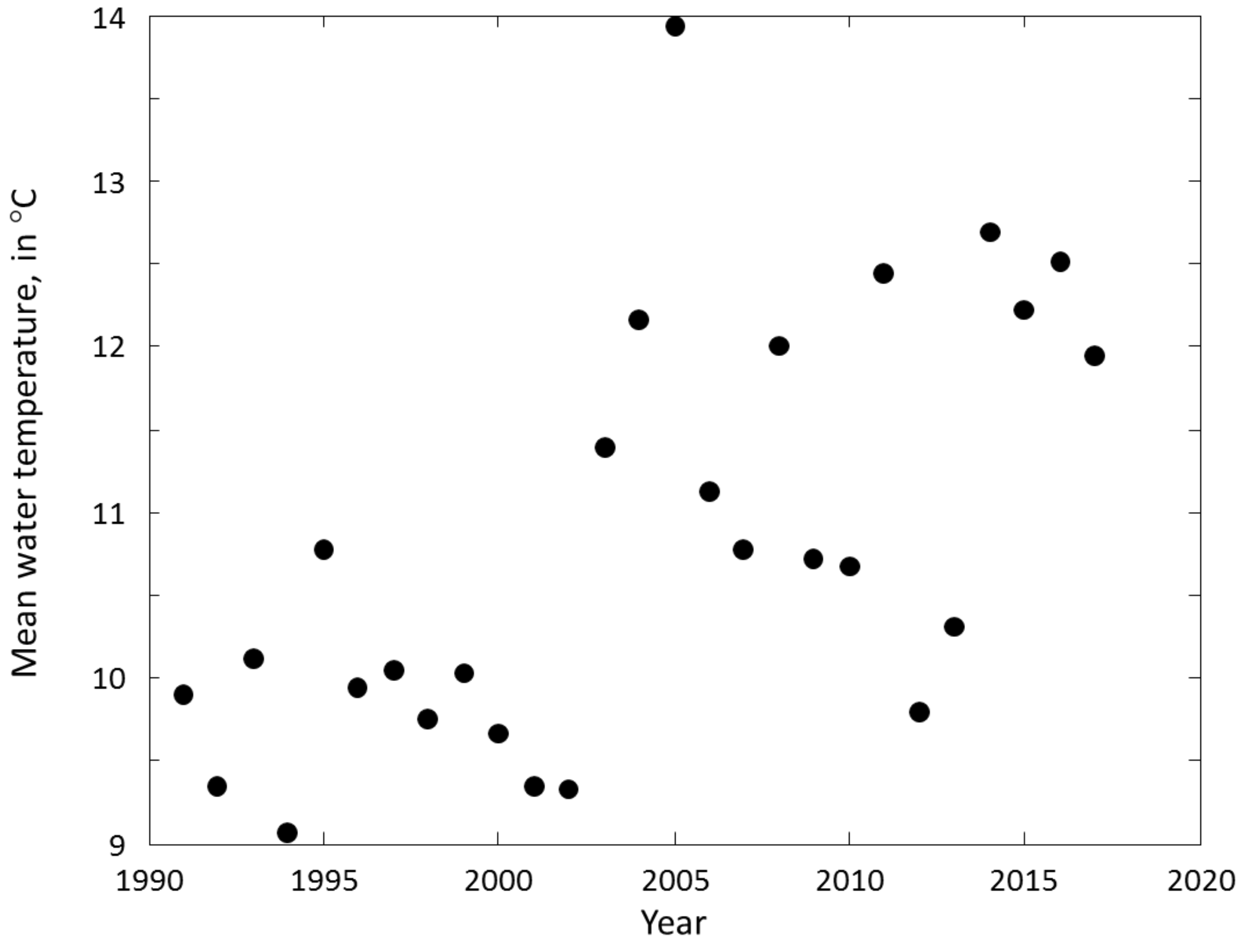

Figure 8. Graph of mean water temperature of the Colorado River at Lees Ferry during the brown trout reproduction season (September–January), 1991–2017. The point graphed for 1991, for instance, is the mean temperature over the period September 1990 through January 1991.

Reconstruction of the Lees Ferry Brown Trout Population

To investigate the relation between brown trout dynamics in the Lees Ferry reach and possible causal mechanisms, we developed a model that integrates mark-recapture data collected during 2012–2017 by the Natal Origins (NO) study[8] with the catch-based data collected during 2000–2017 by AGFD's monitoring project. We represented brown trout population dynamics in Lees Ferry with a size-structured population model (fig. 9) that includes survival and growth rates of three size classes (juveniles, <200 mm TL; small adults, 200–350 mm TL; and large adults, >350 mm TL), reproductive rates for the two larger classes, and immigration of large adults.

[8] The Natal Origins study was a large-scale mark-recapture study from fall 2011 to January 2017 between Lees Ferry and the LCR designed primarily to estimate the rate of movement and the system-wide abundance of rainbow trout (Korman and others, 2016). Brown trout were also captured, marked, and released.

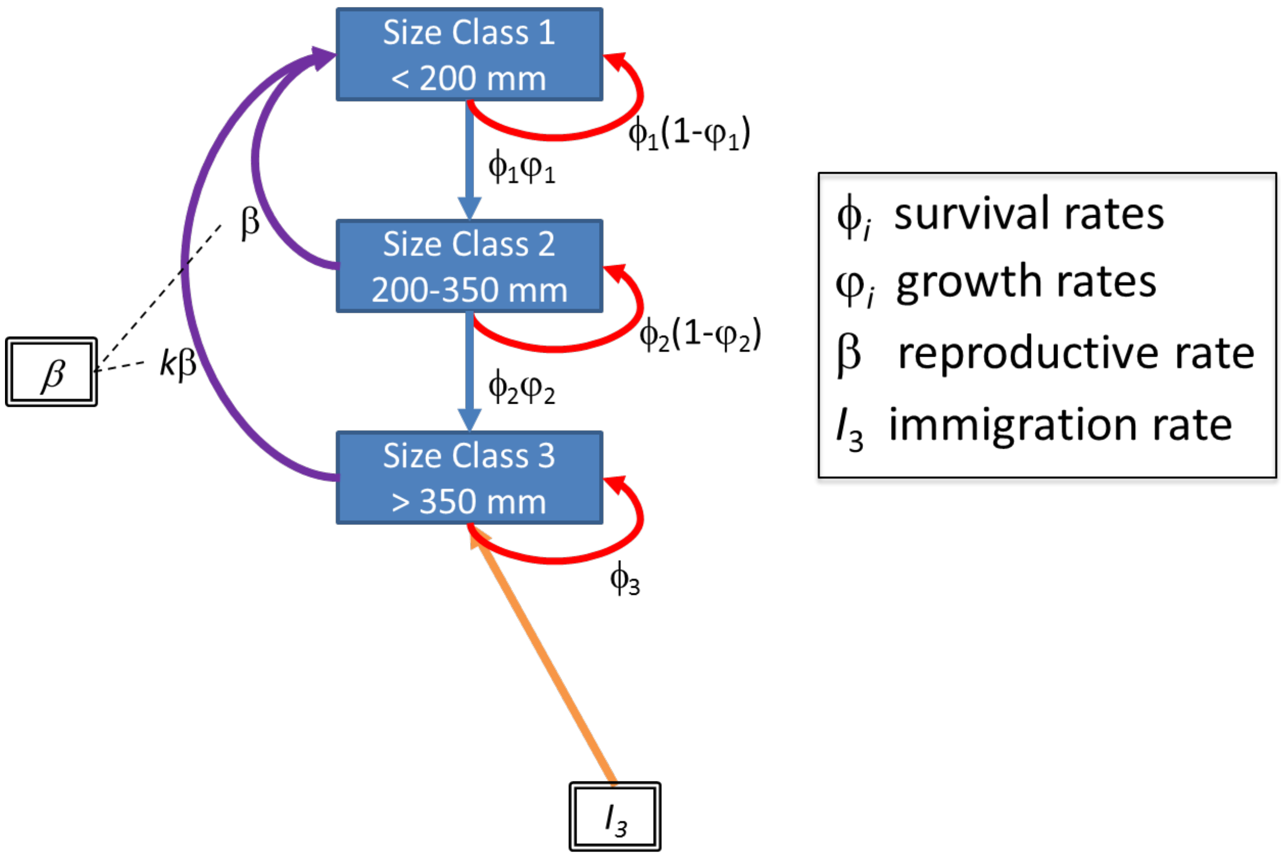

Figure 9. Life-history diagram for a size-structured model of brown trout. This is a size-structured model, with three size categories: size class 1 (<200 millimeters [mm] total length [TL]); size class 2 (200–350 mm TL); and size class 3 (>350 mm TL). Both size class 2 and size class 3 fish can reproduce, but the larger fish reproduce at a greater rate (as represented by the multiplier k >1). Transitions among classes are governed by survival rates (ϕ_i), growth rates (φ_i), and reproductive rates (β), where i indexes the size class. The number of size class 3 fish is augmented by immigration (I_3).

The model operates on a quarterly (seasonal) time step and begins in the fall of 2000. In the model, brown trout spawning occurs during the winter season (November–January), however juveniles do not appear until the following fall season (August–October). This gap occurs because young-of-the year brown trout have not been reported in the catch during the intervening periods (spring, February–April; or summer, May–July). The reproductive rate (β_y) for each year (y) is thus defined as the number of juvenile brown trout recruiting in the fall of the year per weighted adult in the preceding winter, where small adults are given a weight of one and large adults are given a weight of four (k=4, fig. 9). These weights were assigned based on the average mass of small and large adults captured during the study period and the relative fecundities of brown trout as a function of mass, as calculated from brown trout sacrificed during the Bright Angel removal project (Brian Healy, NPS, oral commun., August 1, 2017). Juvenile brown trout transition (grow) into the smaller adult size class during the subsequent seasons; the model allows these transition rates to vary among seasons, but holds the rates constant across years. All juvenile brown trout remaining in the juvenile size class in the summer season transition into the small adult size class prior to addition of that year's recruitment during the fall.

Transitions between small and large adult size classes were assumed to be seasonally constant because data on transitions were relatively sparse and there was no clear seasonality in the available data. Immigration of large adults ($I_{3,t}$) occurred in between each quarter (t). Survival was allowed to vary between seasons and size classes, however, survival was given a prior distribution based on the mean observed mass in that season and size class and the Lorenzen relation between natural mortality (inverse of survival) and fish mass (Lorenzen, 1996).

The model is implemented in a Bayesian framework, allowing us to incorporate prior information and random effects, which are both essential for making inferences from the relatively sparse data available. To reconstruct population dynamics we first assumed that annual reproductive rates and quarterly immigration rates were drawn from separate log-normal distributions with mean and variance hyper-parameters that were given uninformative priors; however, we later modified this assumption under different hypotheses. Mark-recapture data were analyzed using a multistate Cormack-Jolly-Seber formulation (Brownie and others, 1993), and catch from both NO and AGFD efforts were assumed to come from a Poisson distribution where the expected catch in each trip was based on trip and size-class specific capture probabilities, adjusted to account for variation in effort between trips (and in the case of NO data to account for the fact that only a portion of the population was included in the study area). Trip and size-class specific capture probabilities were inverse-logit transformations of deviates drawn from normal distributions with the same variance, but with different modes based on the size class and sampling trip type. The NO and AGFD sampling had different parameters describing the average capture probability of the three different size classes, and trips during the winter season had a different capture probability for large adults, reflecting their increased susceptibility to capture while spawning.

Estimates from population reconstruction suggest that prior to 2010, the Lees Ferry brown trout population largely consisted of older fish (size class 3; >350 mm TL), presumably from some low, sustained level of immigration, without evidence of successful reproduction (fig. 10). In 2011 and 2013, there were brief reproductive events that produced size class 1 fish (<200 mm TL), and size class 2 fish in the following year. Between fall 2014 and winter 2014–15, a substantial immigration event occurred (as evidenced by the large increase between the fall 2014 and fall 2015 size class 3 estimates, fig. 10). This was followed by high rates of local reproduction in 2015–2017. The large number of young-of-the year in 2016 produced a large increase in size class 2 fish in 2017. The reversal in the size-class distribution suggests the population has gone from one maintained by immigration to one maintained by local reproduction. The two most salient clues to the change in status are:

1. A burst of immigration in the fall of 2014 and
2. Increased reproductive rates in 2011, 2013, and from 2015 onwards.

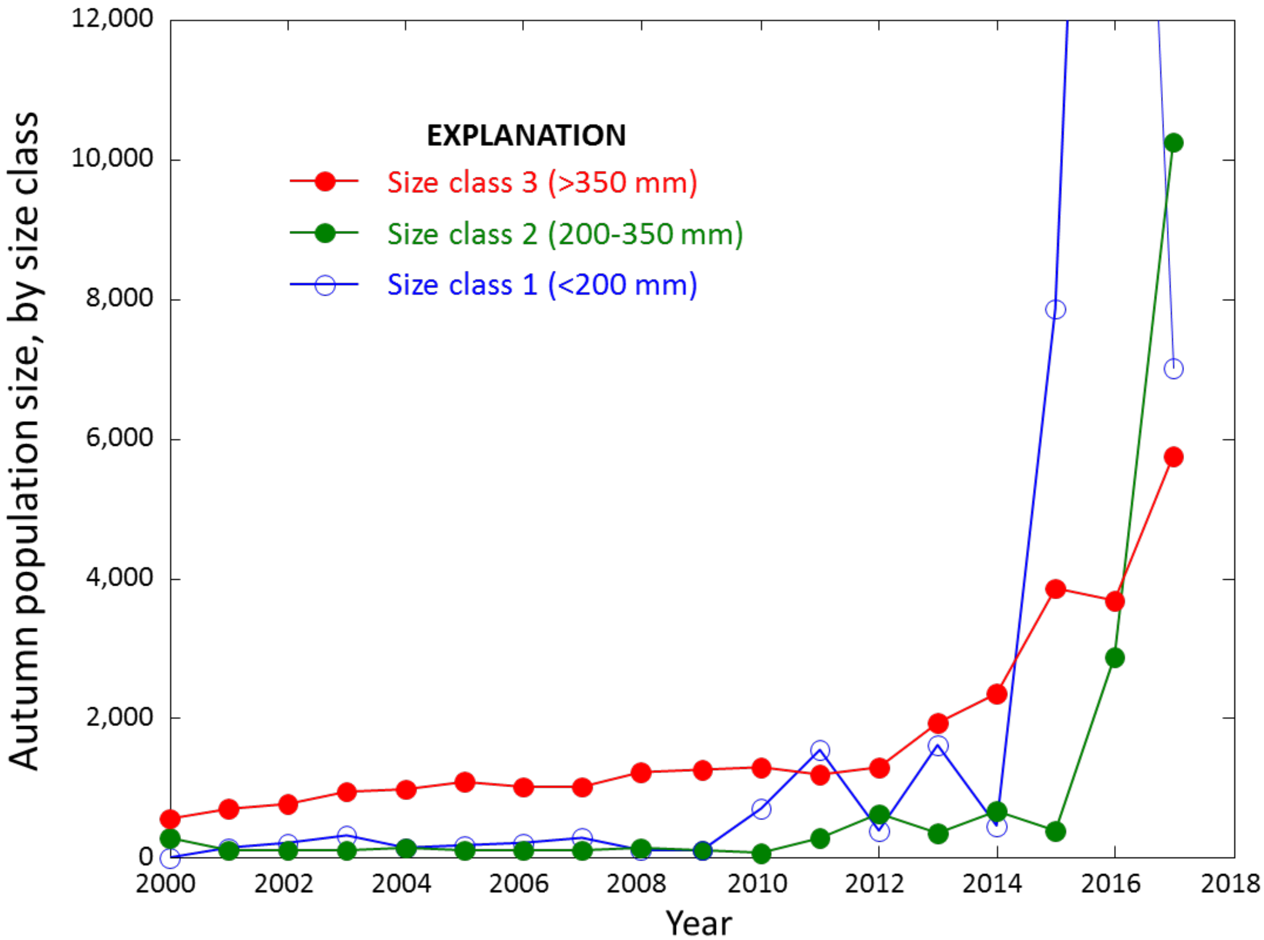

Figure 10. Graph of autumn brown trout population size in the Lees Ferry reach of the Colorado River, by size class, 2000–2017. The estimated population sizes were reconstructed from catch per unit effort (Arizona Game and Fish Department) and capture-mark-recapture data (Natal Origins study). The population size axis is truncated to better show the trends; the single truncated point is at 26,700 fish (2015, size class 1). mm, millimeter.

Hypotheses for a Change in Immigration Rate

One possible proximate explanation for the change in status of brown trout in Lees Ferry is that there was an increase in immigration rate of size class 3 fish from downstream locations, and the increase in spawners led to an increase in reproduction and growth of the population. But what is the ultimate reason for the change in immigration, and what does that suggest for the future? We considered four hypotheses for the change in immigration.

The first of the immigration hypotheses is that fall HFEs are a cue for ripe and gravid brown trout to migrate into Glen Canyon. Ovidio and others (1998) found brown trout migration to spawning grounds was triggered by high variance in flow and temperature, similar to what occurs during HFEs. HFEs were implemented in the first or second week of November in 4 of 5 years from 2012 to 2016. These fall HFEs lasted 5–6 days with an upramp from a base flow of about 8,000 cubic feet per second (cfs) to about 40,000 cfs in the first day. This change in dam releases causes high variation in river flow and a short-term decrease in temperature of about 1–3 °C. Brown trout worldwide spawn in the fall with decreasing photoperiod and at a range of about 8–14 °C. Movement of adult brown trout commonly increases during spawning, usually in October–November (Meyers and others, 1992; Burrell and others, 2000; Quinn and Kwak, 2011). The major source of adult brown trout in Grand Canyon is the area around Bright Angel Creek (Reach 3, fig. 4), where a large number of individuals was present, as indicated by a large catch in a weir during winter of 2012–13 (fig. 5).

This hypothesis supposes that the increase in numbers of brown trout in the Lees Ferry reach starting in 2013 and increasing through 2016 was the result of immigration from the Bright Angel Creek area through Marble Canyon in a “stepping stone” fashion. Based on observed distances moved by adult brown trout in other systems (0.74 km/day, Ovidio and others, 1998 to 4.0 km/day, Marmulla and Ingendahl, 1996) and assuming movement occurred only on days when water temperature was consistently >10 °C, total distances moved could be between 26 and 140 km per year. The distance from Bright Angel Creek to Lees Ferry is 141 km (90 river miles), suggesting 2 to 3 years of fall HFEs would be needed to induce migration the full distance. Immigration rates are low in years without an HFE in the previous fall (fig. 11). For years in which there was an HFE in the previous fall, it appears the immigration rate increases with the number of fall HFEs in the previous three years (fig. 11), although this inference depends heavily on the single observation of a spike in immigration in 2015, a year that followed three sequential fall HFEs. Thus, this hypothesis is plausible given what we know about brown trout behavior, and there is some empirical evidence to support it. For it to continue to act in a similar manner in the future depends on a continued source of migrants from downstream and an assumption that brown trout can stage at various points in Marble Canyon over the years it takes to make the full migration. Currently the abundance of brown trout in the Bright Angel reach, and the next upstream reach is low, relative to 2011–2013, so the source of fish available to migrate is much reduced (fig. 4).

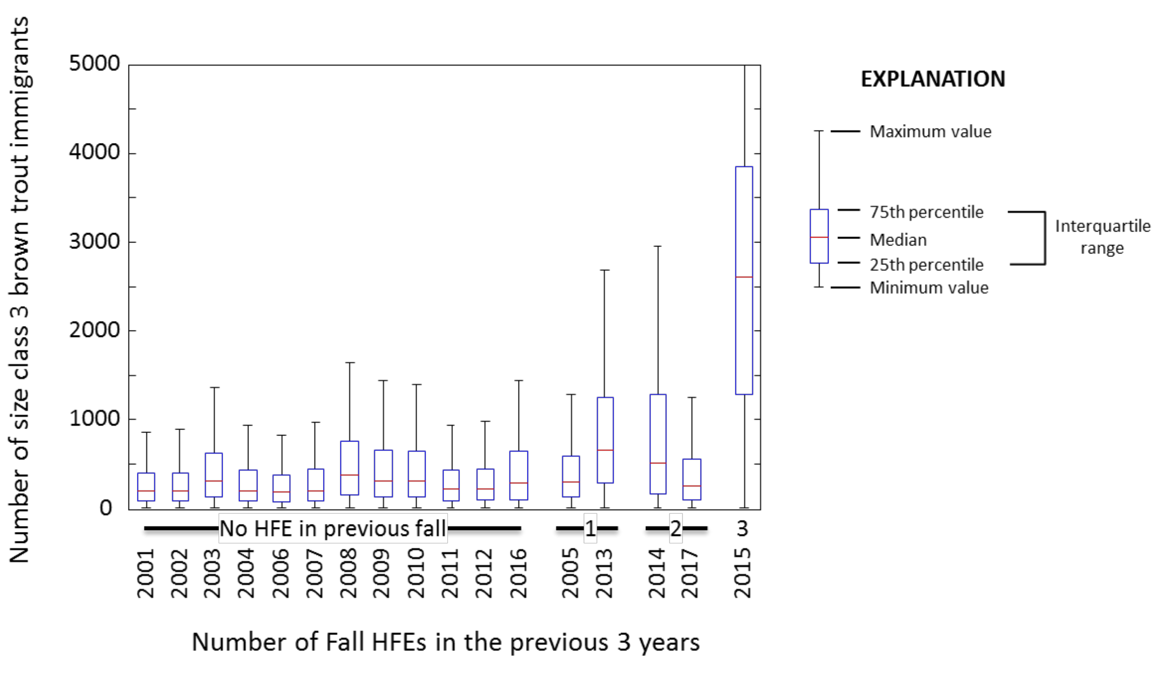

Figure 11. Boxplots of the annual number of size class 3 (>350 millimeters) brown trout immigrating into the Lees Ferry reach of the Colorado River as a function of the number of fall high-flow experiments (HFEs) in the previous three years, 2001–2017. The seasons are grouped into annual cycles beginning in the fall, thus the immigrants grouped in the box labelled 2015 include immigrants from fall 2014 through summer 2015.

The remaining three immigration hypotheses are all "pulse" immigration hypotheses, which posit there was just a single large immigration event in the fall of 2014 driven by special circumstances that are not likely to be repeated often. These three hypotheses differ in the causal explanation for the pulse of immigration, which could have been because of:

- (a) the weir in Bright Angel Creek preventing spawners from returning to the creek and inducing them to look elsewhere upstream;
- (b) compensatory reproduction in Bright Angel Creek as a result of the removal efforts, creating a large cohort that left the creek and began moving upstream; or
- (c) a system-wide reduction in food resources inducing migratory behavior in downstream fish.

The estimated quarterly immigration rate increased somewhat in late 2013 and early 2014, but showed a very large increase in the fall of 2014 (fig. 12). This lends some support to the notion this was a single pulse immigration event, as there is no other evidence of a large immigration event in the available time series. This pulse event in fall 2014 is compatible with the Bright Angel Creek weir hypothesis, as the weir was consistently in place beginning in 2012, and the movement rates cited above suggest a 2–3-year period to move from there to Lees Ferry. There was a compensatory increase in reproduction in Bright Angel Creek in 2013, but if those fish moved upstream, they would only be size class 1 or 2 fish in the fall of 2014, and the immigrants were largely size class 3 fish, so this version of the pulse hypothesis does not have as much support. There was system-wide food limitation, as evidenced by invertebrate drift data and light-trap catches of adult aquatic insects (Kennedy, 2017), fish condition data (Yackulic, 2017), and a large decline in the rainbow trout population (fig. 7), but all of this occurred primarily in 2014, leaving only about 6 months for fish to migrate upstream in search of better conditions, a possible transit time, but a fast one. Thus, the pulse hypothesis is plausible and there is empirical evidence for it, with perhaps more support going to the Bright Angel Creek weir as a causal mechanism than to the other pulse hypotheses. If the pulse hypothesis is true, it suggests such an immigration event would not be expected to occur again in the future, unless another set of unique events precipitated it.

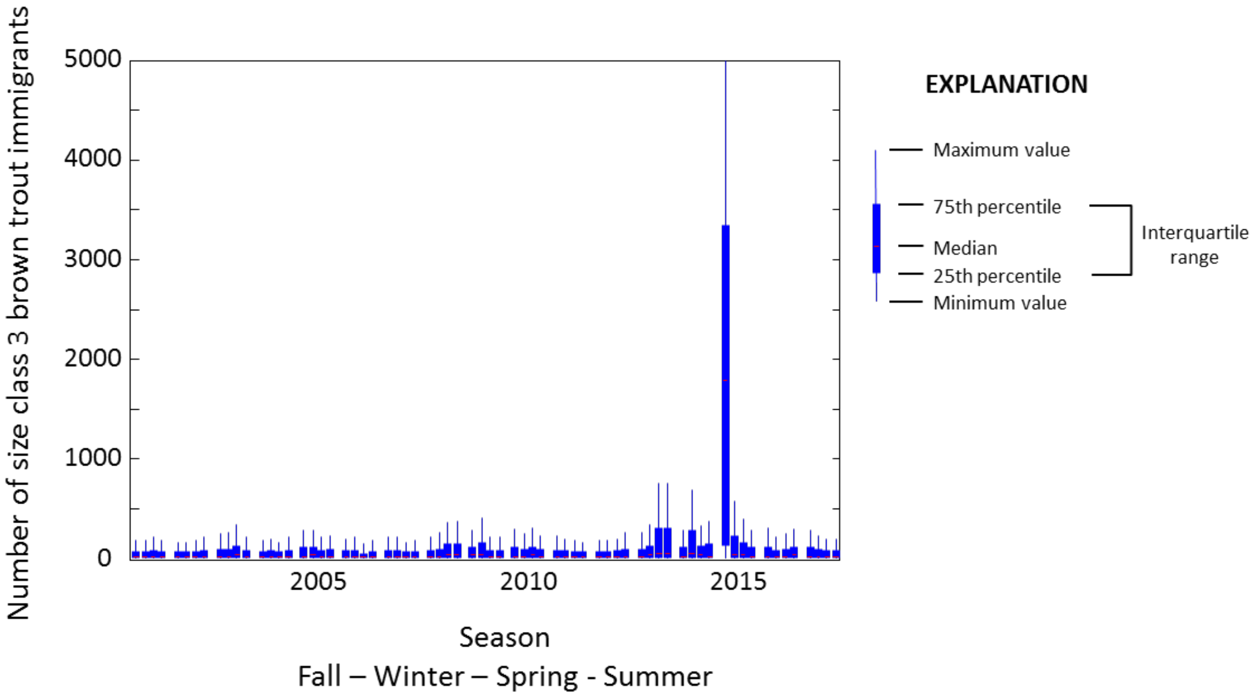

Figure 12. Boxplots of the quarterly number of size class 3 (>350 millimeters) brown trout immigrating into the Lees Ferry reach of the Colorado River, 2001–2017. The seasons are grouped into annual cycles beginning in the fall, thus, the four boxplots labelled 2015 are: fall 2014, winter 2014–15, spring 2015, and summer 2015. A large immigration event was observed in fall 2014.

Hypotheses for a Change in Reproductive Rate

Another possible proximate explanation for the change in status of brown trout in the Lees Ferry reach is that there was an increase in reproductive rate, owing to some causal factor that changed environmental conditions, inducing an increase in spawning or otherwise increasing the success of reproductive stages. We considered four hypotheses for a change in reproductive rate.

The first of the reproductive hypotheses is that the brown trout spawning population crossed an Allee threshold that was limiting reproduction. An Allee effect is a population dynamic in which some demographic rate is depressed at low population densities; for example, in some populations, the reproductive rate is low because animals cannot easily find mates at low density. Under this hypothesis, the historical reproductive rate in Lees Ferry was low because the brown trout spawning density was too low; at some point, through immigration, a synchronizing event, or just random variation, the spawning population increased above the limiting threshold, and reproductive rates increased. If we examine the annual reproductive rate of brown trout in the Lees Ferry reach against the weighted adult population size (a measure that gives size class 3 fish four times the weight in the estimate than size class 2 fish, because of their greater contribution to reproduction), an Allee effect is supported (fig. 13), as the highest reproductive rates have occurred when the population size has been larger, but the relation is noisy, and could arise out of correlation induced by some other factor.

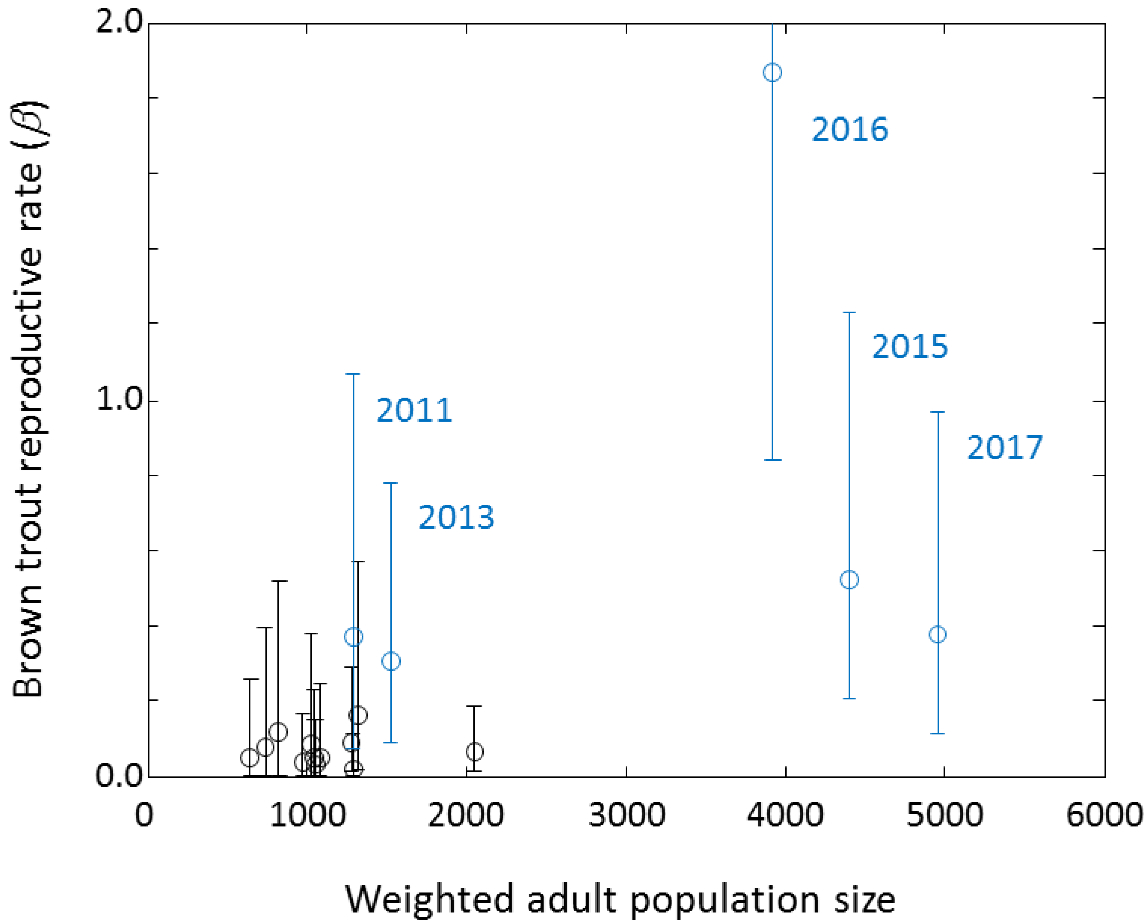

Figure 13. Graph of brown trout reproductive rate in the Lees Ferry reach of the Colorado River as a function of the weighted adult population size, 2001–2017. Years in which the mean estimate of the reproductive rate was above 0.25 are shown in blue (2011, 2013, 2015–17). The open circles show the mean value; the error bars show the 95-percent confidence intervals.

The second of the reproductive hypotheses is that fall-timed HFEs cleanse spawning gravels immediately prior to brown trout spawning thereby improving egg survival and recruitment. As noted above, adult brown trout spawn in the fall, usually from October through December (Elliott, 1994), and fall HFEs increase flow rates substantially for a number of days during that period. This mechanism suggests an immediate effect, such that the number of young-of-the-year fish should depend on whether an HFE occurred in the preceding fall. The empirical evidence for this effect is equivocal (fig. 14). In three out of five years following a fall HFE, the reproductive rate (β) was higher than in almost all other years, but in two years (2005, 2014), the reproductive rate was quite low. Further, the year with the highest estimated reproductive rate (2016) did not follow a fall HFE. If we exclude 2016 from analysis, then average reproductive rate is 0.26 in years following a fall HFE, and 0.10 in years not following a fall HFE. Thus, there is some empirical evidence to support this causal hypothesis, but it is not conclusive.

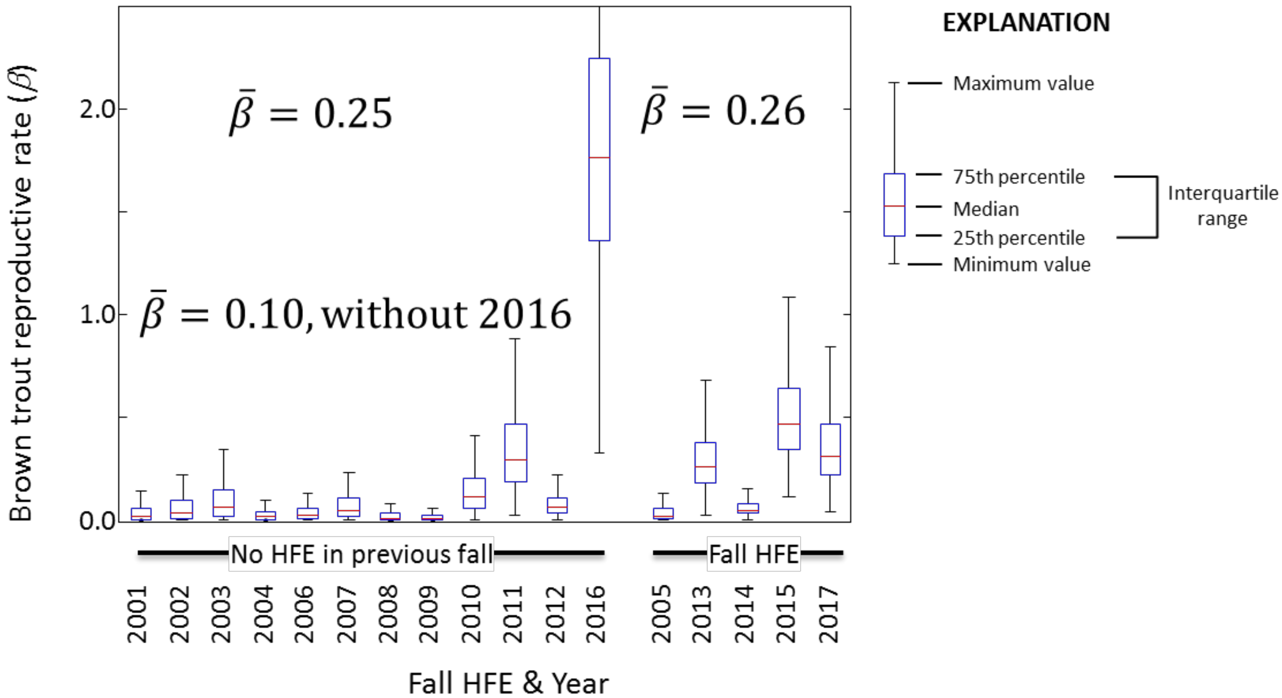

Figure 14. Boxplots of brown trout reproductive rate in the Lees Ferry reach of the Colorado River, grouped into years with and without a high-flow experiment (HFE) in the preceding fall, 2001–2017.

The third of the reproductive hypotheses is that recent warm water temperatures are facilitating increases in brown trout populations by increasing spawning rates, egg survival, or growth rates during the first 9 months of life. As we are able to measure it for brown trout, reproduction includes a number of important events: the physiological preparation of the fish to enter breeding condition (gonadal development); the induction of spawning behavior, including movement to spawning habitat; spawning itself; the survival of eggs; and the survival and growth of young fish. All of these stages could be affected by temperature in a number of ways, but the relevant aspects of water temperature might differ for the events. We assumed that a temperature effect on propensity to spawn was the most likely mechanism that could matter in this system, in part because we noted that winter water temperatures (those that would affect hatching and growth and survival of young) showed very little variation across years. Thus, we focused on water temperatures during gonadal maturation and spawning (September–January). September–January water temperatures downstream of Glen Canyon Dam have been warmer since 2004 than during the previous 12 years (fig. 8). There is, however, very little correlation between the reproductive rate and the fall water temperature at Lees Ferry (fig. 15). Further, temperature-growth relations for rainbow trout are virtually identical to those for brown trout (Elliott, 1994), yet rainbow trout populations declined over this same period that brown trout were increasing. Thus, while the physiological mechanism behind this hypothesis is plausible, there is not empirical evidence to support it. There are a number of other mechanisms for a temperature effect on reproduction that could be posited. For example, the maximum growth efficiency for brown trout feeding on invertebrates occurs at 13°C (Elliott and others, 1995); perhaps there are differences in temperature at a critical growth period during the spring that affect the reproductive rate. A more detailed evaluation of specific mechanisms of temperature effect on brown trout reproductive processes was beyond the scope of this project, because of limitations of both data and time. Such an evaluation could be fruitful, but we do note that the moderating effect of the dam and its flows has tempered the variation in water temperature in this system, particularly during the fall and early winter periods.

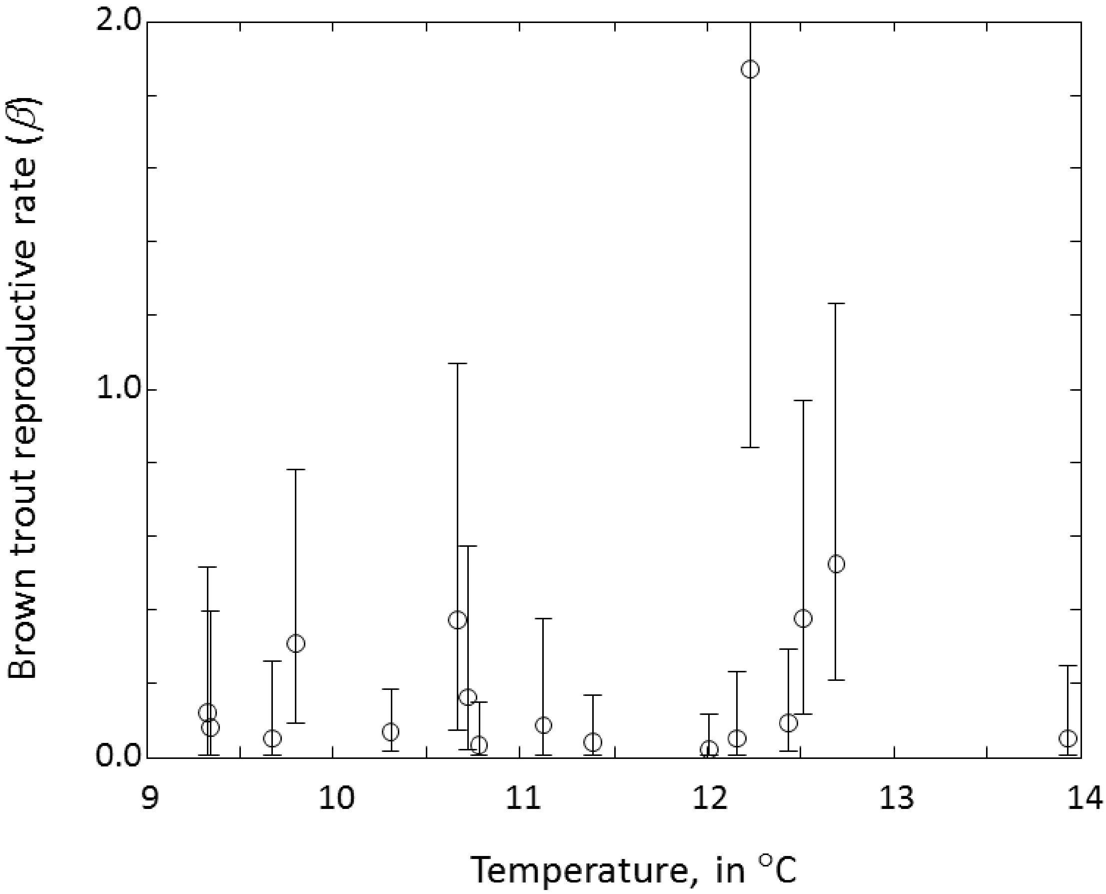

Figure 15. Graph of brown trout reproductive rate in the Lees Ferry reach of the Colorado River as a function of mean September–January water temperature in the preceding fall, 2001–2017. The open circles show the mean value; the error bars show the 95-percent confidence intervals.

The fourth of the reproductive hypotheses is that declines in rainbow trout in Lees Ferry have led to a decrease in interference spawning, and thus an increase in brown trout reproductive success. Rainbow trout spawning could potentially interfere with brown trout reproduction in either of two ways: rainbow trout may compete with brown trout for spawning sites; or rainbow trout that spawn later than brown trout may superimpose eggs on top of brown trout eggs or dislodge them, thereby reducing brown trout egg survival. There is evidence in the literature that superimposition of redds (spawning nests) or redd disturbance by rainbow trout can negatively affect other trout species, including brown trout (Scott and Irvine, 2000; Nomoto and others, 2010). As a proxy for rainbow trout spawning effort at Lees Ferry, we use the estimated rainbow trout reproduction (young-of-the-year) in the following fall. The brown trout reproductive rate shows a weak negative correlation with rainbow trout reproduction (fig. 16), but the correlation is driven by one particular year (2016) when brown trout reproductive rate was high and rainbow trout reproduction was low. There was a similar decrease in rainbow trout populations from 2003–2007 (fig. 7) without a corresponding increase in brown trout reproduction. Thus, while the mechanism for this hypothesis is plausible, there is not strong empirical evidence to support it.

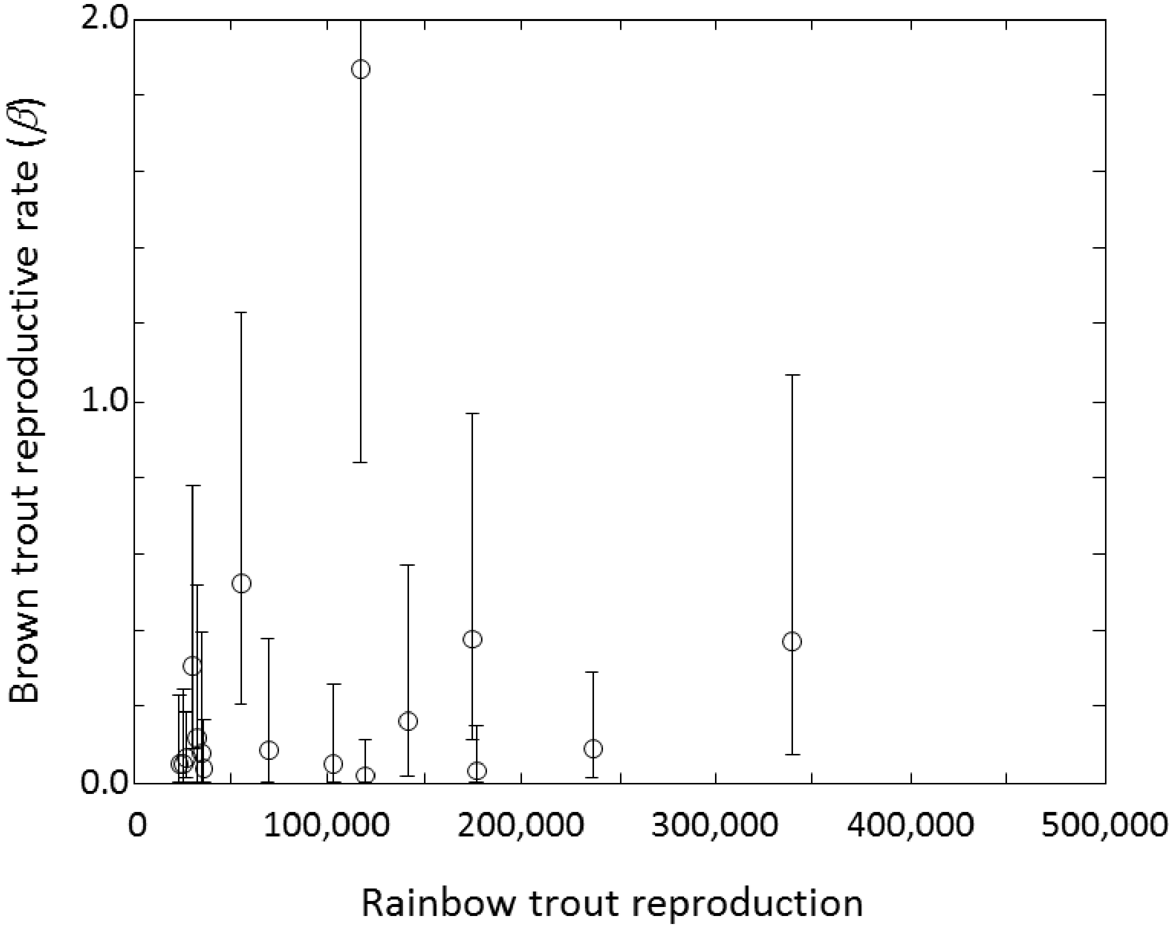

Figure 16. Graph of brown trout reproductive rate in the Lees Ferry reach of the Colorado River as a function of total rainbow trout reproduction in the corresponding year, 2001–2017. The open circles show the mean value; the error bars show the 95-percent confidence intervals.

Combined Hypotheses for the Change in Brown Trout Dynamics

The primary proximate hypotheses we considered for the change in brown trout dynamics focused on changes in immigration rates (Proximate Hypothesis A), changes in reproductive rates (Proximate Hypothesis C), or both (Proximate Hypothesis B), but other proximate mechanisms are also possible. Nested within each of the proximate hypotheses are a series of ultimate hypotheses (or causal mechanisms). A number of these causal hypotheses can occur in combination. Taking this all together, we initially considered 13 hypotheses (table 1). Hypotheses A.1 through A.4 propose that the change in brown trout status was largely driven by a change in immigration rate; the specific causal hypotheses were outlined earlier (see “Hypotheses for a Change in Immigration Rate”). Hypotheses C.7 through C.10 propose that the change in status was largely driven by a change in reproductive rate; the specific causal hypotheses were outlined earlier (see “Hypotheses for a Change in Reproductive Rate”). Hypotheses B.5 and B.6 propose that both immigration rates and reproductive rates changed, either through mechanisms that did not involve fall HFEs (B.5) or mechanisms that did (B.6). An additional set of hypotheses considered mechanisms that also involve changes to survival or growth rates. Hypothesis D.11 proposes that an increase in invertebrate prey in the freshwater amphipod genus *Gammarus* provided an increase in prey base for large brown trout, raising the survival, condition, and reproductive rate of size class 3 fish; Hypothesis E.12 proposes that abundant rainbow trout young provided a prey base for brown trout, increasing the size class 2 and 3 survival rates; and Hypothesis F.13 proposes that small (size class 1) rainbow and brown trout compete for similar resources and a decrease in rainbow trout young increased the growth and survival rates of small brown trout.

Table 1. Proximate and ultimate hypotheses for the increase in brown trout in the Lees Ferry reach of the Colorado River, 2013–present. The proximate demographic hypotheses are noted with a capital letter (A–F) and correspond to particular patterns in the demographic parameters. The ultimate hypotheses are noted with a number and provide a causal explanation for the demographic changes.

[β, reproductive rates; I, immigration rates; ϕ_i, survival rates; φ_i, growth rates; i, indexes the size class; HFE, high-flow experiment; BAC, Bright Angel Creek; RBT, rainbow trout; BT, brown trout]

Hypothesis	Demographic changes					Reason	Carried forward?
	β	I_3	ϕ_3	φ_2	$\phi_1\varphi_1$		
A.1	0	++	0	0	0	Fall HFE	Yes
A.2	0	++	0	0	0	Weir	Yes, as A.2–4
A.3	0	++	0	0	0	Food-limitation downstream	Yes, as A.2–4
A.4	0	++	0	0	0	BAC compensatory pulse	Yes, as A.2–4
B.5	+	+	0	0	0	Allee effect + immigration	Yes
B.6	+	+	0	0	0	Fall HFE	Yes
C.7	++	0	0	0	0	Allee effect + synch. Event	No
C.8	++	0	0	0	0	Temperature	Yes
C.9	++	0	0	0	0	Interference spawning	Yes
C.10	++	0	0	0	0	Fall HFE	Yes
D.11	+	0	+	0	0	Prey base (*Gammarus*)	No
E.12	0	0	+	+	0	RBT as prey for BT	No
F.13	+	0	0	0	+	Prey base (RBT/BT comp.)	No

In an effort to reduce the magnitude of the analytical task, we sought to reduce the number of hypotheses in table 1, using insights into the evidence for each hypothesis, as well as arguments regarding the practical differences among the hypotheses. At the same time, we recognized that these alternative hypotheses serve not only to explain how the system came to be in the state it is in, but also to offer predictions about how the dynamics of brown trout will unfold in the future, under different management strategies. The set of hypotheses was refined as follows:

- Hypotheses A.2 through A.4 can be combined into a single hypothesis that explains the change at Lees Ferry as a result of a pulse of immigration from 2013 to 2015. The particular mechanism that caused the pulse of immigration (the weir at Bright Angel Creek, food-limitation, a compensatory pulse of reproduction from the Bright Angel removal project, or some other reason) is not material to future predictions. The relevant point is that the immigration was short lived.
- Hypothesis C.7 posits an Allee effect on reproductive rate, without an increase in immigration. For this to occur, there would have to be some synchronizing event that allowed a small spawning population to overcome the Allee threshold, at least briefly. While this is possible, we have elected to drop it at this time, because without an understanding of how the synchronizing

event may have come about, we cannot anticipate how this hypothesis would play out in the future.

- Under Hypothesis F.13, if the bulk of the prey competition is between brown and rainbow trout in very early life stages (prior to stage 1), then this hypothesis actually looks similar to Hypothesis C.9, and we can merge the two. Granted the mechanism of competition is different (interference spawning versus prey competition), but the demographic consequences are similar.
- The remaining two prey hypotheses (D.11 and E.12) do not, at first glance, provide a good explanation for the timing of the changes seen in the observed capture data of brown trout at Lees Ferry. Although these hypotheses may well be plausible, more work is needed to examine their mechanisms. In the interest of time, we are not analyzing them in detail.

We recognize that there are more possible combinations of hypotheses than we have articulated. In particular, the Proximate Hypothesis B could have as many as 8 versions, even under our reduced set (2 immigration mechanisms times 4 reproductive mechanisms). We chose to consider just two of those 8 (B.5 and B.6) because they represent an important contrast between hypotheses that involve fall HFEs and those that do not; we felt the remaining combinations represent more subtle differences than we can discern at this time. We also recognize there are other mechanistic hypotheses that have been proposed (for example, whirling disease acting on rainbow trout to provide some advantage to brown trout). Our set of hypotheses is not meant to be exhaustive, rather, it is meant to represent the mechanisms that seem most plausible and relevant to us, given the information available at this time.

Thus, we carried forward seven hypotheses for further analysis (A.1, A.2–4, B.5, B.6, C.8, C.9, and C.10). We have not assigned a quantitative weight of evidence to these hypotheses at this time, but either an empirical (likelihood-based) method or a process of expert judgment could be used in the future to do so. That said, of the seven hypotheses, we assign the most credibility to B.5 and B.6, because there is evidence for both a change in immigration and a change in reproduction. In figure 17, we depict how the causal relations implied by these hypotheses interact with the population model for brown trout. These relations are embedded in the analytical work described later in this report.

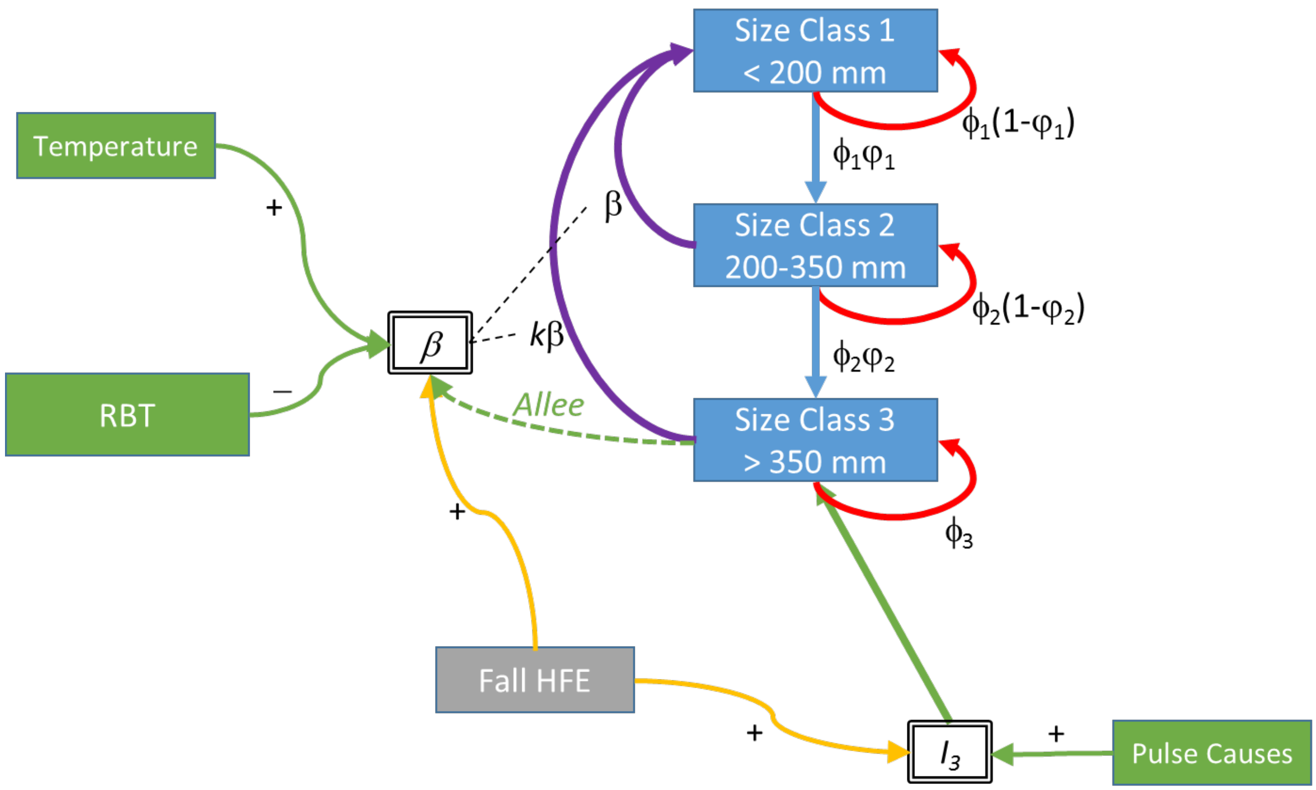

Figure 17. Influence diagram showing proposed causal mechanisms for the increase in brown trout in the Lees Ferry reach of the Colorado River. β, reproductive rates; I, immigration rates; ϕ_i, survival rates; φ_i, growth rates; *i*, indexes the size class; HFE, high-flow experiment; RBT, rainbow trout; mm, millimeter.

Management Objectives

Management of brown trout downstream of Glen Canyon Dam takes place in the context of management of a complex system with many desired outcomes. In February 2012, the AMWG adopted and transmitted to the Secretary of the Interior a set of desired future conditions (DFCs) for the Colorado River ecosystem, divided into four categories (Colorado River ecosystem, power, cultural resources, and recreation) that expressed the range of important outcomes the stakeholders want to see from management of Glen Canyon Dam and related resources. The 2016 LTEMP used the DFCs as the basis for a set of resource goals that were evaluated in the LTEMP FEIS, and the LTEMP ROD adopted these resource goals as the guide for the future of the GCDAMP. These efforts reveal a critical aspect of management of this ecosystem; no one component can be managed in isolation of other components (Schmidt and others, 1998). There are difficult tradeoffs to consider in choosing management actions. The values-based challenge for the decision makers is how to weigh those tradeoffs, and this requires consideration of legal, economic, social, and political considerations, but the first step is articulation of the management objectives under consideration.

Regarding management of brown trout, the February 2017 AMWG letter and the charge from the Secretary's designee both suggest that objectives related to the following considerations are important: compliance with the ESA, tribal concerns with taking of life, condition of the rainbow trout fishery, and potential interactions with HFEs. Based on this guidance, as well as discussion with management agencies and stakeholders at the September 2017 brown trout workshop, we took into consideration six management objectives concerning; brown trout, humpback chub, the rainbow trout fishery, sediment resources, hydropower generation, implementation costs, and tribal values. These objectives and the performance metrics we used to evaluate them are discussed in the subsections that follow.

Brown Trout

The trigger for this project was concern that brown trout have become established and are expanding in the Lees Ferry reach. Thus, at first glance, it appears that minimizing brown trout in the Lees Ferry reach is an objective of management, but it is not clear whether it is a fundamental objective, or simply a presumed means to achieve other objectives. The GCDAMP resource goals described in the LTEMP ROD include the desire to “minimize or reduce the presence and expansion of aquatic nonnative invasive species” (U.S. Department of Interior, 2016b), which includes a desire to reduce brown trout throughout the Colorado River, including the Lees Ferry reach. The NPS CFMP identifies, for Grand Canyon National Park (GCNP), an objective to “prevent further introductions of nonnative (exotic) aquatic species, and remove, when possible, or otherwise contain, individuals or populations of nonnative species already established in GCNP”; and for Glen Canyon National Recreation Area (GCNRA), an objective to “prevent further introductions of nonnative (exotic) species” (National Park Service, 2013b). For the purposes of this paper, we do not need to resolve the policy question of whether minimizing brown trout in the Less Ferry reach is a fundamental or means objective; it is enough to note that there is a concern about brown trout in Lees Ferry. As a measure of this concern, in the analyses that follow, we focus on projections of adult (size class 3) brown trout in Lees Ferry over the next 20 years (the planning period for LTEMP). In most cases, we report the projected mean number of size class 3 adult brown trout over the next 20 years.

Humpback Chub

One of the threats to the endangered humpback chub is competition with and predation by nonnative fishes, including brown trout. The LTEMP FEIS included a resource goal to “meet humpback chub recovery goals including maintaining a self-sustaining population, spawning habitat, and aggregations in the natural range of the humpback chub in the Colorado River and its tributaries below the Glen Canyon Dam.” As a performance metric for a self-sustaining population, the LTEMP FEIS evaluated the expected minimum number of adult humpback chub in the LCR population during the 20 years of the LTEMP implementation period. We use this same performance metric in the analyses that follow.

Condition of the Rainbow Trout Fishery

The blue-ribbon rainbow trout fishery in the Lees Ferry reach of the Colorado River is an important recreational resource that generates an estimated $2.7 million annually in economic value to the area surrounding Lees Ferry (Bair and others, 2016). Efforts to control brown trout, whether through flow manipulations or mechanical removal, might also affect rainbow trout. The LTEMP FEIS included a resource goal to “achieve a healthy high-quality recreational rainbow trout fishery in the Glen Canyon National Recreation Area and reduce or eliminate downstream rainbow trout migration consistent with NPS fish management and ESA compliance.” Several performance metrics were used to evaluate achievement of this objective: the rainbow trout catch rate (age 2+ fish per angler-hour), the rainbow trout emigration rate (number of age–0 trout moving downstream into Marble Canyon per year), and the abundance of high-quality rainbow trout (greater than 16 inches) in the Lees Ferry reach. The NPS

CFMP (National Park Service, 2013a) includes a goal to "maintain a highly valued recreational rainbow trout fishery with minimal emigration of rainbow trout downstream to Grand Canyon National Park." In 2015, AGFD finalized a fisheries management plan for Lees Ferry (Rogers, 2015). The objectives in the fisheries management plan were similar to those in the LTEMP FEIS: (1) "Maintain a healthy population of Rainbow Trout at Lees Ferry to support recreational fishing"; (2) "Provide a quality trout fishing experience with catch frequency commensurate with the Blue Ribbon status of the fishery"; (3) "Grow quality sized trout that are available to the angler, consistent with the Blue Ribbon status of the fishery"; and (4) "Avoid catastrophic failure of the trout population, and establish protocols for emergency recovery from population loss." Two performance metrics that best capture these objectives would be the projected catch rate of rainbow trout and the projected abundance of rainbow trout greater than 16 inches, but we did not have available a rainbow trout model that could project those two metrics reliably. Instead, as a performance metric in this paper, we used the mean abundance of rainbow trout (≥1 year old) in the Lees Ferry reach over the next 20 years. In addition, we include a narrative evaluation of the long-term economic effects on the Lees Ferry rainbow trout fishery, without using a quantitative performance metric.

Sediment Resources

The June 2017 letter from the Acting Secretary's Designee to the NPS included the request that the evaluation of management actions directed toward brown trout in Lees Ferry consider "potential interactions with high-flow experiments." We interpret this as a request to evaluate sediment resources and related resource goals. The HFEs are intended to mimic aspects of natural high flows and deposit fine sediment at higher elevations, for its inherent value, its value to riparian vegetation, its use as camping sites, and its role in protecting historical sites. In the LTEMP FEIS (U.S. Department of Interior, 2016a), four resource goals were directly or indirectly tied to sediment, but one is perhaps most useful, to "increase and retain fine sediment volume, area, and distribution in Glen, Marble, and Grand Canyon reaches above the elevation of the average base flow for ecological, cultural, and recreational purposes." The performance metric used in the LTEMP FEIS was a Sand Load Index (the cumulative sand load transported by high flows [greater than 31,500 cfs] divided by the cumulative sand load transported in total). The analysis in the LTEMP FEIS, however, showed that much of the variation in the Sand Load Index was driven by the frequency of HFEs. Thus, for expediency, we used the projected mean number of HFEs (of any kind) over the next 20 years as a performance metric to reflect the effect on sediment resources and related objectives.

Hydropower Generation

Glen Canyon Dam generates about $150 million worth of hydroelectric energy per year. The amount of energy generated, and its value, are affected by the operations of the dam. In the LTEMP ROD (U.S. Department of the Interior, 2016b), one of the resource goals identified for the GCDAMP is, "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." Some of the alternatives proposed for managing brown trout involve changes to the flow operations of Glen Canyon Dam, and these may affect the value of electricity generated. In the LTEMP FEIS (U.S. Department of the Interior, 2016a), the effects of the alternatives on both hydroelectric generation and hydroelectric capacity were evaluated. In this report, we have only considered effects on hydroelectric generation, because none of the alternatives we considered were expected to significantly alter flows during August, the month that plays the most important role in determining the value of hydroelectric capacity of the dam to the power system. As a performance metric for hydroelectric generation, we used the discounted cost of hydropower generation over the 20-year planning period, measured in millions of dollars, where cost is owing to flow operations that either forego generation (high-flow experiments) or undertake generation at less valuable times (trout management flows).

Costs of Implementation

In addition to the effects on various resources of concern, some of the alternatives under consideration would require direct outlay of expenses for implementation. All other things equal, the desire is to minimize such costs. As a performance measure for this objective, we used the total discounted cost over the 20-year planning period, in millions of dollars.

Tribal Concerns with the Taking of Life

To many of the tribes associated with the Colorado River, life itself is sacred, and human activities should promote life, not destroy it. These tribes recognize that it is appropriate for humans to take life in some circumstances, especially when it is used to support other life, but the taking should be the minimum needed and should be carried out in a manner that is respectful. Several tribes have expressed concerns with lethal management of nonnative fish species. For example, the people of the Pueblo of Zuni have familial and spiritual relationships to all aquatic life—including native fish, nonnative fish, and macroinvertebrates—and have raised concerns that the taking of life through mechanical removal is contrary to their cultural values and adversely affects their well-being. In the LTEMP FEIS, two performance metrics were used to evaluate options (the frequency of mechanical removal, and the frequency of trout management flows), but these were acknowledged to be coarse measures that did not capture all the nuances of this objective. In this report, we have not undertaken a quantitative evaluation of tribal objectives; instead we include a narrative discussion of the alternatives relative to some of the values raised by several tribes.

Other Objectives

There are a number of objectives identified in the LTEMP resource goals that could potentially be affected by actions directed at brown trout management, including effects on other native fish, and effects on recreation (especially, boating and rafting). The intent of this paper is not to undertake the in-depth analyses across nearly two dozen resource goals that were undertaken in the LTEMP FEIS, but instead to focus on the objectives that seem most likely to be affected by potential brown trout management actions. We acknowledge, however, that this analysis may be incomplete.

Potential Management Strategies

We evaluated six potential management strategies aimed at decreasing the abundance of brown trout in the Lees Ferry reach of the Colorado River. These alternative strategies are not meant to be the kind of operational alternatives considered in a management plan or NEPA evaluation, rather they are thematic strategies designed to provide insight about a particular type of intervention. Any actual implementation is likely to be more complex, to contain condition-dependent triggers, and to include experimental and adaptive components; we have not attempted to describe such alternatives. Any actual implementation also needs to be undertaken under the statutory and regulatory authority of the responsible agency or agencies; we have not attempted to identify who would take action nor what authority they would be acting under, indeed, it may be that no single agency has the authority to consider all of the alternatives described below. Our intent is that the evaluation of these thematic strategies provides insight for the generation of operational strategies in the future.

The February 2017 AMWG letter articulated a focus on "…any new actions to manage brown trout in the Lees Ferry reach of the Colorado River," so the alternatives described here are meant to have a direct effect on brown trout at Lees Ferry. Other sorts of interventions are conceivable, for example, preventing movement of brown trout into the LCR reach as a way to protect humpback chub, but we saw these as outside the scope of what was asked.

The six alternatives we considered include the status quo, two strategies aimed at removing adult brown trout, and three strategies designed to discourage immigration or reproduction through flow operations. These six alternatives are not meant to be comprehensive. There is certainly a much larger set of possible interventions, including large infrastructure options like building a temperature control device on the dam. We have focused on practical approaches whose implementation seemed to us to be possible in the near term (say, the next five years).

Alternative 1: Status Quo

The status quo alternative is the selected alternative described in the LTEMP ROD (U.S. Department of Interior, 2016b). This is a version of Alternative D in the LTEMP FEIS (specifically, long-term strategy D2). This alternative specifies the detailed operational characteristics for Glen Canyon Dam, including monthly volumes, daily ranges, and ramp rates, as well as the triggering conditions for fall HFEs, spring HFEs, rainbow trout management flows, and mechanical removal of rainbow trout at the LCR, among other details. In the absence of any change in operations specifically to address brown trout, this is the strategy that is expected to be carried out over the next 20 years. The remaining strategies describe departures from the status quo, any details not described are assumed to follow the status quo.

Alternative 2: Incentivized Take of Brown Trout

Angling regulations and incentives may be an effective tool for management of brown trout populations. Currently, there are no harvest limits on brown trout in Lees Ferry, but many anglers practice catch-and-release for brown, as well as rainbow, trout. Harvest incentives, such as bounties for target fish species, may help to educate the public and encourage support from anglers for nonnative species control measures, and may be most effective when included as one of multiple management actions targeting the species in question. Under this potential management strategy, we imagine that a concerted effort would be undertaken to incentivize take of brown trout, through focused educational outreach, a graduated bounty on brown trout (with bounties increasing with size of the fish), and possibly also large rewards for a small number of specially-tagged, "prize" fish. We assume that such a program would be developed through collaboration with the fishing and guiding communities; for this reason, we did not attempt to describe the details of such a program. In the evaluation that follows, we do make a few assumptions to allow us to calculate the costs and effectiveness of such a program, but these are meant to be illustrative, not prescriptive, of what might be designed.

Alternative 3: Suspension of Fall High-flow Experiments

The timing of HFEs is potentially an effective tool for the management of brown trout populations. Brown trout populations have been shown to be sensitive to the details of the hydrological regime, with extremes in discharge (both floods and droughts) often inhibiting recruitment, even to the point of population collapses (Lobón-Cerviá, 2009). This vulnerability of recruiting classes to hydrologic disturbance is short in duration, and is restricted to the period immediately prior to and surrounding fry emergence, when young fish are searching out territories and feeding positions (Cattanéo and others, 2002; Cattanéo and others, 2003; Lobón-Cerviá, 2009). Conversely, age-1 and older cohorts are resistant to high mortality associated with floods (Jensen and Johnsen, 1999). Such is the influence of hydrologic variation on early life stages that the ability of both rainbow trout (Fausch and others, 2001) and brown trout (Wood and Budy, 2009) to successfully invade and persist in streams is correlated with a low probability of floods overlapping with emergence, a period bounded for each species by differences in spawning seasonality and water temperature during incubation. An increase in winter floods projected with warmer, rainier winters in a changing climate may specifically disadvantage brown trout in certain systems where they are presently successful (Wenger and others, 2011).

Several of the causal hypotheses for the expansion of brown trout in Lees Ferry involve effects of fall HFEs. For example, under Hypothesis A.1, fall-timed HFEs may cue migration of ripe brown trout into Glen Canyon thereby augmenting the number of spawners. Under Hypothesis C.10, fall-timed HFEs cleanse spawning gravels immediately prior to brown trout spawning thereby improving egg survival and recruitment. If any of these hypotheses are in fact true, then suspending fall HFEs would alter these seasonal outcomes, possibly disadvantaging brown trout.

Alternative 3 simply assumes that fall HFEs are discontinued; no other changes to the LTEMP preferred alternative occur. In particular, spring HFEs continue, with the same triggering conditions as the status quo.

Alternative 4: Enhanced Spring High-flow Experiments

Spring HFEs are potentially an effective tool for the management of brown trout populations. Spring HFEs may decrease brown trout recruitment by inducing high flows at a time when brown trout fry and fingerlings may be vulnerable to flood-induced mortality. Spring HFEs may also disadvantage brown trout and favor rainbow trout and native fishes through shifts in the food base. For example, the 2008 spring HFE reduced by 66 percent the biomass of scuds (*Gammarus lacustris*; Cross and others, 2011), a nonnative aquatic amphipod that may promote growth and survival of brown trout. In addition, the 2008 spring HFE stimulated production of aquatic insects (midges and black flies) that are preferred prey of rainbow trout, humpback chub, and other native fishes (Cross and others, 2011, 2013). These findings from Grand Canyon concerning the effects of spring-timed HFEs on the prey base are corroborated by a recent national synthesis of invertebrate data from 728 streams and rivers throughout the United States (Carlisle and others, 2017). These authors found that healthy aquatic invertebrate communities were associated with streams and rivers where high flows occurred in spring, and impaired invertebrate assemblages were found in systems where spring high flows were absent or high flows occurred at other times of year. Sediment-triggered spring HFEs, beginning as early as 2020, are an element of the LTEMP preferred alternative (U.S. Department of the Interior, 2016a), and are expected to be triggered in about 6 out of 20 years.

Under Alternative 4, we assume fall HFEs would be discontinued, and the triggering conditions for spring HFEs would be changed so that they are more frequent than under the status quo. Specifically, we assume that in any year that a fall or spring HFE would be triggered under the status quo, a spring HFE would be triggered under Alternative 4.

Alternative 5: Brown Trout Management Flows

Brown trout TMFs may be an effective tool for the management of brown trout populations in the Lees Ferry reach. The LTEMP ROD describes rainbow trout TMFs as 2 or 3 days of elevated flows followed by a very sharp drop to a minimum flow, to strand young-of-year rainbow trout on low-angle shorelines (U.S. Department of Interior, 2016a). In the LTEMP, these flows are proposed to be conducted in the spring and summer months (May–July) and consist of relatively high flows (for example, 20,000 cfs) followed by low flows that are within the minimum flow level (for example, 5,000 cfs to 8,000 cfs) and maintained for less than 12 hours. Ramp-up rates are consistent with normal operations (4,000 cfs/hour) while the down-ramp rate would be 15,000 cfs/hour (U.S. Department of Interior, 2016a).

Under Alternative 5, TMFs designed specifically to affect brown trout would be implemented. These would target young-of-year in nearshore habitats in February through April. We have little information on the occurrence and behavior of young brown trout in the Lees Ferry reach, and we did not have in mind any particular design for such TMFs, but assumed they would be approximately as effective as rainbow trout management flows.

Alternative 6: Brown Trout Mechanical Removal

Mechanical removal of brown trout in Lees Ferry is potentially an effective tool for management of brown trout populations. Significant reductions in densities and recruitment of nonnative salmonids have been obtained from removal efforts in Yellowstone National Park (Meyer and others, 2017) and high elevation streams in Wyoming (Thompson and Rahel, 1996). Even when removal efforts have failed to reduce total abundance, as in the case of efforts to remove nonnative northern pike (*Esox lucius*) in the Yampa River, reductions in the largest size-classes have resulted, likely reducing predation on native species (Zelasko and others, 2016). Positive responses in populations of desirable species living in sympatry with the species targeted for removal have also been documented (Peterson and others, 2008; Meyer and others, 2017; Schelly and others, 2017). On the other hand, short-term mechanical removal can increase abundance by releasing young-of-year cohorts from density-dependent mortality, and populations can rebound in as little as two years upon cessation of removal (Saunders and others, 2015; Meyer and others, 2017). This effect may not currently apply in the Lees Ferry brown trout population, however, if it is assumed to be far from density-dependent equilibrium, with rainbow trout still comprising approximately 95 percent of the fish community.

Under Alternative 6, brown trout would be removed from Lees Ferry through a concerted electrofishing effort during the peak of spawning (November–January), targeting the largest and most reproductively successful fish. We assume the removal would be conducted annually, and would consist of 8 passes per year at the speed used by AGFD (which targets larger fish), rather than the speed used in the NO study.

Hybrid, Condition-dependent, and Other Strategies

Multiple management options or a sequence of multiple management actions and experiments may be more effective and possibly efficient at managing brown trout populations. However, evaluating combinations of management actions is beyond the scope of this report. We anticipate that the evaluation in this report will provide insights into the first-order effects of these different approaches and motivate design of more sophisticated approaches, through combinations of strategies, triggering conditions, and adaptive implementation. Other strategies (for example, introduction of “YY” male brown trout, Schill and others, 2017), which were judged to be too experimental and out-of-reach to evaluate quantitatively at this time, may also be valuable components of a long-term approach.

Evaluation Methods

We quantitatively evaluated the six alternative management strategies against six objectives using a variety of prediction methods. We relied heavily on the assessment methods from the LTEMP FEIS (U.S. Department of Interior, 2016a), using the LTEMP results directly where possible and adapting the methods where needed. The alternatives were qualitatively evaluated against several additional objectives, for which quantitative methods are not available at this time.

Fish Model Overview

Three of the objectives were evaluated using quantitative models for fish population dynamics. The fish models can be thought of in three parts: (1) a model of brown trout and rainbow trout population dynamics in Glen Canyon, (2) a model of brown trout and rainbow trout movement and survival downstream from Lees Ferry through Marble Canyon to the Little Colorado River, and (3) a model of how humpback chub population dynamics in the LCR and Colorado River respond to monthly temperatures and monthly abundances of rainbow and brown trout (fig. 18). In the following sections we provide further overviews of each component. For more details, including input data and code to run simulations, we refer readers to the associated data and code release (Yackulic and others, 2018a).

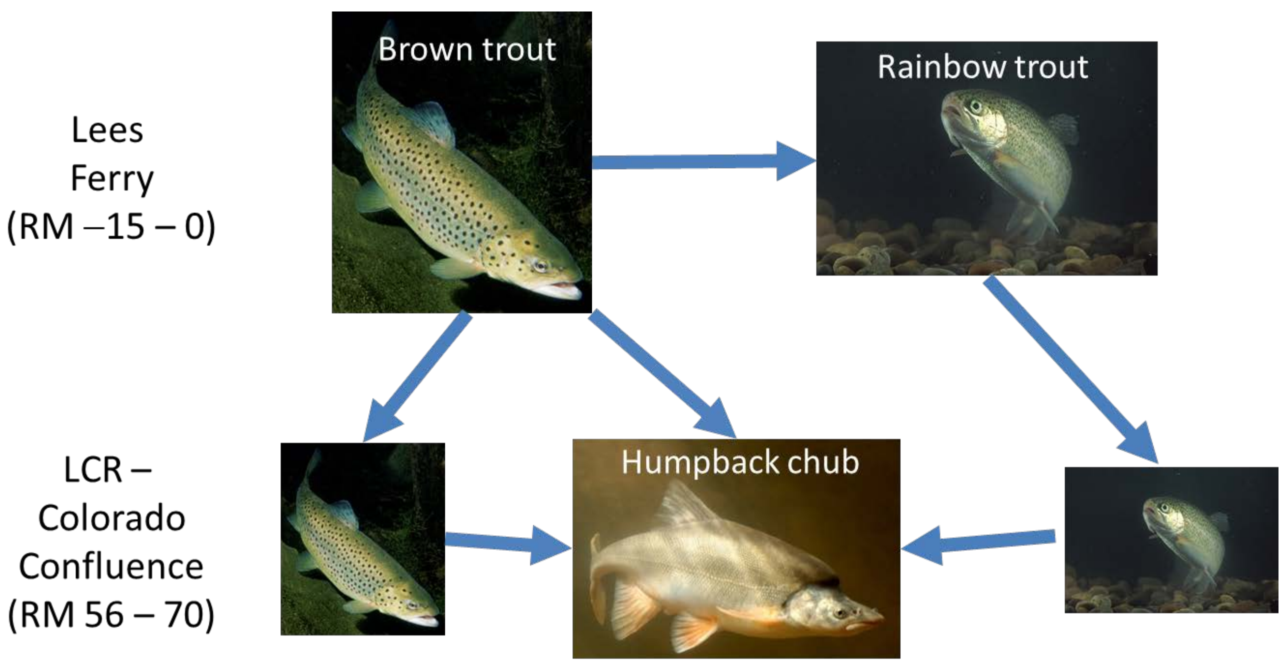

Figure 18. Diagram of the linkages among the fish models used for evaluation. Brown trout populations are modelled both in the Lees Ferry reach and near the confluence of the Colorado River and the Little Colorado River (LCR), with a connection via movement through Marble Canyon. Likewise, rainbow trout populations are modelled in the same two places. The humpback chub population at the confluence can be affected directly by both brown trout and rainbow trout, and indirectly through other management actions aimed at affecting brown trout in Lees Ferry.

We generated results from the linked fish models in 43 scenarios: the six management alternatives in combinations with the seven causal hypotheses; plus, an additional null causal model run under status quo conditions (see "Effects on Brown Trout"). Each scenario consisted of 1,000 replicate 20-year forecasts, with the replicates capturing parametric uncertainty by sampling from the posterior distributions for the parameters. Temporal variability within the 20-year traces was generated from the LTEMP hydrological and sediment traces. The predictive distributions formed from the replicates were the basis of the results.

Forecasting Brown Trout in Glen Canyon

The brown trout Glen Canyon simulation model extends the integrated population model used to reconstruct brown trout population dynamics. Versions of the integrated population model were fit for each of the seven causal hypotheses we carried forward. Each version included the same general structure described in the "Reconstruction of the Lees Ferry Brown Trout Population" section above, with modifications occurring only with respect to the portions of the model that dealt with each year's reproductive rate (β_y) and each quarter's immigration rate ($I_{3,t}$). Covariates representing different hypotheses were integrated into the model using the following general forms:

$$\log(\beta_y) = \mu_\beta + \delta_\beta X_{\beta,y} + \varepsilon_{\beta,y} \tag{1}$$

$$\log(I_{3,t}) = \mu_I + \delta_I X_{I,t} + \varepsilon_{I,t} \tag{2}$$

where μ_β and μ_I represent the logs of the expected reproductive rate and immigration rate when the covariates of interest ($X_{\beta,y}$ or $X_{I,t}$) are set equal to zero and $\varepsilon_{\beta,y}$ and $\varepsilon_{I,t}$ account for variation in the reproductive rate and immigration rate not accounted for by the covariate of interest (residuals) and are drawn from normal distributions centered on zero with standard deviations given by hyper-parameters, σ_β and σ_I, respectively. Values of $X_{\beta,y}$ and $X_{I,t}$ depended on the hypothesis being tested and the priors on δ_β were informed by an expert elicitation (the authors of this report served as the expert panel). Under hypothesis B.5 only, β_y was modelled using a different functional form to express the hypothesized Allee effect:

$$\beta_y = {\beta_{max} e^{\varepsilon_{\beta,y}}} \Big/ {\left(1 + e^{-m(N_{2,y}+4N_{3,y})-c}\right)} \tag{3}$$

where β_{max} is the asymptotic reproductive rate for brown trout; $e^{\varepsilon_{\beta,y}}$ are deviates drawn from a distribution centered on zero with a standard deviation, σ_β; m is a slope parameter describing how the reproductive rate increased as the weighted sum of adult spawners increased; and c was parameterized to represent the number of weighted adult spawners at which the reproductive rate was 95 percent of β_{max}.

Posterior distributions of all relevant parameters (including survival, growth, and capture probabilities in addition to parameters related to reproductive rate and immigration) were generated under each of the seven hypotheses. Although we were able to generate estimates for many parameters in our brown trout simulation model using this framework, certain parameters, such as the potential carrying capacity of brown trout, required analysis of data outside our system, while others describing the potential effects of the management alternatives on brown trout population dynamics (fig. 19) were estimated through literature reviews and expert elicitation. Below we briefly describe how we derived these parameter estimates.

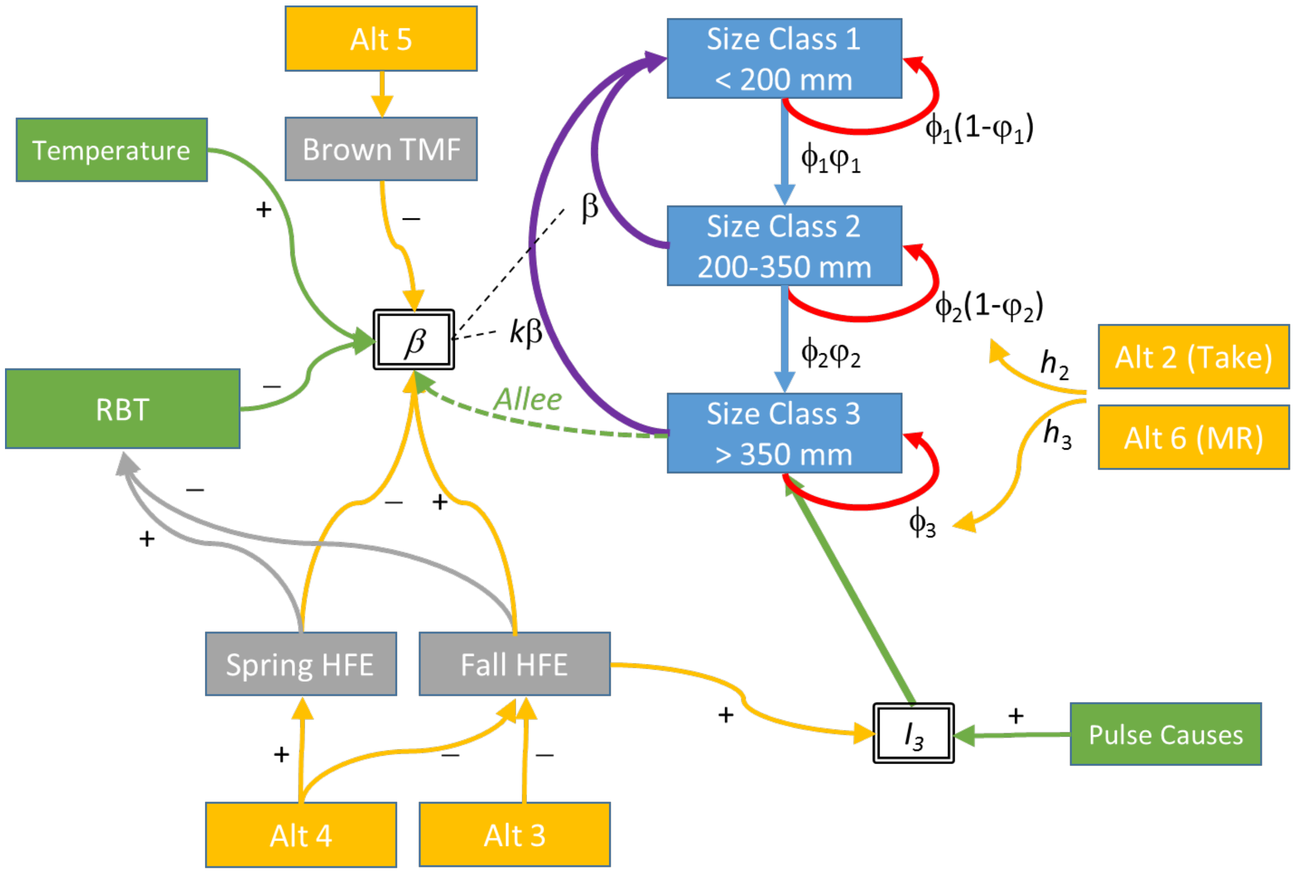

Figure 19. Influence diagram showing the pathways by which the management alternatives affect brown trout dynamics in the Lees Ferry reach of the Colorado River. Alt, alternative; TMF, trout-management flow; mm, millimeter; RBT, rainbow trout; HFE, high-flow experiment; Take, incentivized take; MR, mechanical removal; β, reproductive rate; k, reproductive rate multiplier for size class 3 brown trout relative to size class 2 brown trout; I, immigration rates; ϕ_i, survival rates; φ_i, growth rates; i, indexes the size class.

Carrying capacity for brown trout

To calculate the potential size of a brown trout fishery and the expected effect on rainbow trout, we first calculated two intermediate quantities, the expected ratio of adult brown trout to adult rainbow trout (R) and the per capita negative effect of brown trout on rainbow trout (C). We discuss these quantities below and use them to derive brown trout carrying capacity estimates.

What are the potential ratios, *R*, of adult rainbow trout to brown trout in Lees Ferry? To address this question, we examined a subset of CPUE data previously analyzed by Dibble and others (2015), which focused on tail waters in the western USA. Specifically, we focused on systems with six or more years of data where stocking was not occurring and data were included for both rainbow and brown trout, and we focused only on adults (300 mm+ for rainbow trout; 350 mm+ for brown trout). Other tail waters are typically sampled during the fall (September–October), so we focused on this period to make comparisons to Lees Ferry reach catch. In each system, we calculated the log of the ratio of the two species in each year and calculated the mean and standard deviations of these log ratios for each system across years. If zero rainbow or brown trout were caught in a particular year, that year's data were removed from the analysis. We ran a random-effects meta-analysis across systems; the results suggest that in the average mixed fishery in the western USA the ratio of adult rainbow to brown trout is approximately 1.3:1, however there is substantial variation (standard deviation of 0.59 on a log scale, fig. 20). Comparison to other tail waters illustrates the degree to which Lees Ferry has historically, and remains, exceptionally dominated by rainbow trout.

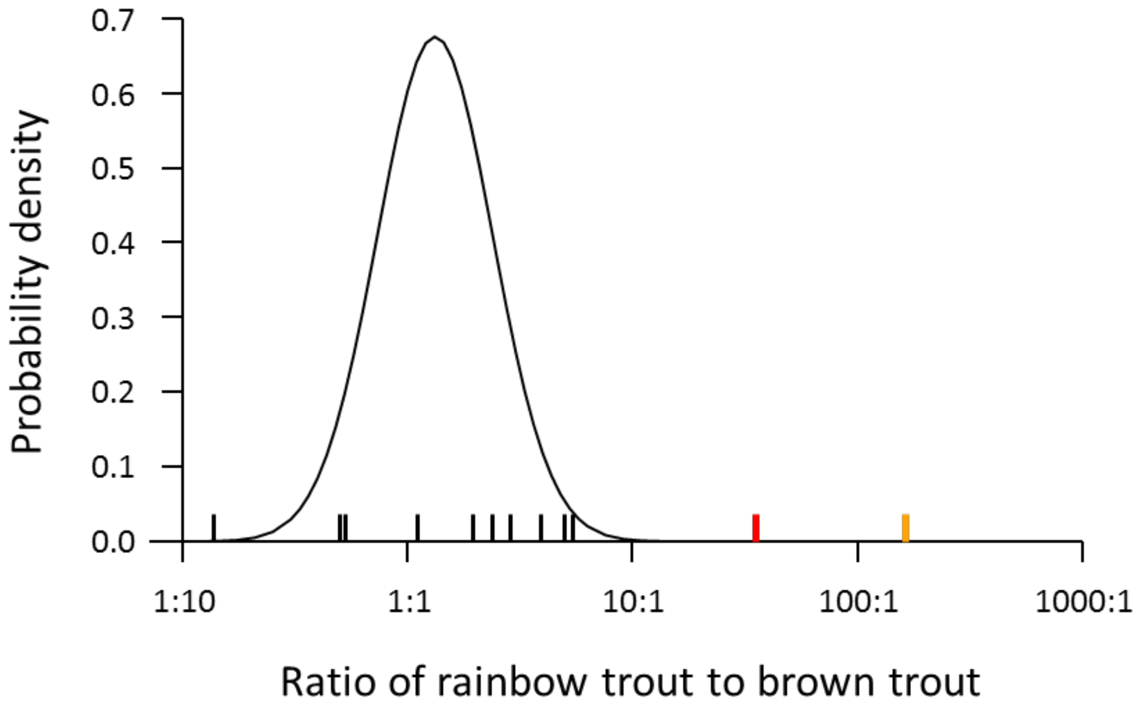

Figure 20. Graph of the probability distribution for the ratio of adult rainbow trout catch to adult brown trout catch across western United States tail waters without stocking. The black marks show the data from the individual tail waters used to generate the probability distribution. The red mark is the ratio in the Lees Ferry reach of the Colorado River in 2016, and the orange mark is the ratio at Lees Ferry from 1999–2012.

What is the per capita effect, *C*, of an adult brown trout on an adult rainbow trout population size? To address this question, we used the same dataset as above. Within this subset, we regressed brown trout CPUE against rainbow trout CPUE in each system. The largest negative effect of brown trout on rainbow trout occurred in the Spinney Mountain tail water, where each additional brown trout caught was associated with 3.5 fewer rainbow trout caught. In two systems, rainbow trout and brown trout adult CPUE had relatively strong positive correlations. A fixed-effect meta-analysis across systems suggested an overall weak negative effect (−0.008) and a relatively equal likelihood that brown trout would lead to increases in rainbow trout as compared to decreases; however, these analyses do not control for other sources of variation that may benefit both rainbow and brown trout (for example, flows identified in Dibble and others, 2015). Furthermore, most other tail waters are not as limited by small prey size as our system (Dodrill and others, 2016), and given the similar bioenergetics of the two species it is hard to imagine there would not be at least some competition between the two species for food. Lastly, a review of the broader literature indicates there is evidence to support cases where rainbow trout abundance decreases in response to brown trout population expansion (for example, Chitose River, Japan; Hasegawa and others, 2014, 2017; Hasegawa, 2016) and other instances where rainbow trout invasion into new habitats has been limited by native brown trout population presence (for example, Europe; Fausch and others, 2001). Therefore, we instead forced positive estimates to a very weak negative effect (−0.0001) and fit a gamma distribution to different systems, estimating values of 0.15 and 2.9 for shape and scale parameters, which suggests an average per capita effect of −0.44 (an increase in the adult brown trout population of 100 individuals will be associated with 44 fewer adult rainbow trout), but with large uncertainty and a high probability that brown trout will not substantially suppress rainbow trout.

Estimating and incorporating a carrying capacity into the population model. Models developed for the LTEMP predicted that the average adult rainbow trout population under alternatives that most resemble the selected alternative was approximately 100,000 individuals. Using this as a baseline, we can estimate an adult brown trout carrying capacity according to the following equation:

$$\text{Brown trout carrying capacity} = 100{,}000/(R\text{–}C) \quad (4)$$

where R and C are defined by the distributions derived above. Under this equation, the brown trout carrying capacity has a 90 percent probability of falling between 20,000 and 150,000 and we used these bounds to define carrying capacity within our simulations. Carrying capacity was incorporated into the model by: (1) calculating the expected number of recruits without a carrying capacity, (2) calculating whether the sum of these recruits multiplied by an approximate juvenile survival rate of 0.5 plus the existing adults multiplied by an approximate adult survival rate 0.7 would lead to the carrying capacity being exceeded in the next year, and (3) adjusting the predicted recruits down so as not to exceed the carrying capacity if it was predicted to exceed carrying capacity without such an adjustment.

Forecasting the effects of management on brown trout

To simulate effects of the six management alternatives on brown trout under the seven causal hypotheses we either altered the frequency or timing of floods, added mortality, or decreased the reproductive rate (fig. 19). Under the incentivized take alternative (Alternative 2), a quarterly rate of mortality (equivalent to a 15 percent annual catch rate) was applied to both small and large brown trout, whereas under the mechanical removal alternative (Alternative 6) mortality was applied during the single winter quarter under the assumption of 8 passes using AGFD capture probabilities. Under the brown trout TMF alternative (Alternative 5), the reproductive rate was lowered in every year. Simulations proceeded under the focal hypothesis fixing survival, growth, and hyper-parameters according to a single posterior draw, but also including annual and quarterly variance in reproduction and immigration respectively, according to the estimated residual variation in these processes under the focal hypothesis. Outmigration of juvenile brown trout into Marble Canyon was assumed to occur at the same rate as juvenile rainbow trout, and interactions of brown trout with rainbow trout and humpback chub are described in the following sections. For more details, see the associated R-code (Yackulic and others, 2018a).

Forecasting Rainbow Trout in Glen Canyon

Rainbow trout dynamics were simulated based on an age-structured model of rainbow trout dynamics previously described by Korman and others (2012). The rainbow trout model predicts the abundance and growth of rainbow trout in Glen Canyon, and the number of those rainbow trout that migrate into Marble Canyon. The model makes predictions on an annual time step for ages 1–6 years. Annual recruitment, which we define here as the number of age-0 rainbow trout that enter the population, was predicted based on flow statistics, including different potential management flows, as well as the number of adult brown trout present. Specifically, recruitment of rainbow trout was reduced to account for the effect of brown trout on rainbow trout (according to the ratio, *C*). In addition to the flow effects described in Korman and others (2012), we also included an effect of fall HFEs on rainbow trout recruitment estimated from recent recruitment events following fall HFEs. The number of rainbow trout migrating into Marble Canyon each year (out-migrants) was predicted as a proportion of the previous year's recruitment, and was used as an input in the Marble Canyon trout model. For a more detailed description of the rainbow trout model, including parameter values, see Korman and others (2012), U.S. Department of Interior (2016a), and the code associated with this manuscript.

Movement and survival of rainbow and brown trout in Marble Canyon

The trout movement model (TMM) predicts the monthly abundance of rainbow and brown trout within each one-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 described below. While the management strategies we evaluated were not focused on locations downstream of approximately RM 66 (the downstream limit of the LCR reach), the TMM extends beyond this location to avoid boundary problems (modeling discrepancies that can arise in the terminal segment). The TMM requires as input: annual estimates of brown trout and rainbow trout out-migrants from the Lees Ferry reach provided by the Lees Ferry models; survival rates for rainbow trout and brown trout; movement parameters for rainbow trout and brown trout; and information on the number, intensity, and timing of nonnative mechanical removal trips conducted each year in Marble Canyon. When mechanical removal in Marble Canyon is triggered (under the LTEMP protocol), we assume 6 electrofishing and removal passes per year that potentially affect the entirety of the LCR aggregation, with removal rates of 0.1 per pass for rainbow trout and 0.03 per pass for brown trout based on best estimates of capture probabilities for adults of the different species. Monthly survival rates for adult rainbow trout and brown trout are assumed to be 0.96 and 0.97 respectively, based on the best available estimates from within the system. The age and size structure of the population is not modeled, though all emigrants from Glen Canyon are assumed to be young-of-year (Korman and others, 2016). At the end of each month, the number of trout within each RM segment is multiplied by some survival rate and then distributed to other RM segments according to a RM segment-specific movement distribution. Monthly movement and dispersion does not depend on trout density and is modeled as a random process following a Cauchy distribution of movement distances. Our understanding of long-distance movement by brown trout in the Colorado River ecosystem is poor. Learning about long-distance movement is difficult because brown trout are still relatively uncommon in the catch, fish capture probabilities are generally low, and the Colorado River ecosystem is very large. The sparse information available (a few recaptures from the NO study and five fish detected on the LCR PIT-tag detection antenna array) suggests adult brown trout are likely to move more than adult rainbow trout; however, our understanding of movement by earlier life stages of brown trout is especially poor. For these reasons, we assumed that brown trout move like rainbow trout, which have been much better studied in this system (Korman and others, 2012). For more thorough descriptions of the movement model, including technical details and sources of estimates, see Bair and others (2018), U.S. Department of Interior (2016a), and the code associated with this manuscript.

Humpback Chub Dynamics in Marble Canyon

A size- and location-structured population dynamics model is 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; >250 mm) and two locations (LCR and Colorado River), for a total of ten "states" (where a state is a unique combination of size and location; for example, a fish in the LCR that is 40–99 mm is in state 1). The structure of this model is based on recent modeling work (Yackulic and others, 2014; Yackulic and others, 2018b). The model is run on a monthly time step and assumes constant survival for all states except for juveniles in the Colorado River (state 6). Juvenile survival depends on the weighted trout abundance (see the following paragraph; Yackulic and others, 2018b). Growth of size class 1 humpback chub depends on temperature and the weighted trout abundance (Yackulic and others, 2018b). Growth for all other size classes in the Colorado River is temperature dependent, using the slope parameter in Yackulic and others (2018b), and intercept parameters from U.S. Department of Interior (2016a). In contrast to fish in the Colorado River mainstem, growth rates for all size classes in the LCR were assumed to be constant (Yackulic and others, 2014). Movement between the LCR and Colorado River is modelled via movement parameters that vary depending on month and size class (see Yackulic and others, 2014, for more details regarding movement parameters). Parameters describing survival, movement, and growth were drawn randomly for each simulation based either on mean and covariance matrices from Yackulic and others (2014) or the posterior distributions from the best model in Yackulic and others (2018b). The simulation model also relies on estimates of the starting abundances in each of the 10 states derived from Yackulic and others (2014), as well as estimated annual recruit abundance, which was simulated as described in U.S. Department of Interior (2016a). For more thorough descriptions of the humpback chub dynamics model, including technical details and sources of estimates, see Yackulic and others (2014, 2018b), U.S. Department of Interior (2016a), and the code associated with this manuscript (Yackulic and others, 2018a).

For the purposes of this report, the existing humpback chub model needed to be modified to account for the effects of brown trout on juvenile humpback chub survival and growth. In each month, we calculated an overall trout effect by adding the number of rainbow trout to the weighted number of brown trout. Field observations suggest that brown trout eat approximately 17 times as many humpback chub per capita as rainbow trout eat (Yard and others, 2011). On the other hand, food-web studies indicate rainbow trout may have greater competitive effects than predatory effects on humpback chub (Cross and others, 2013), such that focusing primarily on predation may overstate the relative risk posed by brown trout. For example, if competitive effects of rainbow trout on humpback chub (such as displacement from preferred habitat; Coggins and others, 2011) are three times as important as predatory effects of rainbow trout on humpback chub, and if brown trout have the same competitive effect as rainbow trout, then we might expect the overall effect of a brown trout on juvenile chub survival and growth to be only 5 times as great ($(17+3)/(1+3) = 5$). On the other hand, if competitive and predatory effects are equal for rainbow trout, and if brown trout have similar competitive effects to rainbow trout, the overall effect of brown trout should be 9 times as great. Based on these lines of evidence, we hypothesize that brown trout will have anywhere from 5 times to 9 times as much effect on humpback chub per capita as rainbow trout with a uniform distribution between these values.

Sediment Resources

To evaluate the effect of the alternative management strategies on sediment resources, we forecast the total number of HFEs over the 20-year planning period, using the results from the LTEMP FEIS as the basis (U.S. Department of Interior, 2016a; see Chapter 4 and Appendix E). The LTEMP analysis simulated the alternatives across 63 traces to capture uncertainty in future hydrological and sediment input. Under our Alternatives 1, 2, 5, and 6, the implementation of HFEs is not altered from the preferred alternative in the ROD, so we used the frequency of HFEs from the LTEMP analysis. (Specifically, we used the results for LTEMP Alternative D2, called “AltR” in the LTEMP simulation output, because it most closely resembles what was chosen in the ROD). For our Alternative 3, we dropped all the fall HFEs, and counted only the spring HFEs to calculate the total. For Alternative 4, a spring HFE occurs if either a fall or spring HFE was called for in a particular year under the status quo alternative. For each alternative, we calculated the weighted mean number of HFEs (the sediment traces were not equally weighted), the weighted 80 percent observed range, and the weighted 95 percent confidence interval for the mean.

Hydropower Resources

To evaluate the effect of the alternative management strategies on hydropower generation, we forecast the change in value of hydropower generation over the 20-year planning period. We based these forecasts on the calculations of the costs of an HFE or a TMF that were included in the LTEMP FEIS: the average economic cost of a single fall or spring HFE was calculated as $1.65 million in current dollars (U.S. Department of Interior, 2016a, page 4–356). We assume that moving monthly volume to accommodate fall and spring HFEs occurs across months of roughly equal hydropower value. The costs associated with HFEs are energy costs alone because no August volumes are changed; thus, capacity values are unaffected. We also assume the value of hydropower is the same in fall and spring, so the cost of a spring HFE is the same as the cost of a fall HFE (U.S. Department of Interior, 2016a, page 4–357). We used the HFE forecasts for the 63 traces associated with LTEMP “AltR” to calculate the expected frequency of HFEs in each year, multiplied these frequencies by the cost of an HFE, discounted the costs at an annual rate of 3.375 percent (the same as used in the LTEMP FEIS), and summed the discounted costs over time.

For Alternative 5, we also included the costs of the brown trout TMFs, which we assumed occurred annually, with a cost of $450,000 per year in lost value of hydropower generation (U.S. Department of Interior, 2016a, page 4–356). We calculated the total cost over the 20-year planning period, discounting future costs at a rate of 3.375 percent per annum.

Implementation Costs

To evaluate the cost associated with brown trout removal in Alternatives 2 and 6, we estimated the total effort (angler harvested brown trout, annual mechanical removal) over the 20-year planning period. For Alternative 2, incentivized take rates were assumed to be on average 15 percent (standard deviation 2.5 percent) per year. The annual cost of Alternative 2 was estimated based on an average angler reward ($150 per fish) and the annual salary of one technician to implement the program (~$50,000). We estimate that angler compensation at $150 per fish, assuming a catch rate of 1 or 2 fish per day, would be roughly equivalent to an angler’s opportunity cost (foregone wages and trip cost), and thus would provide a suitable incentive for participation. Program implementation included a concerted education and outreach program to discuss the value of removing brown trout for the purpose of conservation and managing the incentivized take program. We did not include the costs of a “prize” fish component to the strategy. Costs were discounted at an annual rate of 3.375 percent (the same as used in the LTEMP FEIS) and summed over time.

For Alternative 6, we estimated the cost of brown trout mechanical removal, which we assumed occurred annually and would consist of 8 passes per year through the Lees Ferry reach, with a cost of $480,000 per year (M.D. Yard, USGS, written commun., February 2, 2018). We summed the total cost over the 20-year planning period, discounting future costs at a rate of 3.375 percent per annum. This cost reflects the personnel and equipment necessary for the removal efforts, but does not reflect lost revenues to fishing guides as a result of any negative perceptions of the removal program.

Economic Impacts

To evaluate the effect of alternative management actions on long-term economic condition of the Lees Ferry rainbow trout fishery, we qualitatively describe the possible outcomes over the 20-year planning period. The response of anglers at Lees Ferry to implementation of management actions has an immediate impact on angler demand. Alternatives 5 and 6 would impose additional actions, relative to status quo, that reduce angler access or possibly deter angler participation during implementation. Alternative 5 would limit angler access due to the abrupt changes in flow. Alternative 6 could indirectly limit angler access due to disruption of the rainbow trout fishery. Mechanical removal would occur at night, but reduced rainbow trout catch rate is possible for 2–3 days following removal and anglers may avoid Lees Ferry during removal, decreasing demand in the short-term (J.B. Reynolds, University of Alaska, oral commun., February 2, 2018).

The long-term economic effects of the alternatives specified are more uncertain. Demand for angling at Lees Ferry is determined by trip cost, attributes that attract anglers (for example, quality rainbow trout, seasonal weather, outstanding scenery), availability of alternative locales (for example, Flaming Gorge or Navajo Dam tail waters), and demographic characteristics of the angler (for example, age, income, education). Alternatives that increase trip cost, as a result of trip rescheduling or cancelation, or impact attributes such as rainbow trout quality, could have a long-term consequence for angler demand. Demand can change due to an experienced or perceived decline in quality of the fishery. This is important for Lees Ferry because it is a destination fishery with 81 percent of anglers traveling to Lees Ferry as their sole destination (Duffield and others, 2016). The long-term economic impact of implementation of some actions specified in the alternatives could be decreased with a concerted and targeted education and outreach program.

Tribal Concerns

To evaluate the effect of the alternative management strategies on tribal concerns, we relied on the description of tribal perspectives in the LTEMP FEIS and on input directly from the tribes. As part of development of this report, representatives from NPS and USBR solicited comments from tribal representatives on the AMWG regarding tribal perspectives on brown trout management. The Hopi Tribe and Pueblo of Zuni provided written comment on the brown trout management alternatives. We include these comments in the “Evaluation of Management Alternatives” section.

Other Objectives

There are other resource goals that could be affected by the alternative strategies, but which we have not evaluated in detail. For example, Alternatives 3, 4, and 5 would change recreational access, affecting the recreational experience and economic outcomes associated with it, relative to the status quo; the reduction in expected number of annual HFEs in Alternatives 3 and 4 would increase day-use rafting visits in Glen Canyon relative to the status quo; and recreational access would decrease in Alternative 5 because of TMFs. These, and other resource goals, would need to be evaluated more closely as operational strategies are developed.

Evaluation of Management Alternatives

The February 2017 letter from the AMWG expressed a specific desire to understand the “pros and cons of different…management options” aimed at managing brown trout in the Lees Ferry reach of the Colorado River. In the results that follow, we first discuss effects of the six management strategies on individual objectives, then we assemble those results into consequence tables that illustrate tradeoffs among objectives induced by the different strategies. In many cases, effects of the alternative strategies on the various objectives depend on which of the causal hypotheses might be operating, thus there is uncertainty about outcomes. For the direct effects of the strategies on brown trout, we report results under all seven of the causal hypotheses carried forward; for the remaining objectives, we focus on the two most likely of those causal hypotheses.

Effects on Brown Trout

To measure the underlying risk of brown trout becoming established at Lees Ferry, we took 1,000 samples from the joint posterior distributions for the demographic parameters and separated those samples into two groups, those parameter sets that produced an intrinsic growth rate (λ) less than 1 (36 percent) and those parameter sets that produced λ greater than 1 (64 percent, fig. 21). Under a null causal model for brown trout dynamics, which assumes that variation in the demographic parameters (β, ϕ_i, φ_i, and I_3) is not correlated with any environmental predictors or management actions, those replicate scenarios with $\lambda < 1$ show an adult brown trout population that varies at low numbers with a mean 20-year average size of around 5,800, roughly the same as the current population size (fig. 21, top panel). Importantly, the λ calculation did not include the influences of immigration, so even in scenarios with $\lambda < 1$ the population can occasionally increase in response to large immigration events, but these events are followed by declines as local production is below the replacement level. For those replicate scenarios with $\lambda > 1$, however, the population increases substantially over time, with a mean 20-year average around 16,000 and some trajectories reaching over 60,000 adults (fig. 21, bottom panel). Thus, given current information and under a null causal model, there is a 36-percent chance that the Lees Ferry brown trout population will persist at low levels (with potential for short-term increases from immigration events), and a 64-percent chance that the population will expand 3–10-fold from its current size.

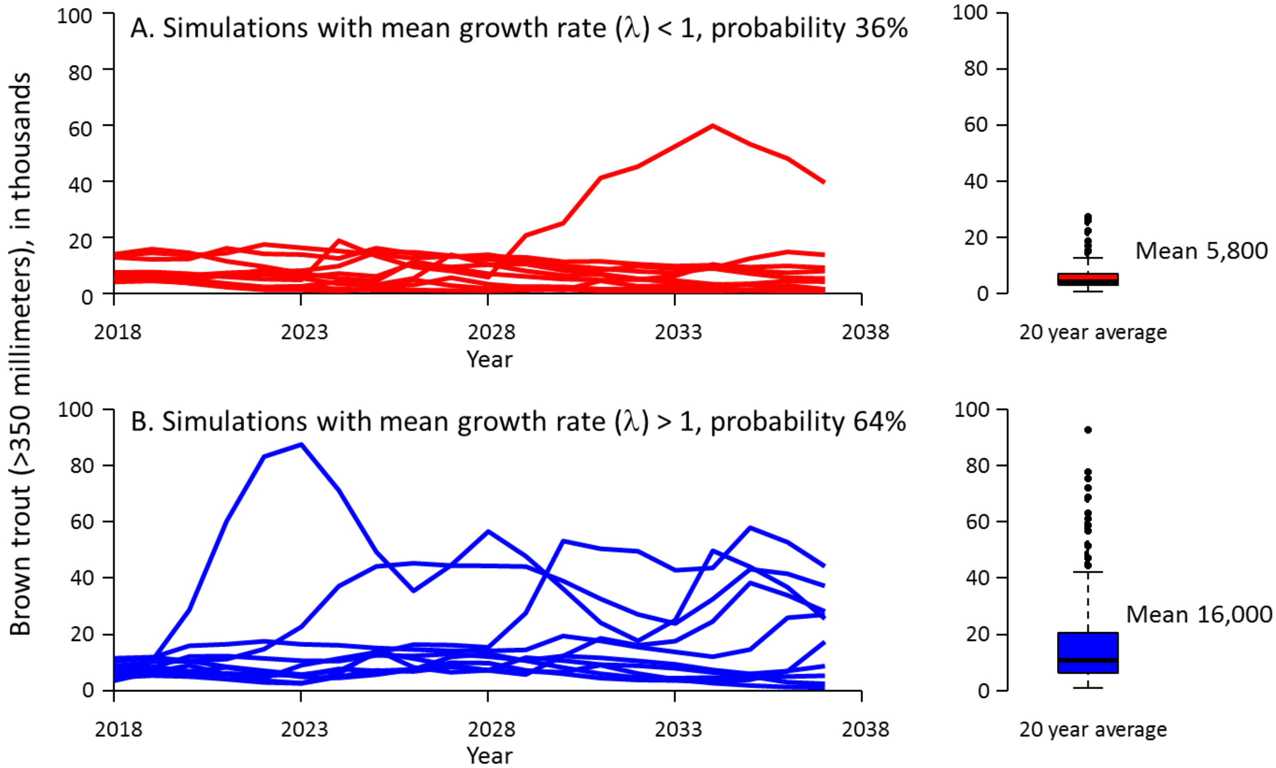

Figure 21. Graphs of forecast large adult brown trout abundance in the Lees Ferry reach of the Colorado River, 2018–2037, under a null causal hypothesis for: *A*, those parameter sets that produce a growth rate (λ) <1; and *B*, those parameter sets that produce a growth rate >1. The graphs each show ten randomly selected replicates from the corresponding sets. The inset boxplots show the distribution of the 20-year mean adult abundance across all replicates.

When we examine the seven causal hypotheses, the forecast trajectories under the status quo (Alternative 1) differ across hypotheses, as do the effects of the alternative management strategies. Under Hypothesis A.1, the explanation for the change in brown trout status is that repeated fall HFEs induced a large immigration event, and those new spawners took advantage of existing conditions to reproduce and expand in Lees Ferry. Under this hypothesis and status quo management (Alternative 1), the brown trout population is forecast to increase 2–3-fold, with a median 20-year average adult population size of 9,300 (fig. 22), because the future frequency of fall HFEs will induce continued immigration to Lees Ferry. Ceasing those fall HFEs (Alternative 3) stops the signal for immigration, and the median 20-year average adult population size drops to 3,900, although there remains a risk that the population already established has the capacity to expand considerably. Ceasing the fall HFEs and increasing the frequency of spring HFEs (Alternative 4) lowers the forecast population size even further, to 3,400, because the spring HFEs are assumed to be disadvantageous for brown trout reproduction. Under this hypothesis, the removal strategies (Alternatives 2 and 6) reduce the trajectories for brown trout, with median values about 40 percent lower than the status quo, but they are not as effective as the flow strategies (Alternatives 3 and 4). The TMF strategy (Alternative 5) reduces the median adult population size compared to the status quo, but only to 8,100, because the trout management flows are only 10–50-percent effective in reducing reproduction, and they target a life-history stage to which the population growth rate is not very sensitive.

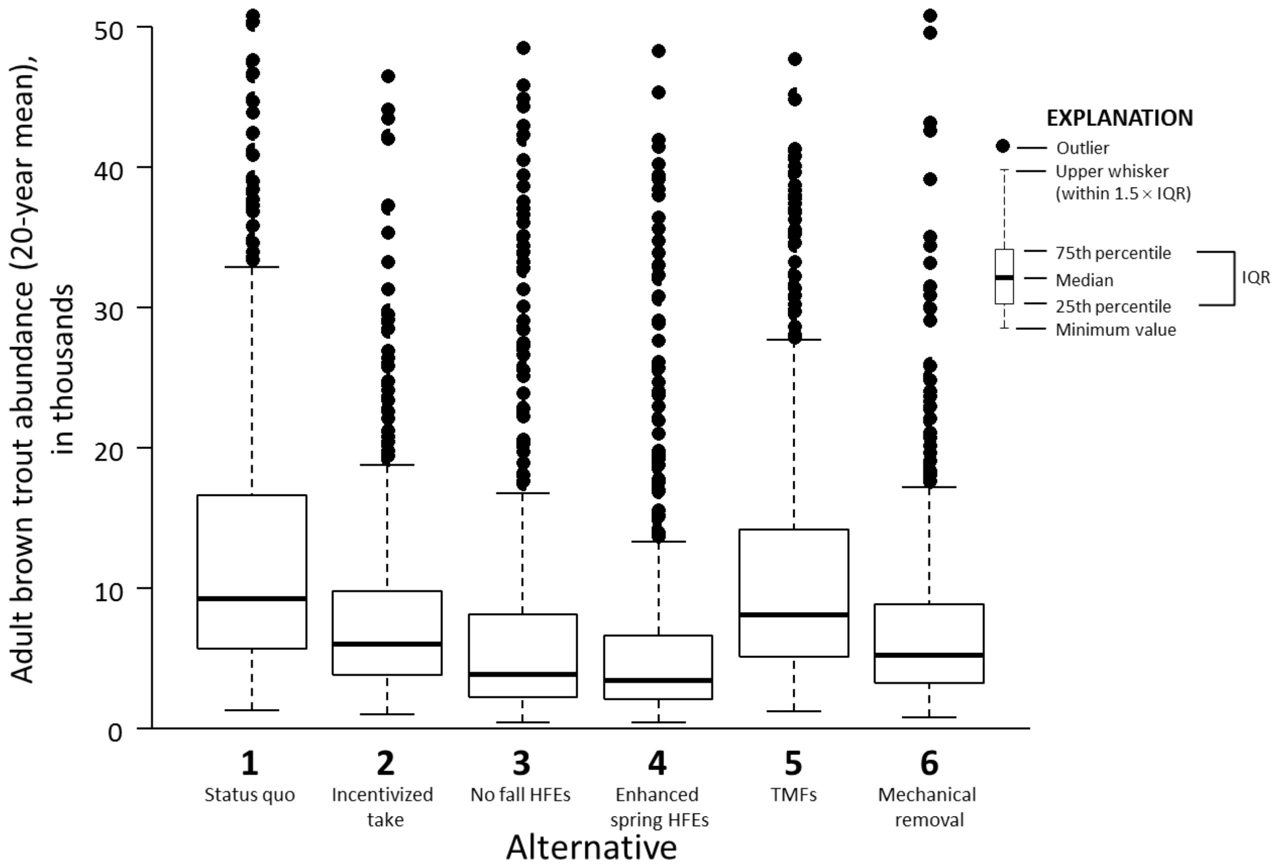

Figure 22. Boxplots of the mean number of large adult brown trout (size class 3) in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypothesis A.1. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

Under Hypothesis A.2–4, the explanation for the change in brown trout status is that there was a single, pulse immigration event that brought more spawners into the Lees Ferry reach, but otherwise nothing in the system changed. Under this hypothesis, assuming such a pulse event is rare (occurring on average once every 68 quarters), the status quo trajectories (Alternative 1) produce lower numbers than under Hypothesis A.1, with a median 20-year average adult population size of 6,800 (fig. 23). Under this hypothesis, ceasing fall HFEs has no effect, so Alternative 3 produces results identical to the status quo, and Alternative 4 shows only a small decrease in adult brown trout population size. The removal strategies (Alternatives 2 and 6) are the most effective in reducing brown trout under this hypothesis, lowering the median 20-year adult population size to 3,700 and 2,900, respectively. Again, TMFs (Alternative 5) have only a small to moderate effect in reducing the 20-year population size of adult brown trout.

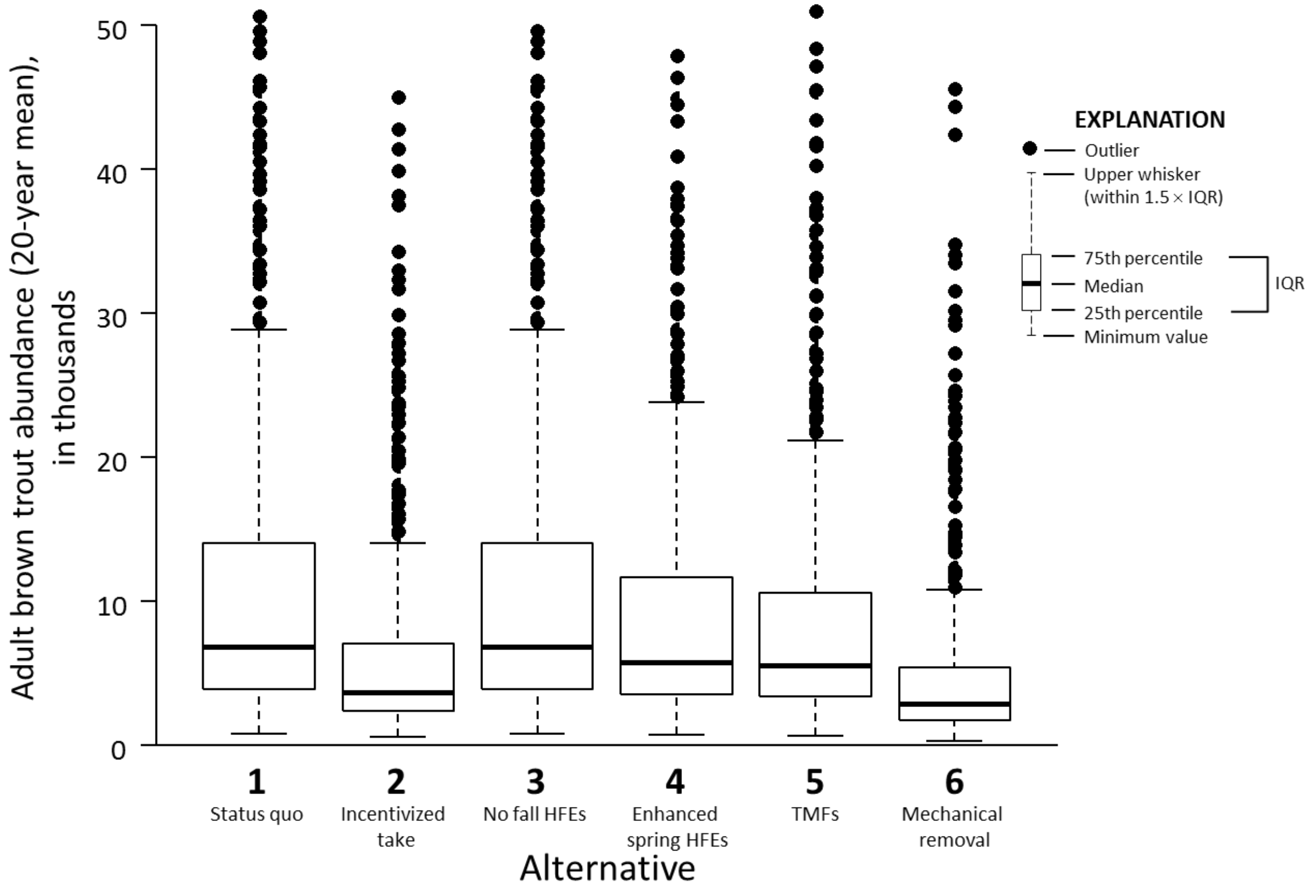

Figure 23. Boxplots of the mean number of large adult brown trout (size class 3) in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypotheses A.2–4. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

Under Hypothesis B.5, brown trout experienced a pulse immigration event that raised the adult population size above an Allee threshold, allowing an increase in reproductive rate as a result. In this scenario, the median adult population size under the status quo (Alternative 1) increases to 10,800, because the effect of even a single immigration pulse produces long-lasting increases in reproduction and recruitment (fig. 24). Removal strategies (Alternatives 2 and 6) are particularly effective under this hypothesis, because they have the chance of lowering the adult population size back down below the Allee threshold, thus indirectly lowering the reproductive rate as well. Ceasing fall HFEs (Alternative 3) is ineffective because it does not address any of the causal mechanisms sustaining the population under this hypothesis. Enhanced spring HFEs (Alternative 4) and TMFs (Alternative 5) are somewhat more effective under this hypothesis than others, because they reduce the reproductive rate induced by the Allee effect.

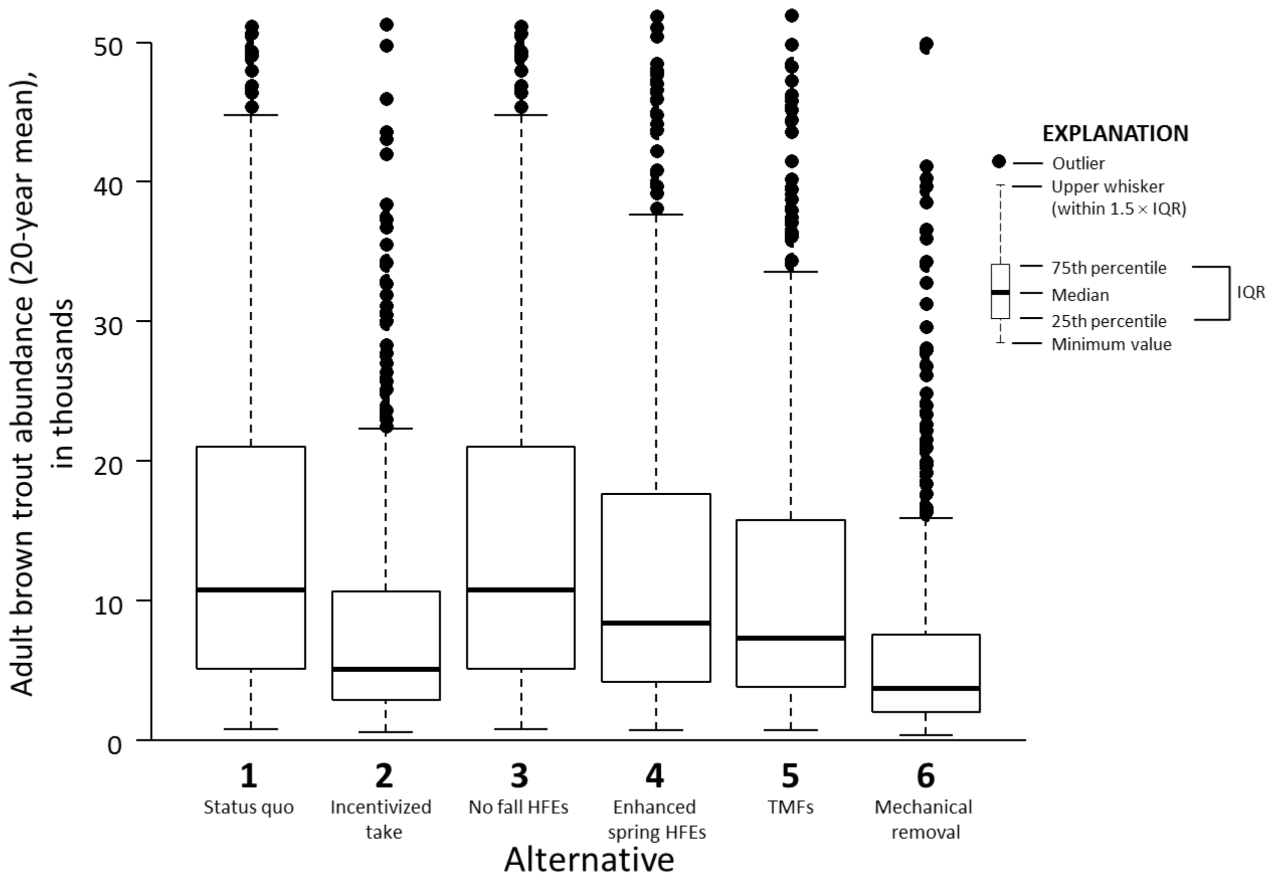

Figure 24. Boxplots of the mean number of large adult brown trout (size class 3) in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypothesis B.5. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

The pattern of management efficacy is starkly different under Hypothesis B.6 compared to Hypothesis B.5 (fig. 25). The forecast trajectories of brown trout population size under the status quo (Alternative 1) are higher under Hypothesis B.6 than any other hypothesis because the causal mechanism (fall HFEs) induces both a sustained increase in immigration and a sustained increase in reproductive rate. The median 20-year average adult population size is 15,500 under the status quo, and 25 percent of the simulations have average adult brown trout abundances greater than 50,000. Ceasing fall HFEs (Alternatives 3 and 4) is particularly effective under this hypothesis, with median adult population sizes dropping to less than 3,800. As in other cases, the removal strategies (Alternatives 2 and 6) are fairly effective, and the TMF strategy (Alternative 5) is not.

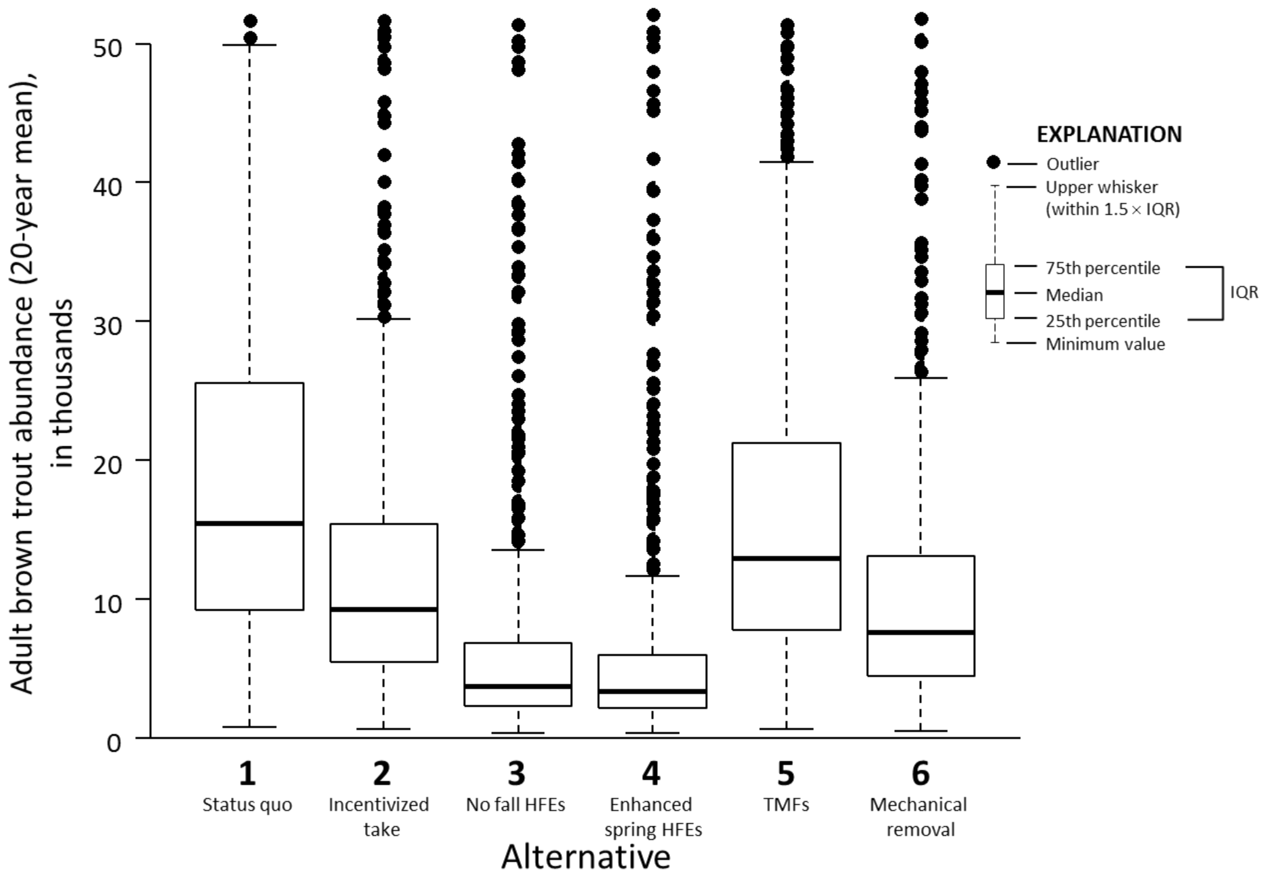

Figure 25. Boxplots of the mean number of large adult brown trout (size class 3) in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypothesis B.6. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

Under Hypothesis C.8, the change in brown trout status is explained by warmer temperatures raising reproductive rates. The observed variation in temperature during the reproductive season (September–January) is fairly small (fig. 15), during spawning season (November–December) even smaller, and the estimated reproductive rates do not correlate very well with temperature, so the effect under this hypothesis is small. Thus, under the status quo (Alternative 1), there is not a large expected increase in adult brown trout (median 20-year average, 7,600; fig. 26). The strategies that adjust flow operations (Alternatives 3, 4, and 5) do not reduce adult brown trout abundance very much, while the removal strategies (Alternatives 2 and 6) reduce the median abundance by about 50 percent. It is worth noting that we used the historically derived hydrological traces from the LTEMP analysis to generate these temperature forecasts, and these traces do not account for the reduction in hydrological input and corresponding warming projected under climate change (Udall and Overpeck, 2017), so these forecasts may underestimate the potential effect of this hypothesis. That said, it seems that brown trout already experience nearly optimal temperatures during spawning, so much improvement in reproductive success owing to temperature may not be likely. In fact, if the temperatures of releases from Lake Powell increase above 18°C for sustained periods, food limitation owing to increased metabolic needs, as well as potential introduction of warm-water nonnative species, are likely to become important, un-modeled factors in the population dynamics of all fish species considered here.

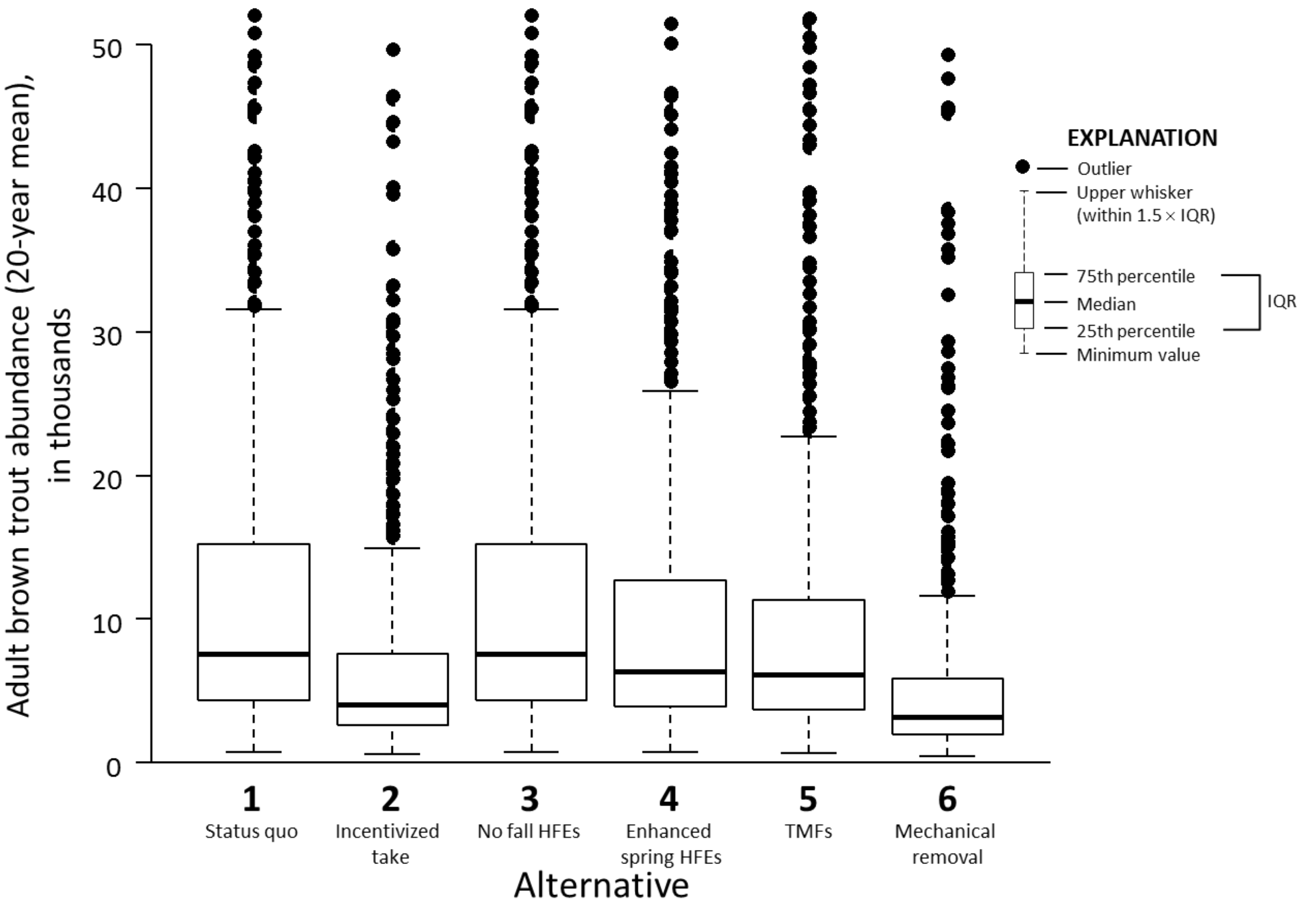

Figure 26. Boxplots of the mean number of large adult brown trout (size class 3) in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypothesis C.8. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

Under Hypothesis C.9, the change in brown trout status is explained by an increase in reproductive rate as a result of decreased spawning competition from rainbow trout. Under this hypothesis, the forecast median adult brown trout population size under the status quo (Alternative 1) is 10,800 (fig. 27). The strategies that reduce the frequency of fall HFEs and increase the frequency of spring HFEs (Alternatives 3 and 4) are forecast to decrease the number of brown trout, because those strategies are hypothesized to increase rainbow trout, and the increase in rainbow trout decreases brown trout reproductive success through interference spawning. As under other hypotheses, the removal strategies (Alternatives 2 and 6) reduce the median adult brown trout population size by about 50 percent relative to the status quo, and TMFs (Alternative 5) are mildly effective.

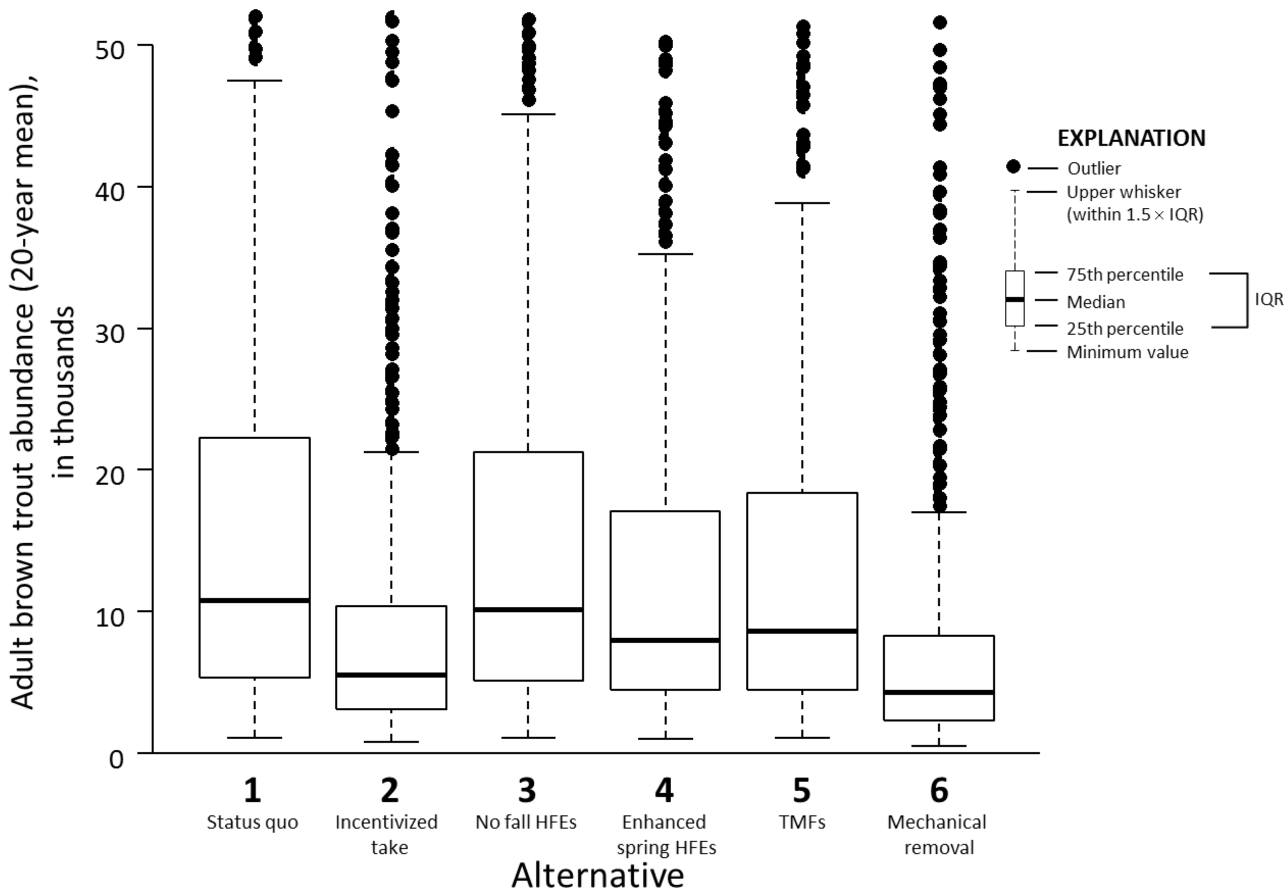

Figure 27. Boxplots of the mean number of large adult brown trout (size class 3) in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypothesis C.9. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

Under Hypothesis C.10, the change in brown trout status is explained by a fall HFE-induced increase in reproductive rates only. The results under this hypothesis are fairly similar to those under Hypothesis B.6, because the influence of fall HFEs on the reproductive rate is the same. Under Hypothesis C.10, however, there is not an effect of fall HFEs on immigration, so the status quo (Alternative 1) forecast of median 20-year adult brown trout abundance is not quite as high (13,800 as opposed to 15,500; fig. 28). The strategies that discontinue fall HFEs (Alternatives 3 and 4) are the most effective at reducing brown trout abundance, removal strategies (Alternatives 2 and 6) reduce abundance by about 50 percent, and TMFs (Alternative 5) have a moderate effect.

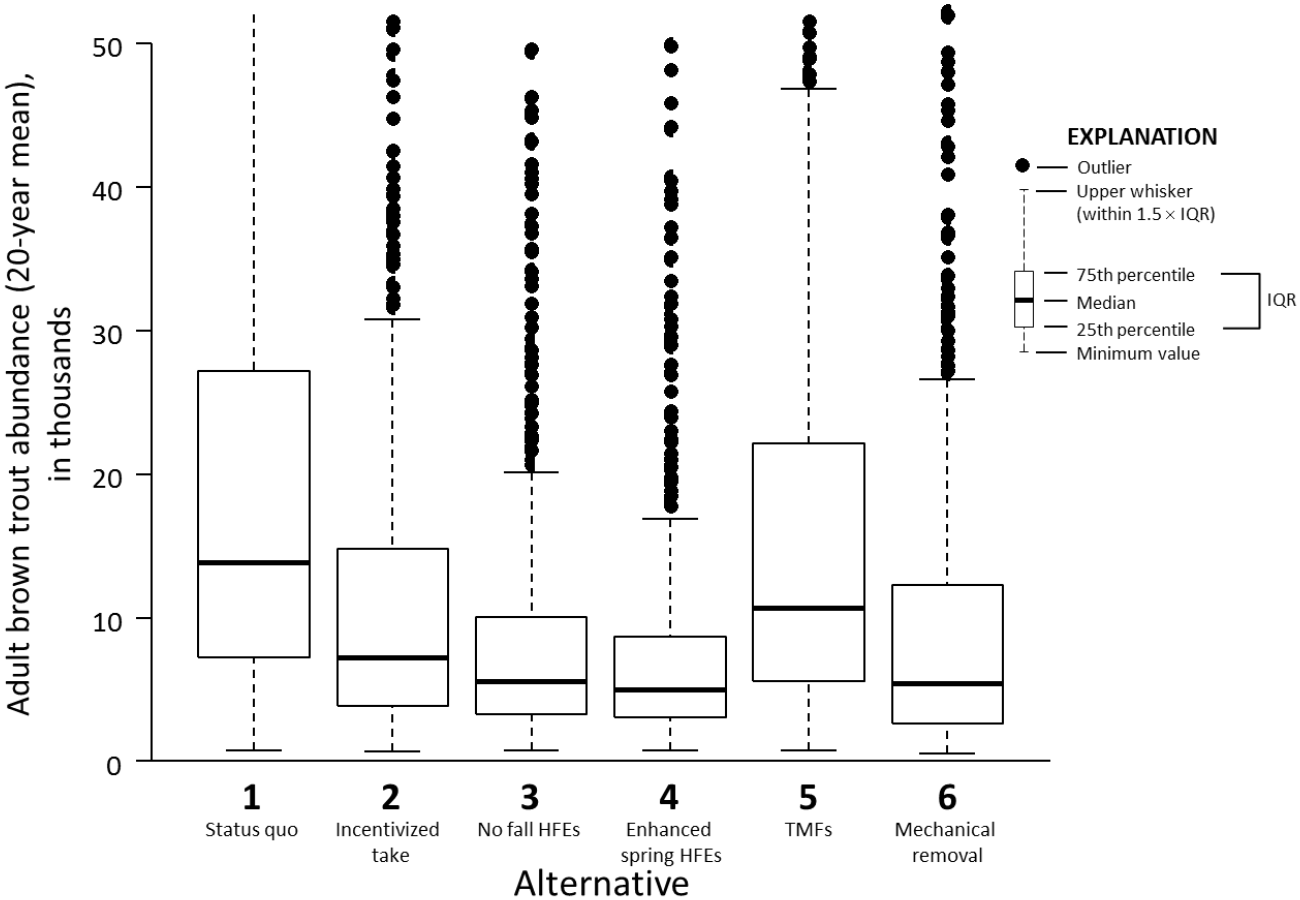

Figure 28. Boxplots of the mean number of large adult brown trout (size class 3) in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypothesis C.10. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

In summary, the effects of the alternative management strategies on brown trout abundance in the Lees Ferry reach of the Colorado River vary considerably across causal hypotheses. The median forecast abundance under the status quo (Alternative 1) varies 6,800 to 15,500 across hypotheses, indicating that the different causal hypotheses have quite different implications for the establishment of brown trout in the absence of intervention. In addition, the pattern of effectiveness of the strategies to reduce brown trout abundance depends substantially on whether fall HFEs play a causal role or not. The comparison of Hypotheses B.5 and B.6 is perhaps most instructive. If fall HFEs are affecting both immigration and reproduction (Hypothesis B.6, fig. 25), then we expect, under the status quo alternative, a more than 3-fold increase in brown trout relative to current levels, and the most effective strategies would involve discontinuing fall HFEs. On the other hand, if fall HFEs are not playing a causal role (Hypothesis B.5, fig. 24), then we only expect a 2-fold increase in brown trout under the status quo, and the most effective strategies would involve some sort of removal effort.

Effects on Humpback Chub

Using the linked set of fish models, we predict an effect of brown trout in the Lees Ferry reach on humpback chub in the LCR reach via emigration from Lees Ferry, movement of trout over time through Marble Canyon, and predation on, or competition with, humpback chub in the LCR reach (fig. 18). To understand the combined effect of these dynamics, we graphed the results from all scenarios (all hypothesis, all management strategies, and all parameter sets) on a single plot of the minimum number of adult humpback chub over 20 years against the mean adult brown trout abundance at Lees Ferry (fig. 29). The minimum number of humpback chub over 20 years at the LCR (a measure of population viability) falls from about 5,000 to about 3,500 as the mean adult brown trout abundance at Lees Ferry increases from about 1,000 to about 50,000, with about half of the effect felt once the adult brown trout abundance reaches 10,000. If the Lees Ferry brown trout population becomes sustained at a very high level (>25,000 adults), we predict there would be enough sustained emigration of trout downstream to essentially eliminate humpback chub from the mainstem of the Colorado River at the confluence with the LCR; the stable number of humpback chub at brown trout populations >25,000 adults would be a result of persistence of chub in the LCR itself. While the models assume that both rainbow and brown trout do not affect dynamics in the LCR, between December 2013 and December 2016, five unique brown trout were detected entering the LCR on the remote PIT-tag antenna array (M.C. Dzul, oral commun., April 3, 2018) and a few hundred rainbow trout were estimated to enter the LCR between November 2013 and March 2014 (Dzul and others, 2017). Note that figure 29 show aggregate measures of abundance of humpback chub and brown trout over the 20-year planning horizon, which obscures the temporal aspects of this relation. The response of adult humpback chub abundance to an increasing brown trout population in the Lees Ferry reach is expected to be lagged, by perhaps as much as 5 to 9 years, owing to the time it takes trout to move downstream and for adult humpback chub to respond to declines in juvenile humpback chub survival. Typically, rainbow trout movement from the Lees Ferry reach to the LCR takes about 1.5 to 2 years (Korman and others, 2016) and juvenile chub take 4 to 7 years to mature into adults (Yackulic and others, 2014).

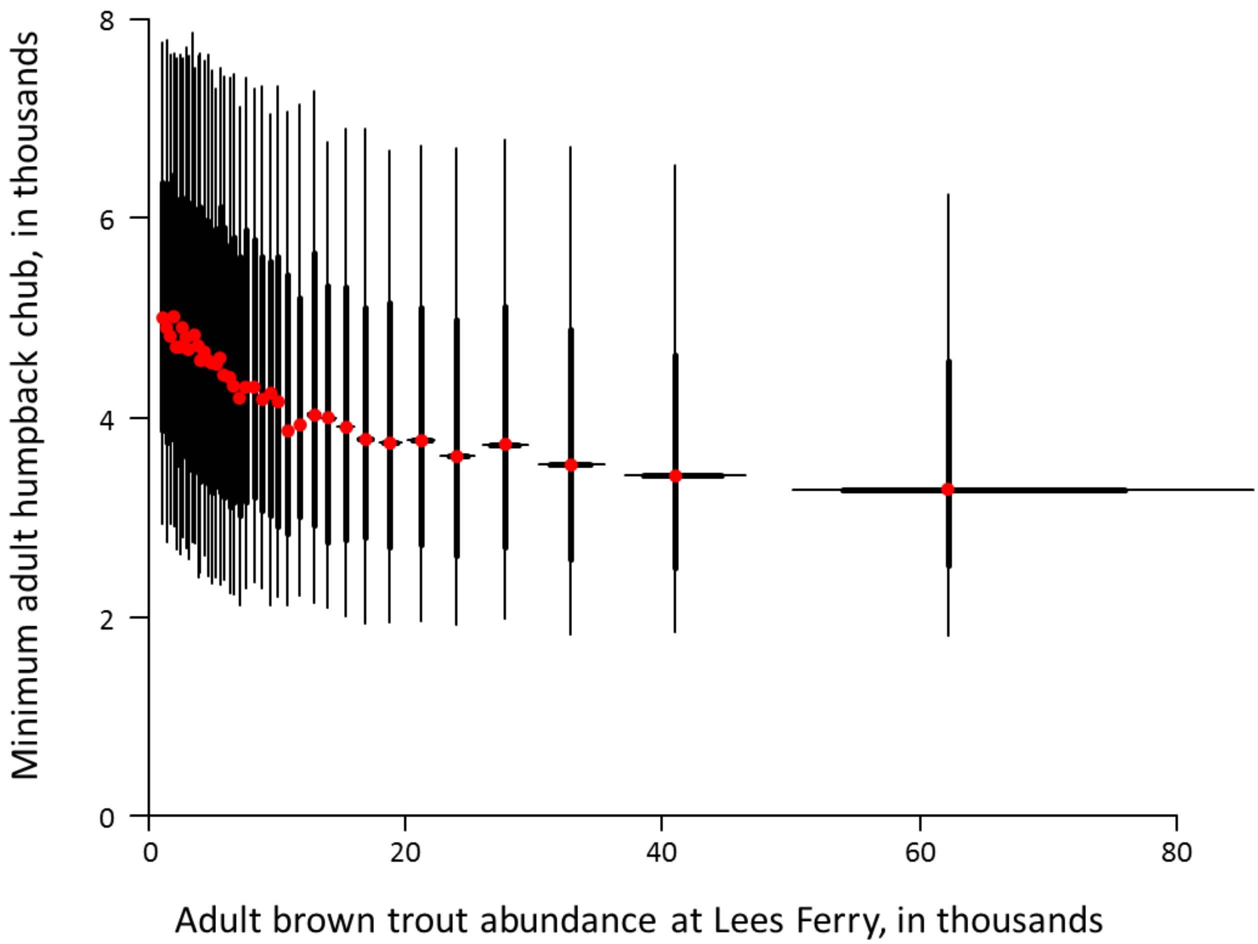

Figure 29. Graph of the minimum number of adult humpback chub in the Little Colorado River aggregation over 20 years as a function of the mean adult brown trout abundance in the Lees Ferry reach of the Colorado River. The red dots are plotted at the median values, the thick black lines extend from the first quartile to the third quartile, and the thin black lines show the 80-percent credible interval.

The effects of the alternative management strategies on humpback chub are complex, but are mostly fairly subtle (figs. 30, 31). Humpback chub are not only influenced by the effects of the alternative strategies on brown trout, they are also influenced directly by some aspects of the strategies (especially to the extent they affect temperature and flow), as well as indirectly through effects on rainbow trout. Under both Hypotheses B.5 and B.6, the status quo (Alternative 1) results in a median value for the humpback chub metric of about 4,000. Under Hypothesis B.5 (pulse immigration; Allee effect on reproduction), differences relative to the status quo are largely insensitive to the management strategy (fig. 30), because the changes in the abundance of brown trout across alternative strategies (fig. 24) are relatively small and attenuated by the downstream movement process. Under Hypothesis B.6 (fall HFEs effects on immigration and reproduction), discontinuing fall HFEs (Alternative 3 and 4) does produce a noticeable benefit to humpback chub relative to the status quo (fig. 31), because of the substantial reduction in brown trout (fig. 25); the other alternative strategies produce only small benefits to humpback chub.

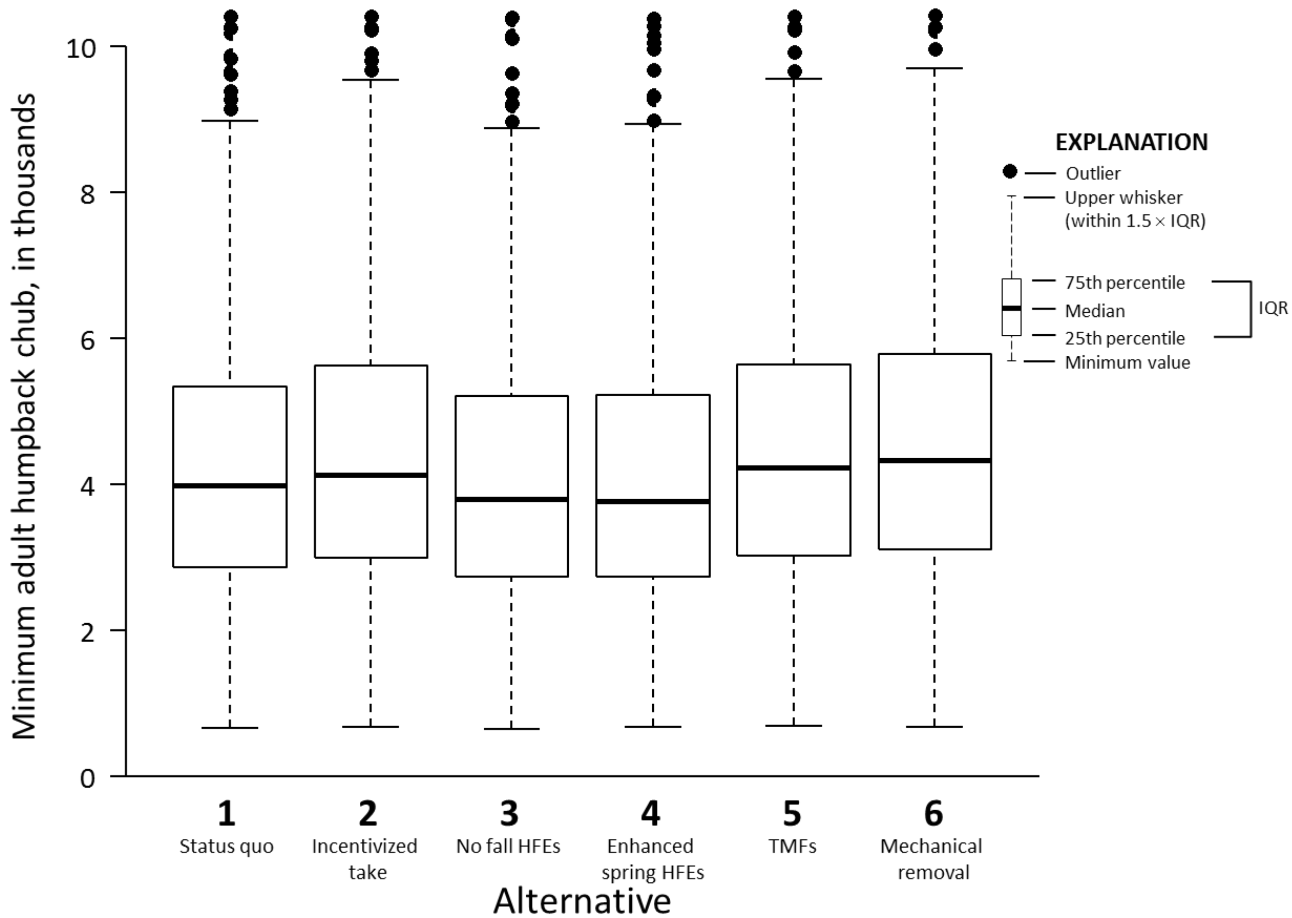

Figure 30. Boxplots of the minimum number of adult humpback chub in the Little Colorado River aggregation over 20 years as a function of the six alternative management strategies, under Hypothesis B.5. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

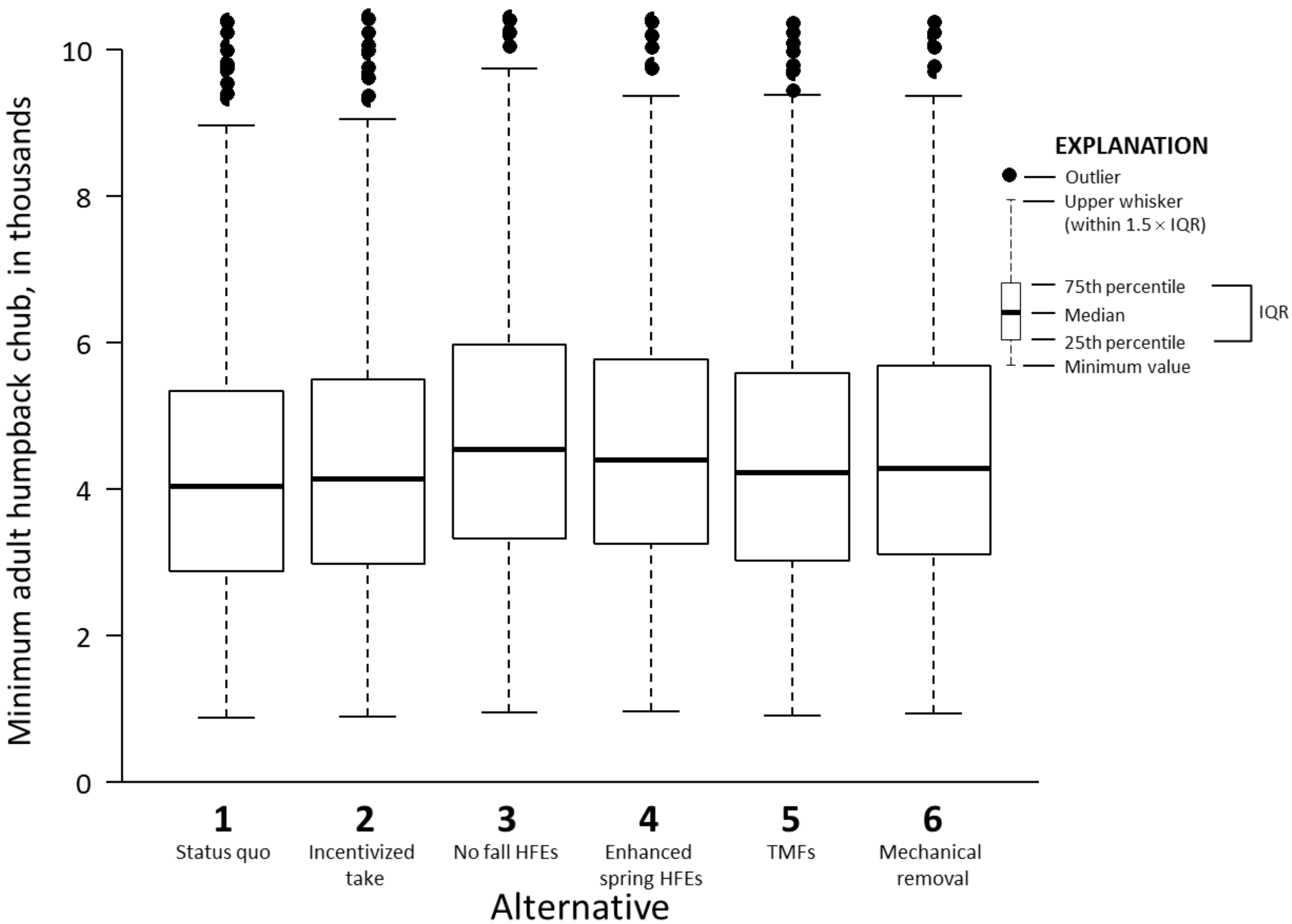

Figure 31. Boxplots of the minimum number of adult humpback chub in the Little Colorado River aggregation over 20 years as a function of the six alternative management strategies, under Hypothesis B.6. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

Effects on the Rainbow Trout Fishery

The effects of the alternative management strategies on the abundance of rainbow trout (age 1 and older) in the Lees Ferry reach of the Colorado River are largely driven by the frequencies of fall and spring HFEs (figs. 32, 33), because rainbow trout recruitment is modelled as being driven by aspects of the flow regime (Korman and others, 2012). Although brown trout directly affect the abundance of rainbow trout in the fish models (via the parameter *C*), the effect is small, and the difference in brown trout abundance across strategies is not large enough to produce noticeable effects on rainbow trout. The average value of *C*, –0.44, suggests that a decrease from 10,000 to 5,000 brown trout would cause an increase of about 2,200 rainbow trout, a small increase relative to the status quo mean abundance of about 60,000. Likewise, although mechanical removal of brown trout (Alternative 6) does have a mortality effect on rainbow trout, the estimated effect is small. The large effects on rainbow trout come from discontinuing fall HFEs (Alternative 3), which are estimated to reduce rainbow trout reproduction; and enhancing spring HFEs (Alternative 4), which are estimated to increase rainbow trout reproduction. The causal hypotheses for brown trout expansion have little influence on the effects of the management strategies on rainbow trout abundance in the Lees Ferry reach (compare figs. 32 and 33). It is worth noting that there are a number of hypotheses currently being advanced for the recent decline in rainbow trout, and there is emerging evidence for one hypothesis that rainbow trout recruitment is primarily driven by phosphorous concentrations in the Lake Powell outflow (Yackulic, 2017), but evaluation of these hypotheses are still in the preliminary stages. Nonetheless, if this nutrient hypothesis or some other hypothesis turns out to be correct, then the predictions reported here may overstate the importance of fall and spring HFEs on management of rainbow trout.

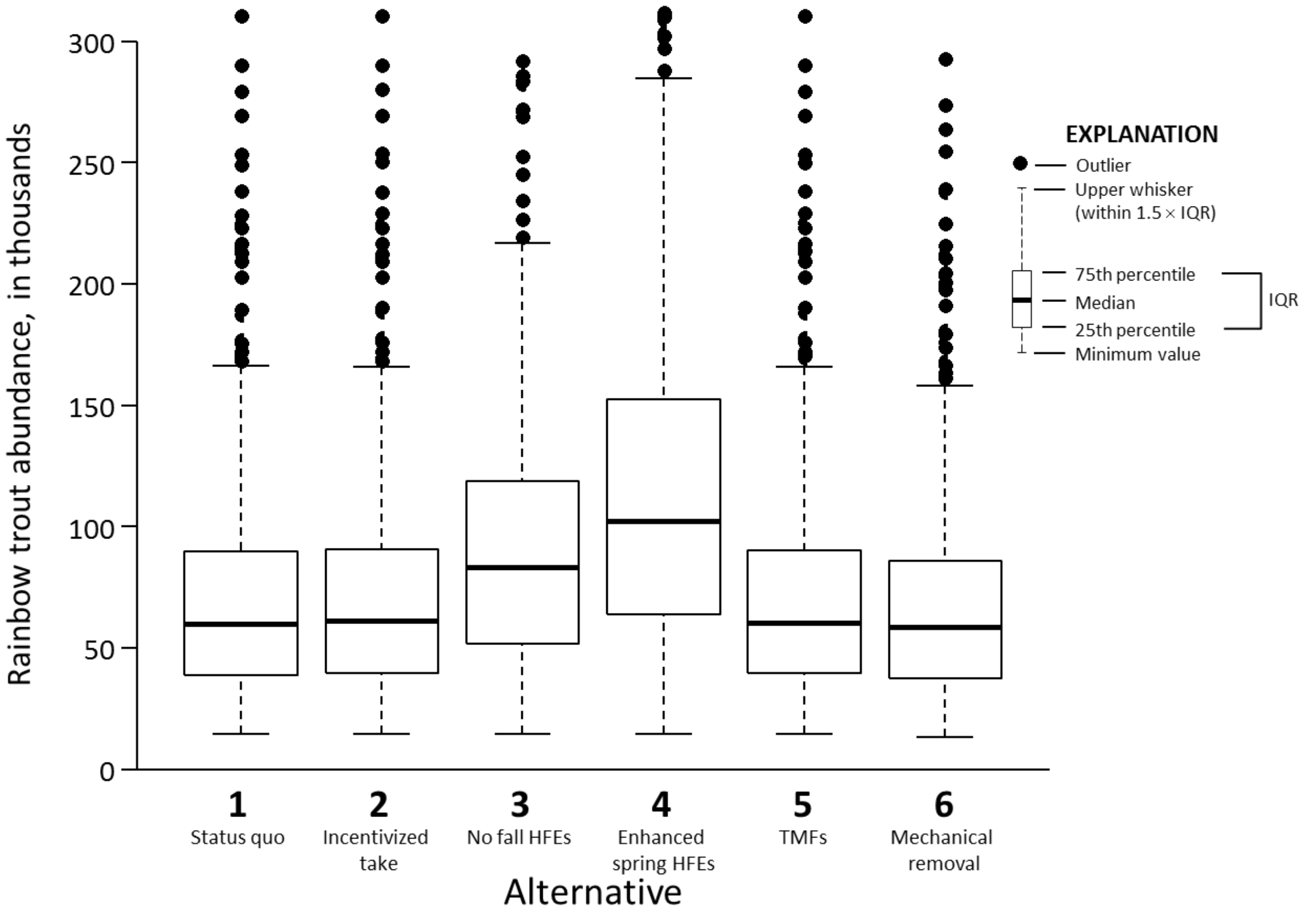

Figure 32. Boxplots of the mean abundance of rainbow trout in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypothesis B.5. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

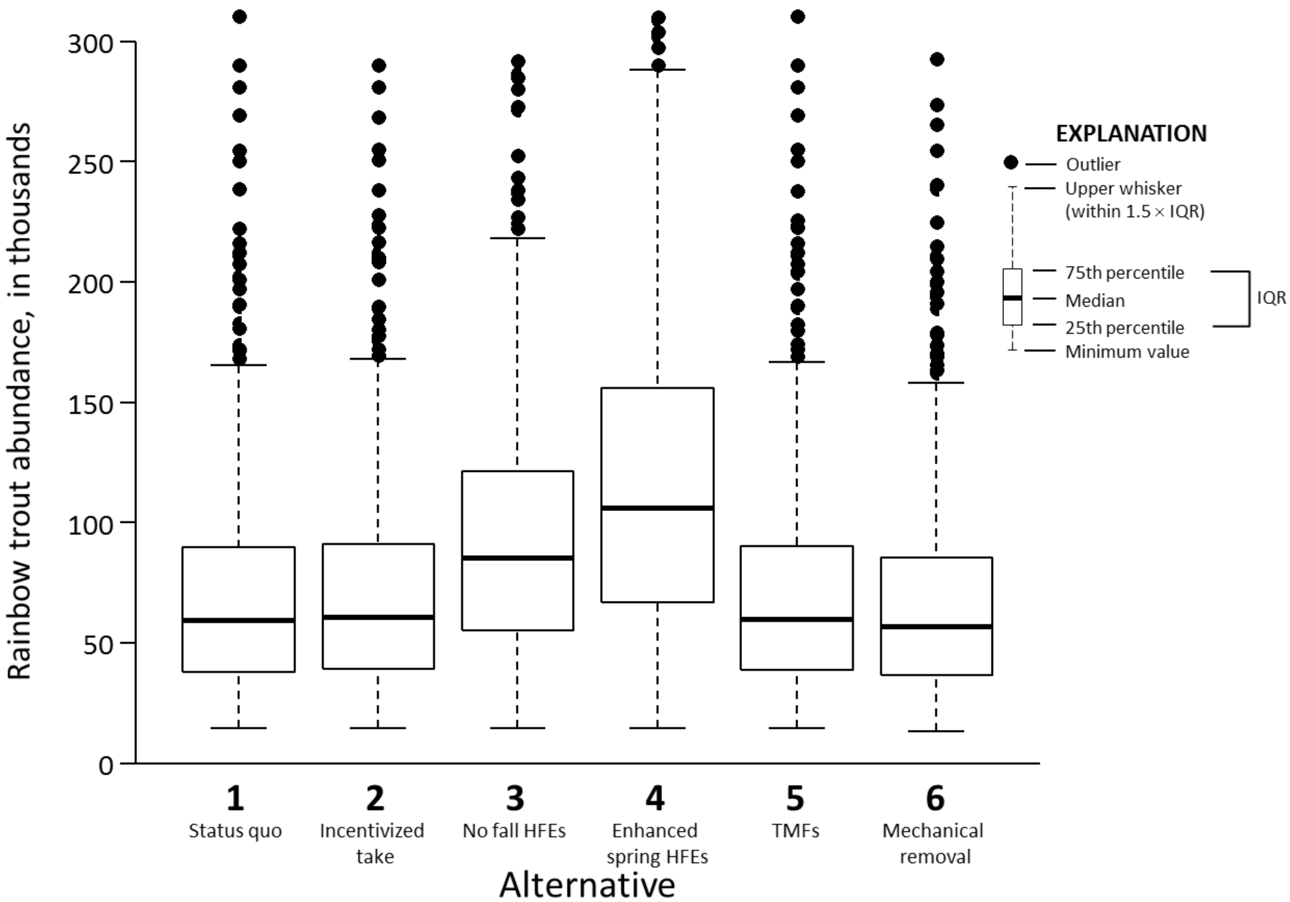

Figure 33. Boxplots of the mean abundance of rainbow trout in the Lees Ferry reach of the Colorado River over 20 years as a function of the six alternative management strategies, under Hypothesis B.6. HFE, high-flow experiment; TMF, trout-management flow; IQR, interquartile range.

Effects on Sediment Resources

Under Alternative 1 (the status quo alternative), the mean total number of HFEs expected over the next 20 years is 20.4 (table 2). There is uncertainty in this forecast, because of uncertainty in the hydrological and sediment inputs that trigger HFEs; the number of HFEs falls between 18 and 24 in 80 percent of the traces, and the 95-percent confidence interval for the mean number of HFEs is 19.6 to 21.1. Fall HFEs are expected to occur more frequently (14.7 out of 20 years) than spring HFEs (5.7 out of 20 years). Note that expected total number of HFEs occurring over 20 years is greater than 20 because there are a number of years when two HFEs (both a fall and a spring HFE) could occur. The sediment results for Alternatives 2, 5, and 6 are identical to the results for the status quo (table 2). Under Alternative 3, total number of HFEs expected over the next 20 years is 5.7 (range 2–10), all of which are spring HFEs; this represents a substantial reduction in the ability to transport sediment relative to the status quo. Under Alternative 4, total number of HFEs expected over the next 20 years is 16.1 (range 14–18), much closer to the status quo than Alternative 3, but still a reduction in ability to transport sediment.

Table 2. Effects of the brown trout management alternatives on sediment resources in the Colorado River, as measured by the number of high-flow experiments expected over the 20-year planning horizon. The weighted mean number of high-flow experiments (HFEs; fall, spring, and total) is shown in bold type. The weighted 80-percent observed range over the sediment and hydrological traces examined in the Long Term Experimental and Monitoring Plan analysis is shown in normal type. The weighted 95-percent confidence interval for the mean number of HFEs is shown in parentheses.

[TMF, trout-management flow]

Alternative	Number of fall HFEs	Number of spring HFEs	Total number of HFEs
1: Status quo	**14.7** 12–17 (14.2, 15.2)	**5.7** 2–10 (4.8, 6.5)	**20.4** 18–24 (19.6, 21.1)
2: Incentivized take	**14.7** 12–17 (14.2, 15.2)	**5.7** 2–10 (4.8, 6.5)	**20.4** 18–24 (19.6, 21.1)
3: No fall HFEs	**0** 0–0 (0, 0)	**5.7** 2–10 (4.8, 6.5)	**5.7** 2–10 (4.8, 6.5)
4: Enhanced spring HFEs	**0** 0–0 (0, 0)	**16.1** 14–18 (15.7, 16.6)	**16.1** 14–18 (15.7, 16.6)
5: TMFs	**14.7** 12–17 (14.2, 15.2)	**5.7** 2–10 (4.8, 6.5)	**20.4** 18–24 (19.6, 21.1)
6: Mechanical removal	**14.7** 12–17 (14.2, 15.2)	**5.7** 2–10 (4.8, 6.5)	**20.4** 18–24 (19.6, 21.1)

Effects on Hydropower Generation at Glen Canyon Dam

Under Alternative 1 (the status quo alternative), the expected cost of HFEs over the next 20 years is $23.5 million (table 3). There is uncertainty in this result, because of uncertainty in the hydrological and sediment inputs that trigger HFEs (see “Effects on Sediment Resources”) and uncertainty in the cost of energy generation because of uncertain future fuel prices, generation mix, and variety of other factors. The hydropower results for Alternatives 2 and 6 are identical to results for the status quo (table 3). Under Alternative 3, total number of HFEs expected over the next 20 years decreases and expected hydropower generation costs decrease to $6.5 million, $17.0 million less than the status quo (table 3). Under Alternative 4, cost of HFEs expected over the next 20 years is $18.7 million, much closer to the status quo than Alternative 3, but still a reduction in costs of $4.9 million. Under Alternative 5, annual brown trout management flows increase expected cost of foregone hydropower value, relative to the status quo, by $6.9 million.

Table 3. Effects of the brown trout management alternatives on hydropower generation at Glen Canyon Dam and trout removal costs over the 20-year planning horizon. Costs incurred over time are discounted at 3.375-percent.

[$M, millions of U.S. dollars; TMF, trout-management flow]

Alternative	Discounted loss of hydropower generation ($M)	Discounted loss of hydropower generation ($M, relative to status quo)[1]	Discounted cost of trout removal efforts ($M)
1: Status quo	23.5	0.0	0.0
2: Incentivized take	23.5	0.0	4.6–8.1[2]
3: No fall HFEs	6.5	–17.0	0.0
4: Enhanced spring HFEs	18.7	–4.9	0.0
5: TMFs	30.0	+6.5	0.0
6: Mechanical removal	23.5	0.0	6.9

[1] This column shows the net loss in value of hydropower generation relative to the status quo. Thus, positive numbers represent a loss in generation because of the change in dam operations associated with the alternative, and negative numbers represent a gain in the value of hydropower generation because the loss of generation embedded in the status quo is reduced.

[2] The discounted cost of trout removal for Alternative 2 is shown as a range because the cost depends on the causal hypothesis for the expansion of brown trout in the Lees Ferry reach.

Costs of Removal

The cost of removal depends on the effort specified in Alternatives 2 and 6. Under Alternative 2 the expected cost of incentivized take is based on the total number of brown trout removed by anglers. Brown trout removal depends on abundance of brown trout and abundance varies under each causal hypothesis. For example, expected abundance of brown trout over the next 20 years is greater under Hypothesis 1 than Hypothesis 2, therefore the expected cost of Alternative 2 is greater under Hypothesis 1. The sum of discounted costs across all hypotheses ranges from $4.6–8.1 million (table 3).

In Alternative 6 mechanical removal of brown trout occurs on an annual basis. Annual removal consists of eight passes of Lees Ferry and the discounted cost over 20 years is $6.9 million (table 3).

Long-term Economic Effects on the Rainbow Trout Fishery

Relative to Alternative 1 (status quo), Alternatives 3 and 4 are likely to have a small but positive effect on the long-term economic condition of Lees Ferry angling. Reducing the expected number of HFEs in a given year increases angler access. This outcome, however, depends on the reduction in HFEs not affecting the quality of the rainbow trout fishery relative to the status quo. Alternatives 2, 5, and 6 could have the largest effect on the long-term economic condition of the Lees Ferry rainbow trout fishery. It is uncertain how angler demand would respond to incentivized take under Alternative 2. An important component of Alterative 2 is the educational and outreach program to highlight the importance of conservation through brown trout management. The incentivized take program could implement a payment design to encourage removal of brown trout but not in a way that discourages angler participation in the rainbow trout fishery. Alternatives 5 and 6 have the largest potential to disrupt the long-term economic condition of the Lees Ferry rainbow trout fishery relative to the status-quo. Alternatives 5 and 6 could negatively affect angler demand through reduced access, a possible reduction in the quality of the rainbow trout fishery, and a general perception of reduced quality of the rainbow trout fishery.

Tribal Values

Several American Indian Tribes have expressed concern about management actions that are lethal to fish, including actions targeting nonnative trout, if such actions constitute what they believe is an unwarranted or unnecessary taking of life (see “Tribal perspectives on nonnative fish removal”). Mechanical removal (Alternative 6) and TMFs (Alternative 5) to reduce brown trout abundance may constitute a significant departure from the values of several tribes. The tribes have indicated that the issues regarding these values are quite subtle, and could include such elements as: the nature of the actions implemented; the number of nonnative fish affected; whether or not fish removed are used for human consumption or other culturally appropriate purposes; the evidence for the need for action; and the intentions of the agencies and personnel carrying out the actions. The need for direct, substantive, and continued collaboration and consultation with the tribes has been a consistent theme of their comments.

Tribal perspectives on nonnative fish removal

Representatives of the Pueblo of Zuni and the Hopi Tribe provided written comments to convey the perspectives of these two tribes regarding fish removal. The following text is the full, unedited set of comments, prepared by Kurt Dongoske (Pueblo of Zuni) and Michael Yeatts (Hopi Tribe).[9]

> Participating Native American Tribes (Hopi Tribe and Pueblo of Zuni) have expressed, through government-to-government consultation, meetings with the Assistant Secretary for Water and Science, and through federal compliance processes associated with the National Environmental Policy Act and the National Historic Preservation Act, concerns to the U.S. Department of the Interior (DOI) regarding management actions described above involving fish suppression flows, mechanical removal of nonnative fish, and other lethal management actions.
>
> In the 2002–2004 GCMRC Biennial Work Plan, a proposal was made to conduct experimental mechanical removal of trout centered on the confluence of the Colorado and Little Colorado Rivers. At the time, the Hopi Tribe expressed concern about the killing of large numbers of fish and the specter of death that would be created by such activity in a culturally significant sacred area. The Hopi Tribe also understood the scientific desire to understand the effect that the non-native trout were having on the native, endangered humpback chub and if there were management options available to control the trout numbers, particularly if they were threatening the existence of the humpback chub. To make the study more culturally acceptable, the Hopi Tribe requested that the fish removed be used for a beneficial purpose, so that the life they were sacrificing wouldn’t be trivialized. The non-native fish were viewed as a fully alive component of the ecosystem, which were there through no fault of their own, and shouldn’t be needlessly punished.
>
> Perspectives of the Hopi Tribe have not significantly changed since the implementation of the original mechanical removal experiment. Killing large numbers of fish (or any other group of animals), unless there is an extraordinary circumstance, is fundamentally wrong! It

[9] Text taken from this inserted section should be cited as: Dongoske, K.E., and Yeatts, M., 2018, Tribal perspectives on nonnative fish removal, *in* Runge, M.C., Yackulic, C.B., Bair, L.S., Kennedy, T.A., Valdez, R.A., Ellsworth, C., Kershner J.L., Rogers, R.S., Trammell, M.A., and Young, K.L., Brown trout in the Lees Ferry reach of the Colorado River—Evaluation of causal hypotheses and potential interventions: U.S. Geological Survey Open-File Report 2018–1069, p. 63–66.

is not the specific species of fish or the method of killing them that is at the heart of the Hopi concern; it is the view that their life is somehow less valuable and they are therefore expendable.

Since 2006, the Hopi Long-term Monitoring Program asked about the appropriateness of removing non-native fish. To date, 46 percent of the Hopi respondents supported removal; 37 percent opposed it; and 17 percent were not sure. Those who support removal, however, clearly state that it should only be used if there is strong evidence that the non-native species is a real threat to the survival of a native species and that other causes are not more significant. Killing just because we think it might help, and we can do it, is not suitable justification. Secondly, they view killing the non-natives as the last resort. If they can be removed alive, that is preferred. Otherwise, they should be used as food for people or possibly for some other culturally appropriate purpose.

Finally, the Hopi express puzzlement at the seemingly conflicting management goals of maintaining native fish and having a recreational trout fishery in the same river; and then fingering the trout as the threat to the native fish. While there are certainly many avenues being pursued that make managers feel that these divergent goals are possible, the simplest reading of the situation is that trying to achieve both of these goals is not appropriate.

Over the past ten years, the Pueblo of Zuni has been the most vocal of the Tribes in expressing objection to these actions because they involve the taking of life without sufficient justification. The remainder of this section focuses on the Pueblo of Zuni's objections to lethal management actions by situating those objections within the appropriate Zuni traditional cultural context. In doing so, a more informed and nuanced understanding of the Zuni position should be obtained.

For the past twenty-five years, the Pueblo of Zuni has repeatedly emphasized to the Department of the Interior the important cultural, religious, and historical ties the Zuni people have to the Grand Canyon, Colorado River, and Little Colorado River. The Grand Canyon is the place of Zuni emergence into this current world at a place called *Chimik'yana'kya dey'a*, near Ribbon Falls in Bright Angel Canyon. The natural environment that Zuni people saw at Emergence became central to traditional Zuni culture. In fact, all of the plants that grow along the stream from Ribbon Falls to the Colorado River, and all the birds and other animals, springs, minerals and natural resources located in the Grand Canyon and its' tributaries, have a central place in Zuni traditional cultural practices and ceremonial activities. The confluence of the Little Colorado and Colorado Rivers is understood to be a spiritual umbilical connection between the Pueblo of Zuni and the Grand Canyon that is facilitated through the union of the Zuni River with the Little Colorado and the Colorado Rivers. The confluence is also held by the Zuni people to be an extremely important and sacred place because of its abundance of aquatic and terrestrial life that simultaneously expresses and represents the fertility of nature.

The Colorado River is a particularly important place to the Zuni people because it was the location of an important historical event. This historical event was conveyed to Frank Hamilton Cushing, an American Anthropologist, by the Zuni in the late nineteenth century and is summarized below to convey the deep, intense, and remarkable significance that the Colorado River and the aquatic life within it indelibly hold for the Zuni people.

"Shortly after Emergence, men of the Bear, Crane, and Seed clans strode into the red waters of the Colorado River and waded across. The men of the clans all crossed successfully. The

women travelling with them carried their children on their backs and they waded into the water. Their children, who were unfinished and immature (because this occurred shortly after Emergence), changed in their terror. Their skins turned cold and scaly and they grew tails. Their hands and feet became webbed and clawed for swimming. The children fell into the swift, red waters. Some of the children became lizards, others turned into frogs, turtles, newts, and fish.

"The children of these clans were lost to the waters. The mothers were able to make it to the other side of the river, where they wailed and cried for their children. The Twins heard them, returned, and advised all the mothers to cherish their children through all dangers. After listening to the Twins, those people who had yet to pass through the river took heart and clutched their children to them and safely proceeded to the opposite shore.

"The people who successfully made it out of the river rested, calmed the remaining children, and then arose and continued their journey to the plane east of the two mountains with the great water between." (Cushing, 1896, 1920, 1988; as summarized in Dongoske and Hays-Gilpin, 2016)

As a consequence of this historical event, all aquatic life is recognized by present day Zunis to be descendants of those Zuni children who were lost to the waters, thus creating a strong and lasting familial bond to all aquatic life and a fundamentally important stewardship responsibility. It is precisely because of this familial bond and stewardship responsibility that the Pueblo of Zuni has for the past ten years communicated to the Department of the Interior objections to any management actions (for example, mechanical removal, trout suppression flows, piscicides) that entail the taking of aquatic life.

The implementation of lethal fish management actions is contrary to Zuni worldview and environmental ethics. Annual ceremonial activities carried out by the Zuni are performed to ensure adequate rainfall and prosperity for all life. Zuni people pray not only for Zuni lands, but for all people and all lands. Zuni prayers are especially aimed at bringing precipitation to the Southwest. In order to successfully carry out Zuni prayers, offerings, and ceremonies necessary to ensure rainfall for crops and the prosperity of all life, Zuni must maintain a balance with all parts of the interconnected universe. The animals, including all aquatic life, birds, plants, rocks, sand, minerals, and water in the Grand Canyon convey special meaning and have significant material and spiritual relationships to the Zuni people. To needlessly take life causes an imbalance in the natural world and also disturbs the harmony and health of the spiritual realm and the Zuni peoples.

Moreover, the Zuni recognize that there is a direct causal relationship between what happens in and to the Colorado River within Grand Canyon and the Pueblo of Zuni. According to Zuni religious and political leaders and illustrative of this point, when the initial mechanical removal efforts were occurring at the confluence of the Little Colorado and Colorado Rivers between 2003 and 2006, Zuni experienced an increased use of taser guns by Zuni police on Zuni community members. The increased use of tasers by Zuni police is viewed by the Zuni religious leaders as a direct adverse effect on the Zuni community that resulted from those mechanical removal efforts. To underscore this Zuni recognition of a cause/effect relationship between the Grand Canyon and Zuni, the Zuni religious leaders expressed their concern that the ongoing mechanical removal of brown trout and other non-natives from Bright Angel Creek by the National Park Service is contributing to an increase in the number of Zuni community members that are dying on a daily basis in Zuni. They emphasized that what happens on the Colorado River in Grand Canyon directly impacts Zuni – a position and recognition that has existed since the time of Emergence.

The implementation of lethal management actions to control non-native aquatic species, especially rainbow and brown trout, within the Colorado River through Glen and Grand Canyons creates a disproportionately negative impact, materially, spiritually, emotionally, and psychologically, on the Zuni people. These actions tend to emphasize strong reliance on reactionary management strategies rather than promoting proactive and productive approaches focused on identifying and controlling the antecedent environmental and structural conditions that promote or allow non-natives to enter and thrive within the system. The continued consideration of lethal management tools to address non-native aquatics demonstrates a disregard for the Zuni familial and stewardship relationship to aquatic life, a devaluation of the special relationship that the Zuni people have with the Grand Canyon and the Colorado River, and a blatant dismissal of previously expressed Zuni concerns to the U.S. Government.

The comparison of management options directed toward the control of non-native aquatics by scientists and managers must respect Zuni perspectives and knowledge sovereignty by providing it equal standing with Western forms of knowledge production. To assume that the only viable method of controlling aquatic non-natives is through lethal means changes the expression and impression of the Colorado River as a waterway of life to a river of death. It is imperative that scientists and managers respective Zuni values through the integration of Zuni perspectives with scientific analyses to make them more compassionate, caring, holistic, and ultimately, productive for all life that depends on the Colorado River. Penned over 56 years ago and directed toward unrestrained pesticide use, Rachel Carson's (1961:275) words expressed in Silent Spring, are prescient when considering the lethal management of non-native aquatics in the Colorado River. She wrote, "Life is a miracle beyond our comprehension, and we should reverence it even where we have to struggle against it…. The resort to weapons such as insecticides to control it is proof of insufficient knowledge and of an incapacity so to guide the processes of nature that brute force becomes unnecessary. Humbleness is in order; there is no excuse for scientific conceit."

Trout management alternatives and Tribal perspectives

With regard to specific alternative strategies considered in this report, Alternatives 5 and 6 would be in direct conflict with concerns of the Hopi Tribe and the Pueblo of Zuni (see "Tribal perspectives on nonnative fish removal" for further explanation). The Hopi Tribe and the Pueblo of Zuni may have similar concerns with Alternatives 2 and 4 if the actions kill brown trout without sufficient justification. Although Alternative 2 may be designed to use angler-caught brown trout for human consumption or in other culturally appropriate ways, the tribes may have other concerns with this alternative that could become evident in consultation. Consultation with the tribes prior to design and implementation of some version of Alternative 2 could assist in addressing potential tribal concerns. Alternatives 1 and 3 are likely to have limited impacts on tribal concerns, at least relative to the position of tribes regarding the LTEMP ROD. It is difficult, however, to fully evaluate the alternative thematic strategies of this report against tribal values, because we have not specified operational details, and those details are important in understanding the full scope and intent of a management strategy.

Summary of Management Consequences

A summary of the effects of the six proposed management strategies, as measured by the means of the forecast performance metrics, reveals the need to consider tradeoffs among objectives and also shows the consequences of uncertainty. Under Hypothesis B.5, in which brown trout immigration is explained by a pulse effect and the increase in reproduction by an Allee effect, there is no one strategy that is best for all objectives (table 4). The status quo strategy (Alternative 1) is best among the strategies investigated for transporting sediment and for minimizing the costs of removal, but it does a poor job of managing the brown trout population, allowing it to increase to a 20-year average of 15,000 stage 3 adults (approximately three times the current size). The two removal strategies (Alternatives 2 and 6) do the best job of managing brown trout at roughly current levels, achieve benefits for humpback chub relative to the status quo, maintain the full ability of the status quo to transport sediment, and do not incur any additional loss of hydropower generation, but they raise tribal concerns, provide little advantage for rainbow trout, and cost on the order of $7 million over the planning period. The two strategies that focus on changing the frequency of HFEs (Alternatives 3 and 4) do a poor job of managing brown trout, result in greater risk to the viability of humpback chub, and forego opportunities to transport sediment, but they benefit rainbow trout and increase the value of hydropower generation. The strategy involving brown trout management flows (Alternative 5) performs better than the status quo on all objectives except for hydropower generation, for which it incurs an additional cost of $6.5 million over the planning period relative to the status quo.

Table 4. Consequence table showing the mean performance for each Lees Ferry brown trout management alternative strategy against each objective evaluated, under Hypothesis B.5. The values in each column are color-coded, with the best-performing strategy shaded in yellow, the worst-performing strategy shaded in dark blue, strategies that perform better than status quo (Alternative 1) shaded in orange, and strategies that perform worse than status quo shaded in turquoise.

[$M, millions of U.S. dollars; TMF, trout-management flow]

Objective / Alternative	Brown Trout	Humpback Chub	Rainbow Trout	Sediment	Hydropower Costs	Removal Costs
Performance metric	*Mean Adults*	*Minimum Adults*	*Age 1+ fish*	*Number of HFEs*	*$M*	*$M*
Desired direction	Low	High	High	High	Low	Low
1: Status quo	15,476	4,323	69,720	20.4	0.0	0.0
2: Incentivized take	8,310	4,476	71,458	20.4	0.0	6.5
3: No fall HFEs	15,476	4,194	90,471	5.7	– 17.0	0.0
4: Enhanced spring HFEs	13,050	4,175	115,826	16.1	– 4.9	0.0
5: TMFs	12,111	4,529	70,723	20.4	+ 6.5	0.0
6: Mechanical removal	6,392	4,623	67,733	20.4	0.0	6.9

The pattern of responses across objectives is not the same under Hypothesis B.6, in which the increases in both brown trout immigration and reproduction are explained by the frequency of fall HFEs (table 5). If HFEs do have a causal role in the expansion of brown trout, then strategies that change the frequency of HFEs (Alternatives 3 and 4) do the best job of managing brown trout numbers in Lees Ferry, benefit both humpback chub and rainbow trout, and increase the value of hydropower generation, but these benefits come at the expense of the ability to transport sediment. The removal options (Alternatives 2 and 6) preserve the ability to transport sediment, and manage brown trout at about twice the current levels, but incur implementation costs and do not benefit rainbow trout. The strategy involving brown trout management flows (Alternative 5) exhibits only a slight improvement relative to the status quo in managing brown trout, humpback chub, and rainbow trout, while incurring $6.5 million in additional losses of hydropower generation.

Table 5. Consequence table showing the mean performance for each Lees Ferry brown trout management alternative strategy against each objective evaluated, under Hypothesis B.6. The values in each column are color-coded, with the best-performing strategy shaded in yellow, the worst-performing strategy shaded in dark blue, strategies that perform better than status quo (Alternative 1) shaded in orange, and strategies that perform worse than status quo shaded in turquoise.

[$M, millions of U.S. dollars; TMF, trout-management flow]

Alternative / Objective	Brown Trout	Humpback Chub	Rainbow Trout	Sediment	Hydropower Costs	Removal Costs
Performance metric	*Mean Adults*	*Minimum Adults*	*Age 1 fish*	*Number of HFEs*	*$M*	*$M*
Desired direction	Low	High	High	High	Low	Low
1: Status quo	19,820	4,344	69,108	20.4	0.0	0.0
2: Incentivized take	12,097	4,464	70,613	20.4	0.0	8.1
3: No fall HFEs	6,881	4,769	93,864	5.7	– 17.0	0.0
4: Enhanced spring HFEs	5,928	4,650	119,326	16.1	– 4.9	0.0
5: TMFs	16,951	4,521	69,801	20.4	+ 6.5	0.0
6: Mechanical removal	10,328	4,571	66,716	20.4	0.0	6.9

Thus, the choice among these management strategies is made difficult both by the contrasting pattern of benefits across objectives and the uncertainty in the underlying cause of the brown trout expansion. To navigate the tradeoffs, decision makers would need to weigh the objectives evaluated (and other objectives they deemed important), considering how much they might be willing to sacrifice on some objectives to achieve benefits on others. Such a deliberation is an expression of values, reflecting the decision makers' interpretation of the governing statutes and regulations as well as other outcomes that are important to stakeholders and the public. This challenge is exacerbated by uncertainty, because the pattern in the benefits across objectives depends on the underlying causal mechanisms. Techniques from the field of decision analysis, such as multi-criteria decision analysis and value of information, could be used to help decision makers in these deliberations (Runge and others, 2015).

Of course, these six strategies are not the only choices available to management agencies. It may be possible to balance some of the tradeoffs by considering hybrid strategies that trigger actions only under particular conditions; this could be a way to achieve benefits without incurring as many costs. Further, adaptive strategies could also be created that take different actions depending on how the uncertainty about the causal mechanisms resolved. The patterns in the results in this paper provide insights about the primary effects that may be useful in crafting more sophisticated operational strategies.

Monitoring and Research Considerations

Brown Trout Population Monitoring

Monitoring and research are important for assessing the status of the brown trout population and to evaluate species response to management actions. Most brown trout research and monitoring in Glen, Marble, and Grand Canyons is currently being done as part of other ongoing studies conducted by the GCMRC and its cooperators, with support from the GCDAMP. Ongoing studies include long-term

CPUE-based monitoring of the trout fishery in the Lees Ferry reach, mark-recapture studies of brown and rainbow trout in the Lees Ferry reach to provide abundance and demographic rate estimates, and monitoring of rainbow trout and brown trout abundance near the LCR.

The rapid expansion of brown trout numbers during 2013–2016 (fig. 2) caused concern because of the potential effect of brown trout on the rainbow trout fishery and the potential for brown trout to affect the humpback chub population downstream. The primary monitoring question for brown trout will be: "Is the population of brown trout in the Lees Ferry reach of the Colorado River increasing, decreasing, or remaining stable?" If abundance-based management triggers are adopted, a related question will be whether abundances warrant changes in management actions. Historically, the AGFD has monitored the rainbow trout fishery at Lees Ferry using CPUE methods and this will likely be sufficient to monitor trends, especially if size classes are presented separately. If managers adopt abundance-based triggers, ongoing mark-recapture studies by GCMRC will allow estimation of capture probabilities, and thus more accurate estimates of abundance. Mark-recapture methods will also provide estimates of demographic rates to examine proximate causes of population trends, such as whether potential increases are driven by immigration events, local recruitment, or both.

While it is important to monitor the brown trout population in the Lees Ferry reach, it will also be necessary to monitor the dynamics of brown trout numbers in downstream reaches. Surveys downstream of Lees Ferry indicate that brown trout populations in mainstem reaches adjacent to the Bright Angel Creek inflow (where NPS control efforts are ongoing) are decreasing or stable, while brown trout numbers may be increasing in the reach immediately downstream of Lees Ferry and in the most downstream reach (below RM 220). This companion monitoring effort to track changes in the brown trout population in downstream areas is necessary to understand how these changes may be affecting downstream aggregations of humpback chub, as well as influencing the dynamics of the Lees Ferry population. Long-term monitoring of the fish community downstream of Lees Ferry is conducted by the AGFD, GCMRC, and the USFWS. This sampling is done annually with electrofishing and hoop nets, and encompasses about 280 miles of river (Lees Ferry to Pearce Ferry) that is deep, swift, and difficult to sample. In addition, there is fixed-site mark-recapture sampling near the LCR (at the "juvenile chub monitoring" site), which currently provides abundance and demographic rate estimates for humpback chub and rainbow trout, and could be expanded to provide estimates for brown trout. These sampling programs need to ensure that sampling is of sufficient sensitivity to characterize the longitudinal distribution of brown trout as well as identify significant sources of large numbers of fish or sources of reproduction, particularly in areas occupied by humpback chub.

Monitoring Effects of Proposed Actions to Reduce Brown Trout in Lees Ferry

A number of management alternatives have been proposed to reduce numbers and recruitment of brown trout in the Lees Ferry reach. There are fundamentally two categories of actions that have been identified, mechanical removal and flow manipulation. Mechanical removal of fish by multiple electrofishing passes is proposed as one possible way to reduce numbers of brown trout. The AGFD CPUE-based monitoring program and GCMRC's mark-recapture population studies, identified in "Brown Trout Population Monitoring", will help managers understand the effect of implementing an expanded electrofishing program.

Also, direct removal of brown trout through incentivized angler take is proposed as a way to remove fish from the population. Mark-recapture population studies, CPUE-based monitoring, and monitoring of angler catch through creel surveys and reward tags will help managers understand whether incentivized take is helping to reduce the number of brown trout in the Lees Ferry reach.

Manipulation of flow releases from Glen Canyon Dam has been proposed as a way to manage numbers of brown trout in Lees Ferry. Trout management flows in late winter or spring (February through May) are proposed to strand or displace young brown trout recently emerged from spawning gravels. Similar trout management flows in summer (May through August) for controlling numbers of juvenile rainbow trout are included in the LTEMP FEIS, but have not yet been implemented.

Ongoing flow management also has the potential of affecting brown trout. Past fall HFEs have been hypothesized as one reason that brown trout have expanded, while spring HFEs, as described in the LTEMP ROD, may help to revitalize the invertebrate community and enhance rainbow trout spawning. The effects of flow manipulation on brown trout dynamics will likely be harder to detect than the effects of direct removal of brown trout. The CPUE-based monitoring program and mark-recapture population studies combined with continued monitoring of the invertebrate community in the Lees Ferry reach will help provide an understanding of how flow management influences the brown trout population, as well as the food base.

There is the potential that these mechanical removal and flow management alternatives will be implemented concurrently. It will be difficult to attribute the response of the brown trout population to any particular action in this scenario, except through detailed study of different life stages. The proposed annual monitoring program would help managers determine the trajectory of the population but may not be useful for attributing cause and effect.

Humpback Chub

Mainstem Colorado River aggregations of humpback chub are monitored annually (CPUE indices), and the abundance of the humpback chub population near the LCR is estimated by combining information from mark-recapture studies in the mainstem and the LCR. This monitoring serves to evaluate the status of humpback chub in the Colorado River downstream of Glen Canyon Dam. The mark-recapture study in the mainstem Colorado River has already estimated relations between rainbow trout abundance and juvenile humpback chub survival, growth, and capture probabilities (Yackulic and others, 2018b), which served as a basis for simulations in this report. Given sufficient time, mark-recapture methods should be able to directly establish similar relations for brown trout.

Brown Trout Related Research Questions

We have identified a number of uncertainties as we attempted to evaluate the potential causes of the brown trout expansion in the Lees Ferry reach. It will be important to ensure the research program in Glen Canyon is sufficient to understand the population dynamics of the brown trout at Lees Ferry as well as some of the mechanisms that are influencing the population. Following are some critical research needs that we have identified.

Where do brown trout spawn in the Lees Ferry reach?

Sympatric populations of brown trout and rainbow trout often use the same type of spawning habitat and hence, the same spawning areas. Where brown trout spawn in late fall (October to January) and rainbow trout spawn in late winter and early spring (January to April), as in the Lees Ferry reach, there is a chance for redd disturbance through interference spawning by rainbow trout and increased mortality of brown trout eggs and fry (Scott and Irvine, 2000). Large numbers of rainbow trout can reduce numbers of sympatric redd-building species (Nomoto and others, 2010). Targeted removal efforts for brown trout on spawning areas may be more effective than reach-wide removals.

To what extent is there overlap in the Lees Ferry reach of rainbow and brown trout habitat?

Rainbow trout and brown trout often use the same or overlapping habitats, as characterized by food, space, and water temperature (Jowett, 1992). This sets the stage for interspecific competition for space and food (Hasegawa and others, 2014). Brown trout are capable of a variety of feeding strategies that enable the species to outcompete other species under altered or changing riverine conditions (Johnson and others, 2007; Young and others, 2010; Sánchez-Hernández and others, 2012; Sánchez-Hernández and Cobo, 2015). Studies show that brown trout are competitively superior to rainbow trout, and therefore, there is the potential for replacement of rainbow trout by brown trout through interspecific competition (Hasegawa, 2016). Removal efforts targeting brown trout may also affect rainbow trout if habitats overlap.

What is the rate of emigration of brown trout from the Lees Ferry reach and is it sufficient to negatively affect humpback chub?

Adult brown trout notably move long distances during the fall spawning period (Meyers and others, 1992; Burrell and others, 2000; Bettinger and Bettoli, 2004; Quinn and Kwak, 2011). This inherent migratory tendency may help to explain the increased numbers of brown trout in the Lees Ferry reach and should be investigated. Downstream dispersal of young brown trout is not well known, but young and adults might be expected to move downstream to habitat used by humpback chub, as rainbow trout have been observed to do, where they are known predators of this native species (Valdez and Ryel, 1995; Yard and others, 2011).

At what population size do brown trout in Lees Ferry noticeably affect the rainbow trout population?

As noted earlier, brown trout both prey on rainbow trout and compete with rainbow trout for habitat, so increases in brown trout are expected to cause reductions in rainbow trout, all other factors being equal. We recognize that complete elimination of brown trout from Lees Ferry—or the Grand Canyon region—is not likely, but the population size may be reduced to a point that limits the effects on rainbow trout. Population size and densities vary where brown trout and rainbow trout are sympatric, and are a function of habitat, space, food, flow, and temperature, as well as management actions. The specifics of how these two species will interact in the Lees Ferry reach is not known; knowledge of that interaction may be valuable for tuning future management.

How do flow manipulations change the invertebrate community in the Lees Ferry reach and do certain manipulation types create conditions that enhance brown trout feeding opportunities?

The macroinvertebrate community of the Lees Ferry reach is quite sensitive to flow manipulation (Cross and others, 2011; Kennedy, 2017). Because invertebrate prey of brown trout and rainbow trout can vary (Hasegawa and others, 2012; Hasegawa, 2016), brown trout could have a competitive advantage with a changing invertebrate community. The diet of brown trout in the Lees Ferry reach and the competitive interaction with rainbow trout are not currently well understood. Resolution of this uncertainty may be valuable in adaptation of future management actions.

What effect does a lower Lake Powell reservoir elevation and subsequent warmer dam releases have on brown trout?

Brown trout respond variously to flow and temperature, and understanding their response to flows downstream of Glen Canyon Dam is important for predicting population response. Optimum temperature for brown trout growth is 12.8–19.0°C (Nevada Division of Environmental Protection, 2016). Brown trout may respond positively to warming temperature regimes as a result of climate change (Al-Chokhachy and others, 2016) and to variable water temperature and discharge (Cattanéo and others, 2002). Water temperature patterns downstream of Glen Canyon Dam differ from natural riverine environments in that the warmest releases occur in September to December, a time of cooling in otherwise uncontrolled rivers. This period coincides with spawning by brown trout and the effect of this altered temperature regime on the species is not yet understood.

Is whirling disease affecting rainbow trout recruitment and ultimately providing an opportunity for brown trout expansion?

Whirling disease is present in the Lees Ferry reach of the Colorado River, but effects of the disease on individual fish have not been observed, which is why we did not explore this causal hypothesis in detail. Nevertheless, if whirling disease increases and affects rainbow trout as it has in other tail waters, insidious declines in the rainbow trout population could occur, and therefore, provide a competitive advantage to brown trout for space, food, and spawning sites.

Six monitoring activities that apply to brown trout were identified in the Triennial Work Plan (2015–2017), as outlined in table 6 (U.S. Department of the Interior, 2014), and are likely to be identified in the next Triennial Work Plan (2018-2020). This section of the report ("Monitoring and Research Considerations") has described the activities that are important for evaluating the status and response of the brown trout, as well as those activities that may require adjustment or refinement for improved evaluation. When possible, ongoing monitoring and research should be used or modified to reduce cost and additional or duplicated effort.

Table 6. Monitoring and research activities identified in the Triennial Work Plan (2015–2017) that apply to brown trout in the Lees Ferry reach of the Colorado River (U.S. Department of the Interior, 2014).

Understanding Factors Determining Recruitment, Population Size, Growth, and Movement of Rainbow Trout in Glen and Marble Canyons
Lees Ferry rainbow trout; monitoring, analysis, and study design
Detection of rainbow trout movement from upper Colorado River downstream of Glen Canyon Dam (Natal Origins study)
Contingency Planning for High Experimental Flows and Subsequent Rainbow Trout Population Management
Mainstem Colorado River Humpback Chub Aggregations and Fish Community Dynamics
Mainstem Colorado River Humpback Chub aggregation monitoring
System Wide Electrofishing
Rainbow Trout Early Life Stage Survey
Lees Ferry Creel Survey
Population Ecology of Humpback Chub in and around the Little Colorado River
Annual spring/fall humpback chub abundance estimates in the lower 13.6 kilometers of the Little Colorado River
Juvenile chub monitoring in the mainstem near the Little Colorado River confluence
Remote passive integrated transponder (PIT) tag array monitoring in the Little Colorado River
Humpback chub population modelling
Experimental Actions to Increase Abundance and Distribution of Native Fishes in Grand Canyon
Translocation and monitoring above Chute Falls
Invasive Species Surveillance and Response
Food Base Monitoring and Research
Insect emergence in Grand Canyon via citizen science
Characterize and monitor drift and insect emergence in Glen Canyon
Natal origins drift monitoring in Glen, Marble, and Grand Canyons
Monitoring dissolved oxygen in Glen, Marble, and Grand Canyons
Sandbars and Sediment Storage Dynamics
Monitoring sandbars using topographic surveys and remote cameras
Monitoring sand bars and shorelines above 8000 cubic feet per second by remote sensing
Sediment storage monitoring

Summary

In 2016, the Bureau of Reclamation and the National Park Service, with the cooperation of many other agencies and American Indian Tribes, completed a multi-year planning process for the long-term operation of Glen Canyon Dam and related management activities, resulting in the development and signing of the Long-term Experimental and Monitoring Plan (U.S. Department of Interior, 2016a, 2016b). Brown trout in the Lees Ferry reach were not a primary concern in that planning process, and evidence for the expansion of the brown trout population did not emerge until after that process was complete. The development of the LTEMP required the consideration of potential effects on many resources, and the design and selection of the preferred alternative sought to carefully balance the tradeoffs inherent in achieving all resource goals. Expansion of brown trout into the Lees Ferry reach of the Colorado River has the potential to upset that carefully crafted plan. The analysis in this report is meant to examine the severity of the potential problem and consider how interventions to manage brown trout might affect other resource goals, as preliminary scientific information that management agencies can use in developing a response.

Do we even have a problem? The growth of the brown trout population in the Lees Ferry reach is in an early stage and it is not yet clear how much it might grow (or decline) in the absence of any change in management. Prior to 2013, it appears that the brown trout population in Lees Ferry largely consisted of a small number of large adults, supported by a low level of immigration, without evidence of much, if any, sustained successful reproduction. Since 2013, there is evidence for at least one very large immigration event and an increase in reproductive success. The size-structure of the Lees Ferry reach population now appears to indicate that successful reproduction is occurring and those young may be recruiting to the spawning class. There is considerable uncertainty about whether the population will continue to grow. Sampling across uncertainty in the estimates of the full suite of demographic rates, there is about a 36-percent chance that the intrinsic growth rate is not high enough to sustain long-term growth, in which case, this population eruption might just die away, and the population will go back to variation around lower levels. On the other hand, there is a 64-percent chance the intrinsic growth rate is large enough to sustain long-term growth; under this circumstance we forecast the population growing to 3 times, or possibly even 10 times, the current size. The uncertainty in this forecast could be reduced with continued monitoring data and focused mark-recapture studies to better understand brown trout dynamics in the Lees Ferry reach. If the brown trout population in the Lees Ferry reach does become established and sustained at much higher levels, there is good reason to believe that downstream migrants could increase the threat to humpback chub near the confluence with the LCR. Growth of the brown trout population does not, however, appear to pose much of a direct threat to the rainbow trout fishery given our estimates of the per capita effect C, although the effects of uncertainty in C warrant further investigation.

Why do we have a problem? Although there is empirical evidence that there has been both an increase in immigration and an increase in reproductive rates of brown trout in the Lees Ferry reach, the causal mechanisms for this change are not clear. It is possible that fall HFEs have played a complicated role in encouraging immigration of large brown trout from downstream reaches, but it is also possible that this immigration arose from a unique set of circumstances unrelated to fall HFEs. Regarding reproduction, there are a number of potential causal variables that have changed over the same period of time as the reproductive rates have increased (water temperature, rainbow trout density, frequency of fall HFEs, and brown trout density), but there is no strong correlational signal in the data. Thus, there is considerable uncertainty about what has caused the increase in brown trout, and this uncertainty affects our ability to estimate the effectiveness of a number of strategies for intervention. Continued and enhanced monitoring may help to reduce this uncertainty to some degree, but it might also be necessary to de-couple some of the correlated variables in order to make a causal inference about the drivers behind the brown trout dynamics.

What can we do about brown trout in the Lees Ferry reach of the Colorado River? A large number of possible interventions have been proposed in a variety of forums to address concerns posed by brown trout. We focused on a small number of thematic strategies designed to reduce brown trout abundance in the Lees Ferry reach that could be implemented in the near future without major technological development. Removal strategies (such as a concerted mechanical removal effort, or a project to incentivize take of brown trout by anglers) would work by targeting adult fish, both to reduce the number of fish and to reduce the reproductive rate by removing spawners; we think these strategies could serve to reduce the brown trout abundance by about 50 percent compared to the status quo, regardless of the causal mechanism for the expansion. Strategies designed around the frequency of HFEs would only work to reduce brown trout abundance if, in fact, fall HFEs are a causal driver of increases in immigration or reproduction; otherwise, they would have little to no effect. Finally, strategies that include trout-management flows designed specifically to strand young brown trout could work to some degree but are not expected to be particularly effective, because they target a life-history stage to which the population growth rate is not very sensitive. Thus, considering only the effect on brown trout (and not other objectives), a removal strategy is likely to be fairly effective regardless of the causal mechanism for the expansion, but a flow strategy would be more effective if fall HFEs are indeed the cause of the expansion.

What are the consequences of intervention? Management of brown trout is likely to be complicated by the effects of any intervention on other objectives of concern. The results of the forecast modeling indicate that decision makers will face significant tradeoffs in costs and benefits of alternative strategies among the key resources of concern. The strategies that decrease the frequency of HFEs (Alternatives 3 and 4) would increase the value of hydropower generation and increase the abundance of rainbow trout, but would decrease the ability to transport sediment (for a variety of purposes, including beach building). The removal strategies and TMF strategy all maintain sediment transport and hydropower generation at the same level as the status quo, but cost roughly $7 million over 20 years to implement. Further, the mechanical removal strategy (Alternative 6) and possibly others represent an affront to tribal values concerning the taking of life. The viability of humpback chub largely correlates with the ability to reduce brown trout, but is not strongly affected by any of the strategies, with the expected minimum number of adult chub over 20 years varying between 4100 and 4800 across strategies and hypotheses. Thus, there are tradeoffs across objectives that may be relevant to management decision making, and the difficulty in making these tradeoffs is exacerbated by uncertainty about the causal mechanism.

We are confident that more effective strategies could be created by combining elements of the strategies we investigated, by developing condition-dependent triggers for those elements, and by including an adaptive design. Ongoing monitoring and research is likely to help resolve some questions about the nature of the brown trout expansion, but causal inference might require experimental intervention.

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