Brown Trout below Glen Canyon Dam: A Preliminary Analysis of Risks and Options

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TABLE OF CONTENTS

INTRODUCTION

A February 2017 recommendation from the Glen Canyon Dam Adaptive Management Program (GCDAMP), Adaptive Management Work Group (AMWG), and a subsequent June 2017 letter from the Secretary of the Interior's Designee to the GCDAMP call on the National Park Service (NPS), the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center (GCMRC), Arizona Game and Fish Department (AZGFD), Bureau of Reclamation (Reclamation), U.S. Fish and Wildlife Service (USFWS), and Western Area Power Administration (WAPA) to plan and hold a workshop for "scientists, managers, tribes and interested stakeholders" before moving forward with any actions related to management of brown trout in the Lees Ferry reach of the Colorado River. The workshop is scheduled to be held in September 2017, in conjunction with an AMWG meeting.

The workshop is intended to address:

(1) The root causes of the increases in brown trout;
(2) The risks associated with an expanding brown trout population to a quality rainbow trout fishery in Lees Ferry and the recovery and conservation of humpback chub and other native fish down river;
(3) The pros and cons of different experimental and management options to address those risks, including but not limited to, mechanical removal, trout management flows, and the current High Flow Experiment protocol;
(4) The research needs to support more informed decisions moving forward; and
(5) The expressed tribal concerns regarding the taking of life, and how those are addressed in any management options under consideration.

The purpose of this whitepaper is to provide background information about brown trout in the Colorado River below Glen Canyon Dam, as a foundation for the discussions at the workshop. It represents the consensus of the authors for each section concerning the state of knowledge, which the authors volunteered to prepare to help advance discussions at the workshop. The results do not represent the official position of any institution or governmental agency, nor of the workshop planning team. This product is a cooperator report to Reclamation and has been peer reviewed and approved for publication consistent with USGS Fundamental Science Practices (http://pubs.usgs.gov/circ/1367/).

The whitepaper has six sections, followed by a comprehensive list of literature cited. The six sections are as follows:

(1) **Context**: Provides background on why the workshop is being held and why the whitepaper has been drafted.

(2) **Scientific Background**: Summarizes relevant scientific background information on brown trout below Glen Canyon Dam, including information on: historical brown trout stocking; known distribution, abundances, and movement (need to pull together multi-agency capture data); current brown trout management activities; and data for recent brown trout expansion in Lees Ferry.

(3) **Management Objectives**: Describes the long-term outcomes important to the management agencies and stakeholders that may be affected by brown trout and their management.

(4) **Root Causes for the Increase in Brown Trout**: Reviews the literature on brown trout invasions, life history, environmental and other parameters documented to limit populations or favor increases; articulates a small number of alternative hypotheses for the increase in brown trout; and evaluates the hypotheses against available data and information.

(5) **Risks to Humpback Chub and Rainbow Trout**: Evaluates the risks of brown trout expansion to humpback chub and to the rainbow trout fishery by articulating and evaluating alternative hypotheses about the mechanisms by which brown trout and their management might affect humpback chub.

(6) **Comparison of Management Options**: Examines a small number of categories of management options, grouping the sorts of actions that have been discussed, and focusing on the brown trout life-history parameters they are intended to affect; estimates a plausible range of effect size for each management option; evaluates the potential outcomes of each management option with regard to the management objectives; and identifies key uncertainties that may affect decision-making.

I. Context

Prepared by Michael C. Runge, USGS, lead; Rob Billerbeck, NPS; Melissa Trammell, NPS; Robert Schelly, NPS; ; Katrina Grantz, Reclamation; Marianne Crawford, Reclamation; Craig Ellsworth, WAPA; Jessica Gwinn, FWS; and Chris Cantrell, AZGFD.

Brown trout (*Salmo trutta*) is one of several non-native, cold-water fish species found in the Colorado River below Glen Canyon Dam. Recent apparent increases in abundance of brown trout have raised concerns about their potential effects on the endangered humpback chub (*Gila cypha*) and the Lees Ferry rainbow trout (*Oncorhynchus mykiss*) fishery. Management of these fish species is part of the larger enterprise of environmental management below Glen Canyon Dam, authority for which is shared among a number of federal, state, and tribal agencies, including the National Park Service (NPS), the Bureau of Reclamation (Reclamation), the U.S. Fish and Wildlife Service (USFWS), the Arizona Game and Fish Department (AZGFD), and several American Indian Tribes.

Brown trout have been collected in low numbers for several decades in the Lees Ferry reach of the Colorado River, but over the period 2014-2016, as part of their fish monitoring program, the AZGFD noticed an increase in an index of abundance of brown trout (Figure 1), concurrent with observations of increased spawning behavior (Korman and others, 2015).

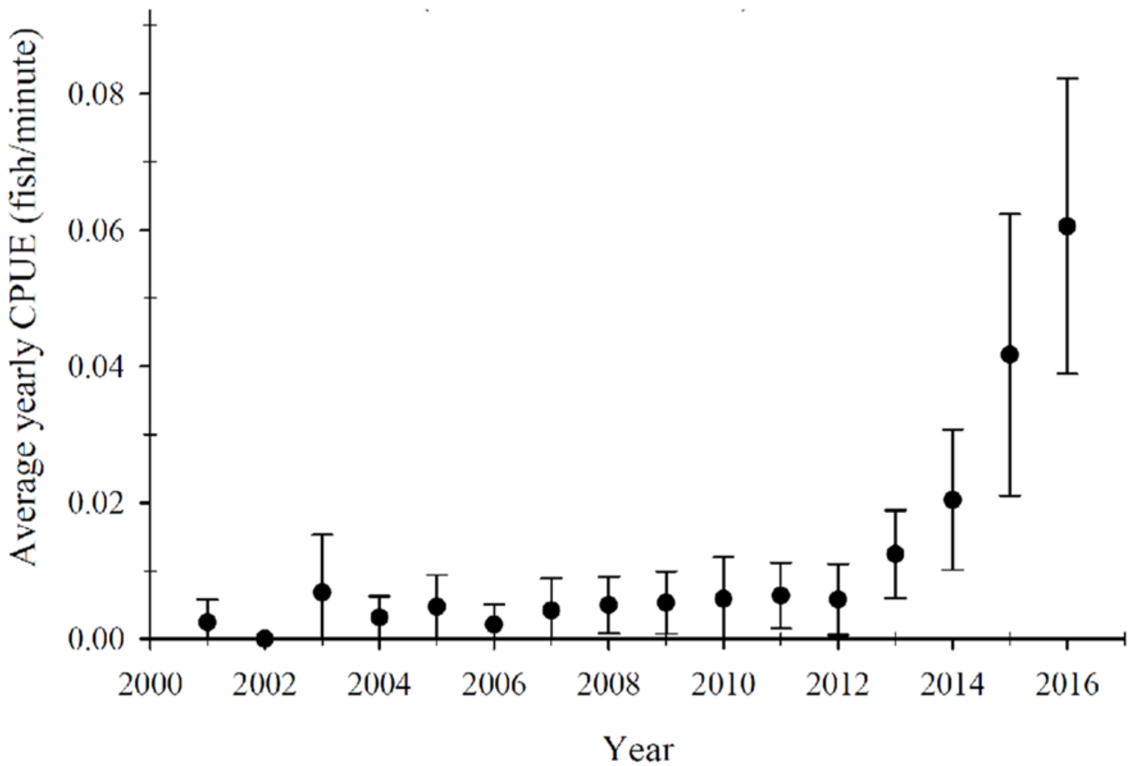

Figure 1. Brown trout average yearly electrofishing catch per unit effort (CPUE; fish/minute) in the Lees Ferry reach, 2001-2016.. The closed circles show the mean value; the whiskers show the 95-percent confidence intervals. Figure from Rogowski (2017).

Brown trout are known to prey on juvenile humpback chub, so their presence has been a management concern for several decades. Studies have indicated that brown trout have a much higher rate of piscivory than rainbow trout on native fish including humpback chub (Yard and others, 2011, Ward and Morton-Starner, 2015). Brown trout also prey on and compete with rainbow trout, so their presence in Lees Ferry raises concerns about the rainbow trout fishery.

Charge from the Secretary's Designee for a Brown Trout Workshop

In February 2017, the Adaptive Management Working Group (AMWG), a group convened under the Federal Advisory Committee Act to advise the Secretary of Interior on aspects related to the operations of Glen Canyon Dam, passed a motion to recommend that the Secretary direct NPS and the US Geological Survey's Grand Canyon Monitoring and Research Center (GCMRC) and request AZGFD to convene a workshop to evaluate the causes of the brown trout increase, the possible risks to the rainbow trout fishery and recovery of humpback chub, and the pros and cons of different management options. In June 2017, the acting Secretary's designee to AMWG asked NPS, GCMRC, AZGFD, Reclamation, USFWS, and the Western Area Power Administration (WAPA) to begin planning for such a workshop.

Federal Guidance and Compliance

Many of the management activities associated with Glen Canyon Dam are described in the 2016 Long-term Experimental and Management Plan (LTEMP) (U.S. Department of Interior, 2016a). Three types of management action that are possibly relevant to 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 by-pass tubes of the dam. These HFEs may last from 1 to 250 hours, depending on the conditions and the type of HFE. The HFEs are used to redistribute accumulated sediment at higher elevations onto beaches located along the river corridor. The LTEMP specifies the conditions under which fall and spring HFEs are triggered, with spring HFEs prohibited until 2020. Trout-management flows are dam operations designed to reduce rainbow trout recruitment, by desiccating redds (spawning nests) or stranding juvenile trout; the TMFs authorized in the LTEMP are focused on periods when rainbow trout young-of-the-year are thought to be most vulnerable (May-August), which may not be the same period when brown trout young are most vulnerable. Mechanical removal consists of using a variety of methods to reduce trout densities (rainbow or brown) to a level that is consistent with management goals designed to allow for the recovery of humpback chub.

The evaluation of management options related to brown trout takes place against the backdrop of many existing management activities and plans, as well as the National Environmental Policy Act (NEPA) and Endangered Species Act (ESA) Section 7 compliance that accompanies them. Recent NEPA and ESA processes provide existing compliance and guidance on non-native fish management actions below Glen Canyon Dam, including: the 2016 LTEMP (U.S. Department of Interior, 2016a), the corresponding Record of Decision (ROD) (U.S. Department of Interior, 2016b), and the USFWS Biological Opinion (BO) (U.S. Fish and Wildlife Service, 2008); and NPS's 2013 Comprehensive Fish Management Plan (National Park Service, 2013a). The LTEMP ROD provided a set of goals and objectives for the future guidance of the Glen Canyon

Dam Adaptive Management Program (GCDAMP) and those objective statements are the guide for how management options will be evaluated in this whitepaper. As stated in the LTEMP ROD, “The goals and objectives in Section l.4 of the LTEMP FEIS will be carried forward as the goals in the GCDAMP guiding documents.” See the “Management Objectives” section below for the goals most relevant to this brown trout issue.

Purposes

The February 2017 recommendation from the AMWG and the June 2017 letter from the Secretary’s designee call on NPS, GCMRC, AZGFD, Reclamation, USFWS, and WAPA to plan and hold a workshop for “scientists, managers, tribes and interested stakeholders” before moving forward with any actions related to management of brown trout in the Lees Ferry reach of the Colorado River. The workshop is scheduled to be held in September 2017, in conjunction with an AMWG meeting. The workshop is intended to address:

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The purpose of this whitepaper is to provide background information about brown trout in the Colorado River below Glen Canyon Dam, as a foundation for the discussions at the workshop.

II. Scientific Background

Prepared by Rich Valdez, SWCA; Bob Schelly, NPS; Dave Rogowski, AGFD; and Scott VanderKooi, USGS.

Introduction

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 is Europe, North Africa, and Western Asia. 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 the Grand Canyon in Arizona.

The Colorado River through Grand Canyon was historically warm, turbid, and unsuited 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 River and the Escalante River, but there were no trout native to tributaries of the Grand Canyon (Behnke, 2002). The Apache trout's (*O. apache*) historical distribution includes the headwaters of the Little Colorado River in the White Mountains and along with the Gila trout (*O. gilae*) were native to the tributaries of the Gila River of the lower Colorado River basin, downstream of the Grand Canyon region.

Historical Brown Trout Stocking

After Grand Canyon was established as a National Park in 1919, the National Park Service began stocking fish into tributaries to provide recreational fishing opportunities for park visitors. Several trout species were introduced, including rainbow trout (*O. mykiss*) into Bright Angel Creek (1923, 1924, 1932-42, 1947, 1950, and 1958), 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 as eyed eggs into Shinumo Creek (1926 and 1930), Garden Creek (1930), and Bright Angel Creek (1930 and 1934) (Brooks, 1931; Stricklin,1950; Carothers and Minckley, 1981). The last stocking of brown trout in Grand Canyon was in Bright Angel Creek in December of 1934. The brook trout evidently did not persist, but rainbow trout and brown trout successfully reproduced and remained confined to the tributaries until the Glen Canyon Dam was built.

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 tailwater. The Arizona Game and Fish Department (AGFD) in cooperation with the National Park Service began to stock cold-water species in the 15-mile reach below the dam known as 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 Marble or Grand Canyon.

Annual stocking of rainbow trout in the Lees Ferry reach continued and the fish survived successfully, but high fluctuating dam releases precluded most natural reproduction. With a change in dam operation from high fluctuating flows to the 1991 interim flows and ultimately the modified low fluctuating flows in 1995 (U.S. Department of the Interior, 1996), rainbow trout began to reproduce and recruit naturally, and stocking the species in the Lees Ferry reach ceased in 1998 (Makinster and others, 2011). Since that time, the Lees Ferry rainbow trout fishery has been maintained through natural reproduction. Except for localized spawning in some downstream tributaries (e.g., Nankoweap, Clear, Bright Angel, Shinumo, Tapeats, Deer, and Havasu Creeks), most rainbow trout reproduction in the Colorado River downstream of Glen Canyon Dam occurs within the Lees Ferry reach.

Reproduction by brown trout occurs primarily in Bright Angel Creek, although young and gravid adults in the mainstem indicate limited but successful mainstem spawning in the 1990s (Valdez and Ryel, 1995). Electrofishing surveys of Shinumo, Deer, Tapeats, Kanab, and Havasu Creeks in February–March of 2004 and 2005 yielded totals of 2, 0, 3, 1, and 0 brown trout, respectively (Leibfried and others, 2006). Notably, one male brown trout in Tapeats Creek was expressing milt and in spawning condition. Removal of nonnative fish by the National Park Service from Shinumo Creek (upstream of the barrier falls) in 2009 and Havasu Creek in 2011, in advance of humpback chub (*Gila cypha*) translocations, yielded no brown trout from either tributary (Healy and others, 2011; Omana Smith and others, 2011).

History of Known Brown Trout Distribution, Abundances, and Movement

The distribution and abundance of brown trout in the Colorado River through 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 0[1]) to Diamond Creek (river mile 226) in 1968 (Miller and Smith, 1972) and in 1970–1976 (Suttkus and others, 1976) reported no brown trout from either the mainstem or tributaries. During 1977–1979, Carothers and Minckley (1981) reported low catch rates of brown trout in the mainstem from the Little Colorado River (river mile 61) to downstream of Shinumo Creek (river mile 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 Little Colorado River, highest catch rates of adults and subadults from the Little Colorado River to Bright Angel Creek (river mile 88), and moderate catch rates of adults and subadults from Bright Angel Creek to National Canyon (river mile 167). An AZGFD report of Lees Ferry fish surveys from 1984-1988 indicated less than 1% of the electrofishing catch were brown trout in 1986 (Reger and others, 1989). Studies during 1990–1993 showed catches of brown trout primarily downstream of the Little Colorado River, with highest catch rates in and near the confluence of Bright Angel Creek, Shinumo Creek, and Tapeats Creek (river mile 134) (Figure 2; Valdez and Ryel, 1995). Surveys from Diamond Creek to Pearce

[1] The use of river miles 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 measured upstream, with negative values (–) and downstream, with positive values (+).

Ferry (river mile 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 stored sediments.

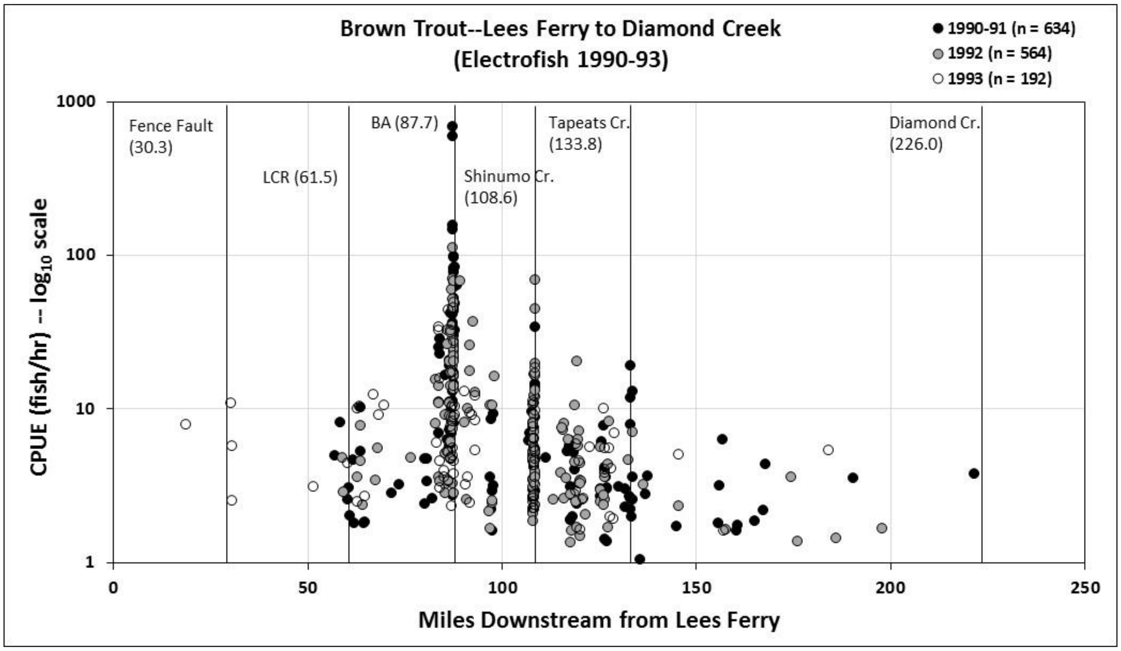

Figure 2. Catch per unit effort (CPUE) of brown trout as number of fish per hour of electrofishing in the mainstem Colorado River from Lees Ferry (river mile 0) to Diamond Creek (river mile 226). Key sites and tributaries, and their locations in river miles downstream from Lees Ferry, identified include Fence Fault (river mile 30.3), the Little Colorado River (LCR; river mile 61.5), Bright Angel Creek (river mile 87.7), Shinumo Creek (river mile 108.6), and Tapeats Creek (river mile 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 the year 2000. Evidently, brown trout were not in detectable numbers in the mainstem prior to about 1976, but were detected afterward, primarily near the mouths of Bright Angel Creek and Shinumo Creek. 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 Lees Ferry. During the 1990s, brown trout began to be captured near the 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 in 2009.

Electrofishing surveys by the AGFD from Lees Ferry to Pearce Ferry starting in 2000 (Makinster and others, 2010; Rogowski and others, 2017) show that mean catch per unit effort (CPUE) of brown trout by reach declined from 2000 to 2006, and subsequently increased to different levels in various reaches (Figure 3). Whereas only one brown trout was captured downstream of river mile 220 during 1990-93, brown trout were caught in this most downstream 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 due to 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.

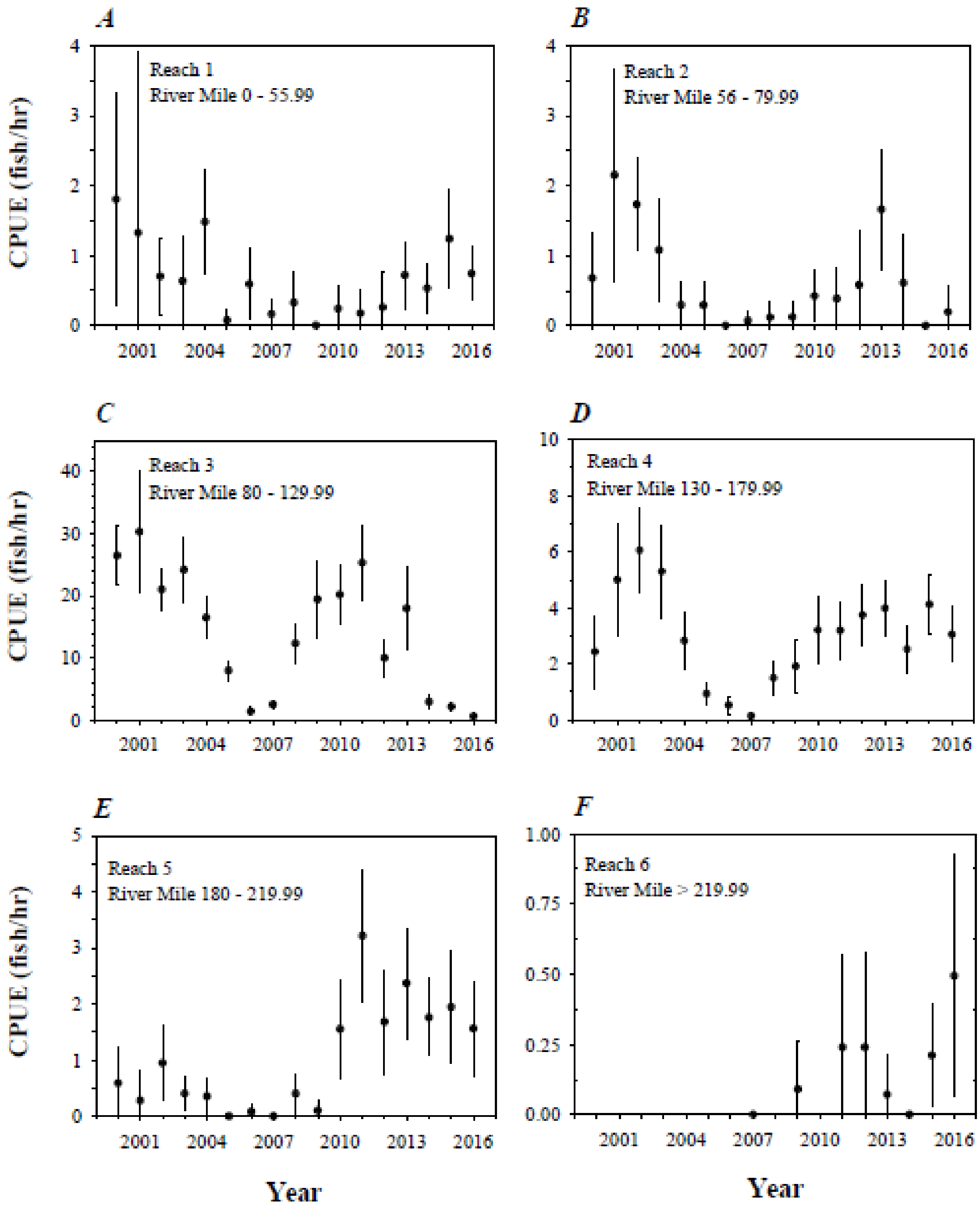

Figure 3. Mean catch per unit effort (CPUE; fish/hour) of brown trout captured during electrofishing surveys on the Colorado River between Lees Ferry and Pearce Ferry for reaches 1-6 (plots A-F), 2000-2016. Reach locations are provided in river miles downstream of Lees Ferry (river mile 0). Error bars represent 95% 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. Figure from Rogowski and others (2017).

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 density appears to be increasing exponentially from <0.01 to 0.06 fish/minute (Figure 1). Brown trout were observed spawning near the 4-mile bar in Glen Canyon (approximately 4 river miles upstream of Lees Ferry) during the fall of 2014. Spawning was also observed during October and November of 2015 near the 4-mile bar in Glen Canyon (Korman and others, 2015).

Length-frequency distributions of brown trout captured in the Lees Ferry reach from 1996 to 2016 show low numbers of fish of various sizes from 1996 through 2012 (Figure 4). Some increases in numbers are seen in 2013 and 2014 with most fish being 200 mm or larger. The lack of smaller fish in previous years suggests these fish either evaded detection while rearing or moved into the Lees Ferry reach from elsewhere. In 2015 and 2016, distinct length modes began to appear for fish < 100 mm, indicating substantial and detectable local reproduction, but with an apparent lack of subsequent age modes and the continued presence of smaller numbers of larger adults. It is unclear whether the fish are not surviving past the first year, or if the number of age-1 fish is too low for detection.

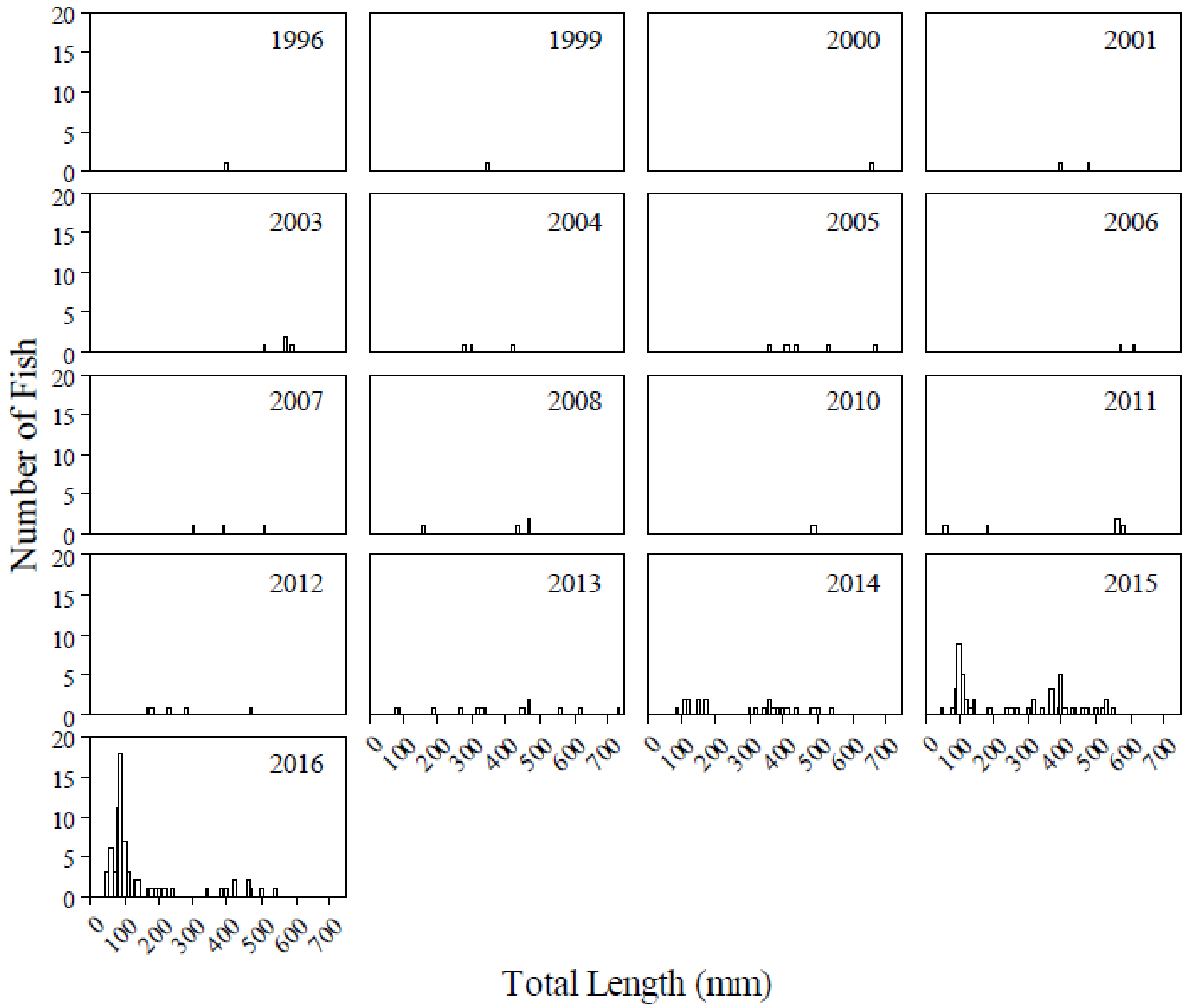

Figure 4. Length frequency distributions of brown trout captured in the Lees Ferry reach, 1996–2016. Figure from Rogowski (2017).

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 in a weir operated by the National Park Service, or by electrofishing, that were originally tagged in other parts of the Colorado River, as far as 85 miles from Bright Angel Creek (Leibfried and others, 2005; Reclamation, 2011; Healy and others, *draft* 2017; Sponholtz and others, 2010). Small numbers of brown trout are also found in other locations within the Grand Canyon, including the vicinity of the Little Colorado River confluence and in Glen Canyon. An indication of the relative abundance of brown and rainbow trout in the vicinity of the Little Colorado River is provided by the numbers captured using electrofishing during trout removal efforts. Of 23,000 nonnative fish captured as part of removal efforts from 2003 to 2006, 19,020 were rainbow trout and 479 were brown trout (Coggins, 2008). All brown trout captured during these efforts were removed from the river.

Brown Trout Management Activities

The brown trout is a known predator of fish in many river systems (Young and others, 2010; Budy and others, 2013). In the Grand Canyon, 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 confirmed these findings and indicate that brown trout remained effective predators of juvenile humpback chub at temperatures as high as 20°C (Ward and Morton-Starner, 2015) and were less affected than rainbow trout in their ability to capture juvenile humpback chub as turbidity levels increased (Ward and others, 2016). Increased numbers of brown trout in the Grand Canyon could pose a substantial threat to native fishes, including the humpback chub.

Two major projects have removed large numbers of brown trout from the Grand Canyon in an attempt to evaluate the efficacy of a large scale non-native fish removal effort to benefit native fishes: (1) mainstem electrofishing in the vicinity of the Little Colorado River from 2003 to 2006, and 2009, and (2) installation and operation of a fish weir to trap fish moving into and from Bright Angel Creek during the winters of 2002-2003, 2006-2007, and every winter from 2010-2017 through the present (see Figure 5). The work in Bright Angel Creek has been complemented by backpack electrofishing removals of nonnative fish from the creek starting in 2010-2011.

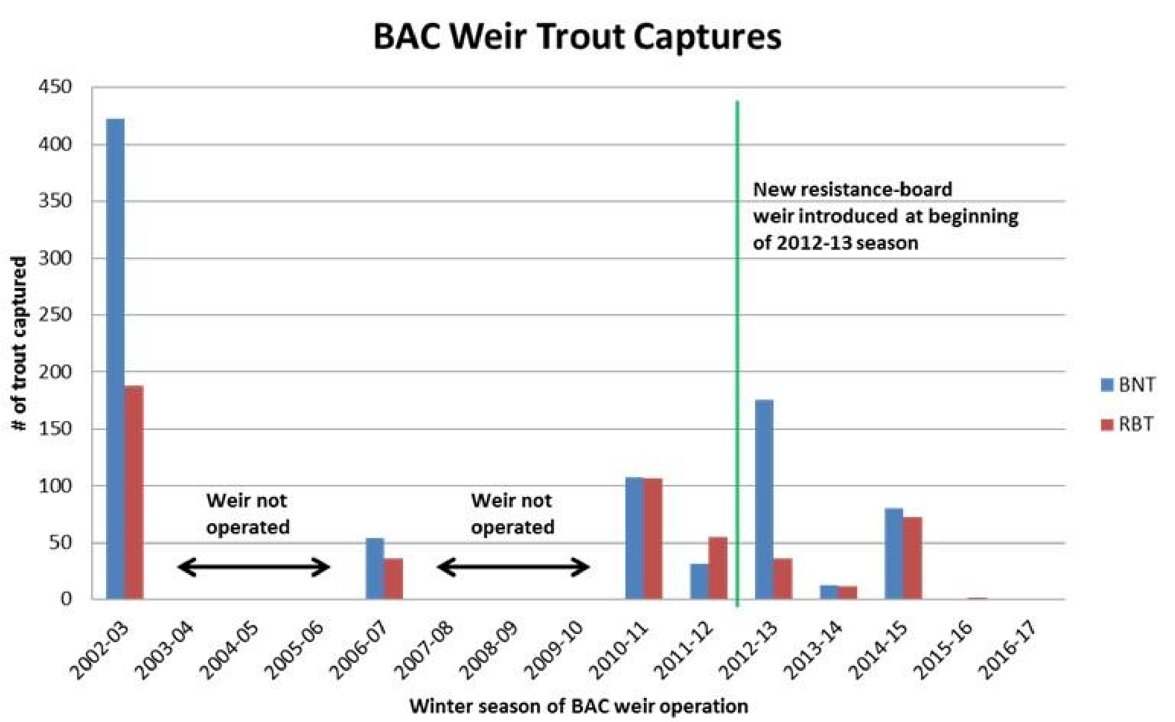

Figure 5. Numbers of brown trout (BNT) and rainbow trout (RBT) captured in a fish weir located near the mouth of Bright Angel Creek. Figure from R. Schelly, National Park Service (unpublished data).

During 2003-2006, over 23,000 nonnative fish, including rainbow trout (19,020; 82%) and brown trout (479; 1%), were removed from a 9.4-mile reach of the Colorado River near the Little Colorado River (Coggins and others, 2011). Concurrent with the mechanical removal, data collected within a control reach of river suggested a systemic decline in rainbow trout unrelated to the fish removal effort. Over this time period of a system-wide decline in rainbow trout and intensive rainbow trout removal at the LCR reach, a rapid shift in fish community composition at the LCR reach was observed from one dominated by cold water salmonids (>90%), to one dominated by native fishes and the nonnative fathead minnow (*Pimephales promelas*) (>90%). Thus, understanding the efficacy of the mechanical removal was confounded by an external systemic decline, particularly in 2005-2006 (Coggins and others, 2011). Another removal effort happened in 2009, with around 2,500 non-native fishes removed from the LCR reach (Makinster and Avery, 2010). Subsequent sampling in the LCR reach shows that the number of rainbow trout and brown trout was higher after 2008 (Figure 3; Makinster and others, 2010), but the total number caught declined for rainbow trout (RBT) and brown trout (BRT) after 2013; i.e., 2012 (484 RBT, 6 BRT), 2013 (926, 43), 2014 (1,186, 23), 2015 (155, 8), 2016 (36, 3), and 2017 (0, 0) (unpublished data from M. Yard, USGS, GCMRC).

The second effort to control nonnative fish, specifically brown trout, was implemented in 2006 in Bright Angel Creek. As recently as the 1970s, brown trout were rare in Bright Angel Creek (Minckley, 1978), despite this tributary having been stocked 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 was observed (Otis, 1994). Bright Angel Creek is now a principal spawning site for brown trout, and a large aggregation is found in the Colorado River near the confluence with Bright Angel Creek (Figure 2; Valdez and Ryel, 1995; Speas, 2002; 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 was implemented. In 2002–2003, a temporary weir was installed 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; Figure 5). In 2006, the Bright Angel Creek Trout Reduction Project Environmental Assessment (EA) and Finding of No Significant Impact (FONSI; NPS, 2006) identified goals and a strategy for reducing brown trout. This project was initiated in cooperation with the U.S. Fish and Wildlife Service (USFWS) in 2006-2007 (National Park Service, 2006; Sponholtz and VanHaverbeke, 2010) following the feasibility study. This effort was resumed in 2010 (Omana Smith and others, 2012) following the 2008 and 2011 Biological Opinions on the Operation of Glen Canyon Dam that identified conservation measures to conduct trout reduction in Bright Angel Creek and to establish population redundancy of humpback chub in Grand Canyon tributaries (U.S. Fish and Wildlife Service, 2008 and 2011).

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

The operation of the weir was also extended from October through February to capture greater temporal variability in the trout spawn (Omana Smith and others, 2012; National Park Service, 2013b). Removal efforts also occurred in the mainstem Colorado River in the Bright Angel Creek inflow reach in 2014 to 2016 (GCMRC, unpublished data). This brown trout removal effort 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 considerably (Table 1) despite similar effort levels 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 (Figure 6).

Table 1. Number of brown trout removed from Bright Angel Creek tributaries and creek segments (reaches) during five seasons (October through February) of backpack electrofishing. Table from R. Schelly, National Park Service (unpublished data).

	2012-13	2013-14	2014-15	2015-16	2016-17
Roaring Springs		85	56	14	
Angel Springs	221	217	156	176	23
Transept Creek		318	128	53	17
Wall Creek		50	16	5	2
Phantom Creek		33		16	
BAC Reach 5: RS/AS confluence to Transept	2906	2323	1495	1528	1103
BAC Reach 4: Transept to Ribbon	2773	3596	2453	1626	1249
BAC Reach 3: Ribbon to beaver ponds	4218	2531	2132	1384	1688
BAC Reach 2: beaver ponds to Phantom Creek	2138	2412	1145	700	717
BAC Reach 1: Phantom Creek to Weir	211	644	163	53	88
BAC Reach -1: Weir to Colorado River		74	65	3	15
Ribbon Falls		129	38		
TOTAL	**12467**	**12412**	**7847**	**5558**	**4902**

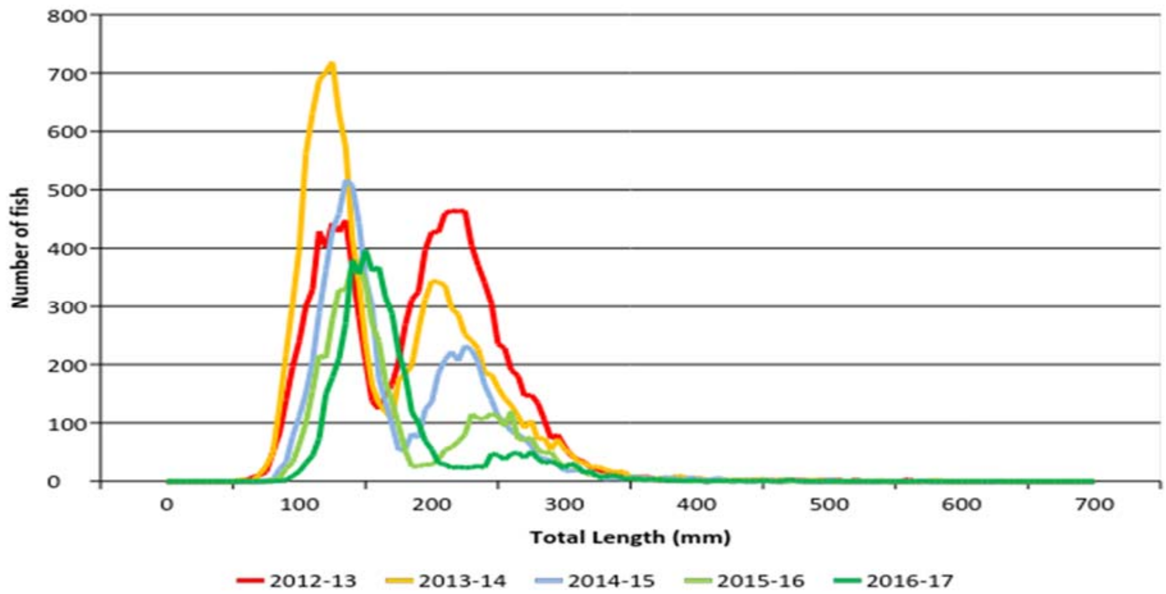

Figure 6. Length-frequencies of brown trout removed from Bright Angel Creek during five seasons (October through February) of backpack electrofishing. Figure from R. Schelly, National Park Service (unpublished data).

Current Brown Trout Research and Monitoring

In addition to the work by the National Park Service mentioned above, most brown trout research and monitoring in Glen and Grand Canyons is being conducted as part of other ongoing studies conducted by the USGS Grand Canyon Monitoring and Research Center (GCMRC) and its cooperators with support from the Glen Canyon Dam Adaptive Management Program. These studies include long-term monitoring of the Lees Ferry trout fishery and the fish community in Grand Canyon by the Arizona Game and Fish Department as well as research by GCMRC directed at understanding the population dynamics and movement of rainbow trout in the Lees Ferry reach. Per guidance in the CFMP, the National Park Service has directed GCMRC and the Arizona Game and Fish Department to sacrifice any brown trout captured during research and monitoring trips. Sacrificed fish are measured and scanned for passive integrated transponder tags since prior to 2017, brown trout captured during ongoing mark-recapture studies of rainbow trout were marked and released.

In addition to studies mentioned above, the National Park Service, in collaboration with BioWest, Inc. and GCMRC, 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 any 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.

III. Management Objectives

Prepared by Michael C. Runge, USGS, lead; Rob Billerbeck, NPS; Melissa Trammell, NPS; Robert Schelly, NPS; ; Katrina Grantz, Reclamation; Marianne Crawford, Reclamation; Craig Ellsworth, WAPA; Jessica Gwinn, FWS; and Chris Cantrell, AZGFD.

Management of brown trout below 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 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 EIS, 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. There are difficult trade-offs to consider in choosing management actions. The values-based challenge for the decision makers is how to weigh those trade-offs, 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 the taking of life, the condition of the rainbow trout fishery, and potential interactions with high flow experiments. These four objectives, which are not necessarily exhaustive, are discussed in more depth below. Any evaluation of management actions related to brown trout will need to consider the effects on these, and possibly other, objectives.

Compliance with the ESA

One of the threats to the endangered humpback chub is competition with and predation by non-native fishes, including brown trout. The LTEMP EIS 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 EIS evaluated the expected minimum number of adult humpback chub in the Little Colorado River population during the 20 years of the LTEMP implementation period. The tier 1 and tier 2 trigger statements from Appendix D of the LTEMP Biological Assessment provide specific quantitative metrics for determining when conservation actions are needed and may also provide useful metrics for evaluation of this management objective. These triggers include metrics for adult humpback chub in the Little Colorado River aggregation, sub-adult humpback chub abundance, and the predator index in the juvenile chub monitoring (JCM) reach (see Appendix D of Appendix O of the LTEMP FEIS; U.S. Department of Interior, 2016a).

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 mechanical removal of nonnative fish species. For example, the Zuni have familial and spiritual relationships to all aquatic life, including native and nonnative fish and macroinvertebrates, and have raised concerns that the taking of life through mechanical removal was contrary to their cultural values and could have adverse effects on their people. In the LTEMP EIS, 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.

Condition of the Rainbow Trout Fishery

The blue-ribbon rainbow trout fishery in the Glen Canyon reach of the Colorado River is an important recreational resource that generates an estimated $2.7 million annually in economic income in the area surrounding Lees Ferry (Bair and others, 2016). Any efforts to control brown trout, whether through flow manipulations or mechanical removal, might also affect rainbow trout. The LTEMP EIS 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 Glen Canyon reach. In 2015, AZGFD finalized a fisheries management plan for Lees Ferry (Rogers, 2015). The objectives in the fisheries management plan were similar to those in the LTEMP EIS: (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." Performance metrics and management thresholds were provided for each objective in the fishery management plan; these metrics may also be useful to evaluate the condition of the rainbow trout fishery in the context of brown trout management.

Potential Interactions with High-Flow Experiments

The HFEs are intended to mimic aspects of natural high flows and deposit fine sediment at higher elevations, for its inherent value, for its value to riparian vegetation, for its use at camping sites, and for its role in protecting historical sites. In the LTEMP EIS (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 was a Sand Load Index (the cumulative sand load transported by high flows [greater than 31,500 ft^3/sec] divided by the cumulative sand load transported in total). If any of the options considered for management of brown trout alter flow actions (including HFEs) from the specifications of the LTEMP ROD (U.S. Department of Interior, 2016b), the effect on sediment delivery will need to be weighed against the benefits to humpback chub and the rainbow trout fishery.

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 changes in hydropower production, effects on other native fish, and effects on recreation (especially, boating and rafting). Also some agency-specific considerations that may not be goals of the AMP, but are important considerations for the individual agencies, such as NPS policies regarding nonnative species or AZGFD goals in their 2015 Lees Ferry Management Plan (Rogers, 2015), may need to be evaluated.

Ease of Implementation

Some of the actions that might be considered to address brown trout and their interactions with the ecosystem can be readily implemented, because they have already been examined in previous planning processes (e.g., LTEMP, NPS Comprehensive Fisheries Management Plan) and comply with NEPA and Section 7 of the ESA. Other actions would take longer to implement, because a planning process would have to be undertaken for review. The ease of implementation is an objective that will be considered along with the other objectives.

The intent of the upcoming workshop is not to re-initiate the in-depth analyses across nearly two dozen resource goals that were undertaken in the LTEMP EIS, but any modifications to existing actions have the potential to change the carefully considered strategies in the LTEMP. The objectives described above are the ones that seem most likely to be affected by potential brown trout management actions, and will be the focus of assessment. Some of the objectives may warrant detailed quantitative evaluation, others may not; the detail with which these management objectives need to be evaluated will be a topic of discussion at the workshop.

IV. Root Causes for the Increase of Brown Trout in the Lees Ferry Reach

Scientists that participated in discussions, expert elicitation, and the writing of this white paper are (alphabetical order): Theodore Kennedy (USGS), Jeff Kershner (USGS-retired), Barry Nehring (Colorado Division of Wildlife-retired), David Rogowski (AGFD), Robert Schelly (NPS), Melissa Trammell (NPS), Rich Valdez (SWCA), David Ward (USGS), Charles Yackulic (USGS), and Mike Yard (USGS).

Background

There have been four consecutive year increases in brown trout catch rates in Lees Ferry from 2012-2016 (Figure 1). From 2001-2012 brown trout catch rates were low and averaged around 0.26 fish/hr. In 2012, brown trout catch rates were around 0.35 fish/hr but by 2016 brown trout catch rates were around 3.6 fish/hr, a 1000% increase in the mean catch rate since 2012 (Rogowski and others, 2017). Catch rates are a proxy for population abundance, so an increase in catch rates of this magnitude reflects substantial increases in the populations (# of fish/km of river) of brown trout in Lees Ferry. Length-frequency histograms, which represent the number of fish in each size class (i.e., juvenile, sub-adult, adult), demonstrate that increases in brown trout populations in 2013-2014 arose from fish from across the entire adult size spectrum, whereas population increases in 2015 -2016 were primarily driven by large numbers of young-of-year brown trout and, to a lesser extent, increases in adult brown trout.

Brown trout spawn late in the year, with the majority of Northern Hemisphere populations spawning between October-December (Elliott, 1994). Thus, the young-of-year brown trout that began showing up in the catch in 2015 were actually spawned at the end of 2014. These trends of increasing adult brown trout populations starting around 2012 followed by multiple successful recruitment events starting in the fall of 2014 are also clearly evident in mark-recapture data that were first collected starting in 2012 (Mike Yard, USGS, personal communication). Although brown trout populations in Lees Ferry have been increasing rapidly since 2013, the density of brown trout in Lees Ferry remains relatively low, with brown trout representing around 6% of the total catch in 2016 (Rogowski and others, 2017). Brown trout catch rates in Lees Ferry are now comparable to catch rates for Grand Canyon (see Figure 7).

This trend of rapidly growing Lees Ferry brown trout populations has occurred against the backdrop of rapidly declining rainbow trout populations (Figure 8). Specifically, catch rates for rainbow trout in Lees Ferry peaked in 2012 at around 480 fish/hr, but by 2016 catch rates had declined by 80% (90 fish/hr) owing to four consecutive year-over year declines (Rogowski and others, 2017). Mark-recapture studies in Lees Ferry show similar declining trends for rainbow trout (Korman and others, 2017). Mark-recapture studies also identified the cause for the rainbow trout decline was low availability of preferred aquatic insect prey (midges and blackflies), which led to poor condition and low adult survival (Yard and others, 2016; Korman and others, 2017). Although the focus of this white paper is on brown trout in Lees Ferry, we have included description of trends in brown trout from other locations, and description of rainbow trout and food base from Lees Ferry, because they provide essential context concerning the state of the Colorado River ecosystem during the time of the brown trout expansion. Further, several of the hypotheses pertaining to growing brown trout populations in Lees Ferry invoke these contradictory trends in rainbow trout and the invertebrate prey base as possible mechanisms responsible for brown trout increases.

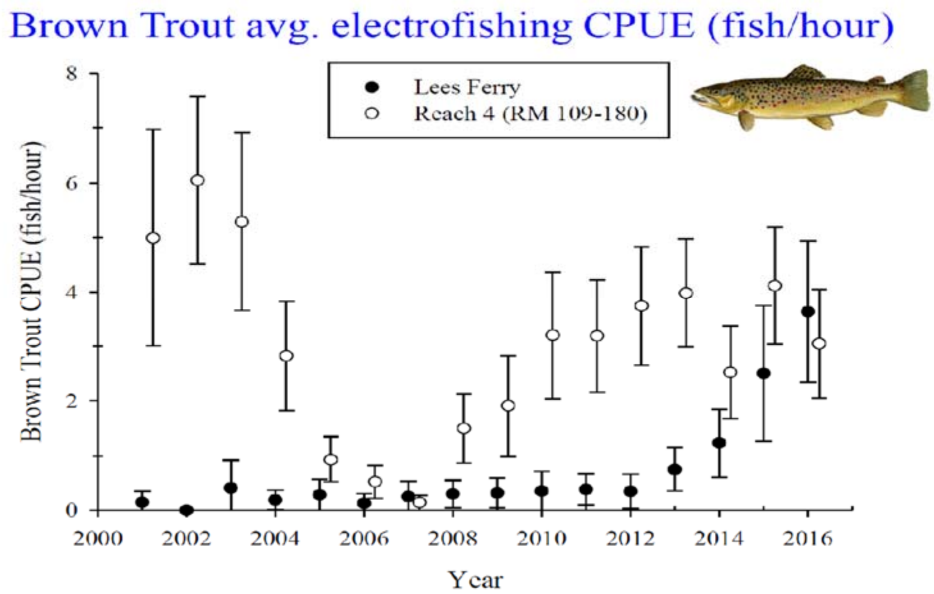

Figure 7. Brown trout catch rates for Lees Ferry (filled circles) and Grand Canyon (open circles) from 2001-2016. Circles represent the mean and whiskers represent the 95 percent confidence interval. Brown trout populations have been increasing in Lees Ferry starting in 2013 while brown trout populations in Grand Canyon have been relatively stable over this same time period. Figure courtesy of David Rogowski, AZGFD.

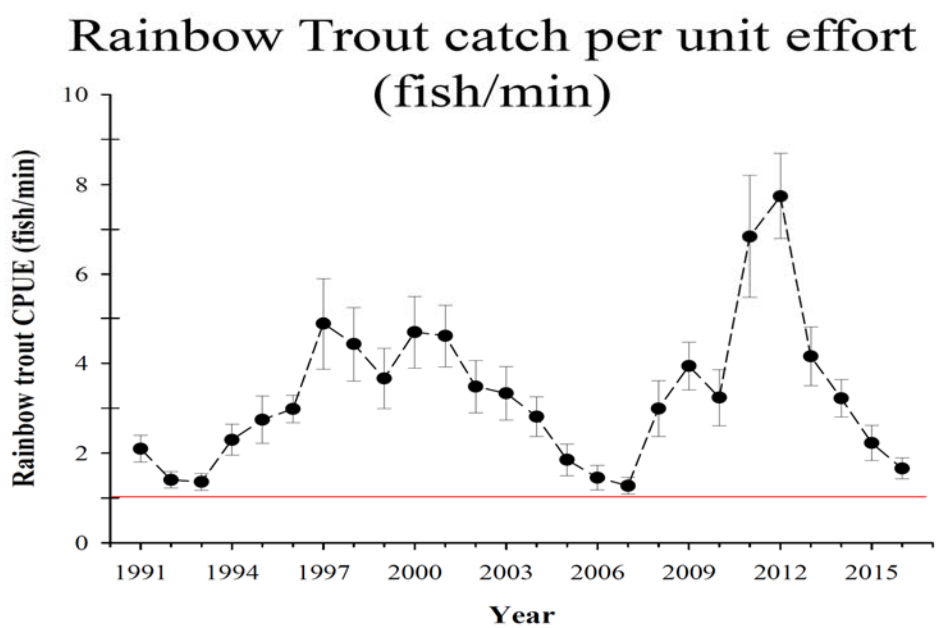

Figure 8. Graph showing rainbow trout catch rates for Lees Ferry from 1991-2016. The circles represent the mean and the whiskers represent the 95 percent confidence interval. The red line represents a catch rate of 1 fish/minute. Figure courtesy of David Rogowski, AZGFD.

Root Causes Hypotheses

In late 2016 and early 2017 many of the biologists involved in the Glen Canyon Dam Adaptive Management Program began formally meeting and discussing the root causes of the brown trout increase. These deliberations included the development of hypotheses and two expert elicitation exercises where hypotheses were ranked in order of credibility. The outcomes of these initial expert elicitation exercises were presented at the Annual Reporting Meeting in Phoenix (Muehlbauer and Bair, 2017).

In July of 2017 these discussions about brown trout were restarted, and over the course of five conference calls, a group of up to 10 scientists evaluated the hypotheses that had previously been developed and added new hypotheses for consideration. Ultimately, seven unique hypotheses that may explain why Lees Ferry brown trout populations are growing were considered in this latest round of deliberations. To ensure these deliberations about hypotheses remained objective and unbiased, Jim Peterson and/or Mike Runge sat-in on calls but neither voted or developed any hypotheses. Additionally, after the seven hypotheses had been developed by local experts, two salmonid experts that were not familiar with the Adaptive Management Program were invited to participate in discussions and vote. These outside scientists were also given the opportunity to develop new hypotheses but declined. The scientists that participated in these discussions and ranking exercises spanned a range of expertise including the biology and life history of salmonids and fish, aquatic ecology, population modeling, and whirling disease. The scientists involved also represented a variety of agencies, organizations, and geographies (i.e., Arizona Game and Fish Department, Colorado Division of Wildlife, National Park Service, SWCA, U.S. Geological Survey; see list of participants at end of document).

Next we present descriptions of each hypothesis including the evidence for and against. Hypotheses are presented in the order they were developed. Following description of each hypothesis, we present the results of the final expert elicitation conducted September 8-11, where scientists were asked to rank and rate the credibility of each hypothesis. Finally, we conclude this section of the white paper with a brief discussion of the strongest hypotheses.

Description of hypotheses

Hypothesis 1: Fall High Flow Experiments (HFE) are responsible for the increases in brown trout, because they are a cue for ripe brown trout to migrate into Glen Canyon (i.e., increase in spawners) and these disturbances cleanse spawning gravels.

<u>Background:</u>

1) Adult brown trout spawn in the fall, usually from October through December (Elliott, 1994).

<u>Hypothesized mechanism:</u>

1) Fall-timed HFEs cue migration of ripe brown trout into Glen Canyon thereby augmenting the number of spawners.

2) Fall-timed HFEs cleanse spawning gravels immediately prior to brown trout spawning thereby improving egg survival and recruitment.

Evidence For:

1) Brown trout catch rates are highly correlated with occurrence of fall HFEs (see Figure 9).
2) Ovidio and others (1998) found brown trout migration to spawning grounds (up to 5 km per night) was triggered by high variance in flow and temperature, similar to what occurs during HFEs.

Evidence Against:

1) No fall HFE occurred in 2015, and yet brown trout numbers continued to increase in 2016.
2) No positive brown trout response to 2004 fall HFE.

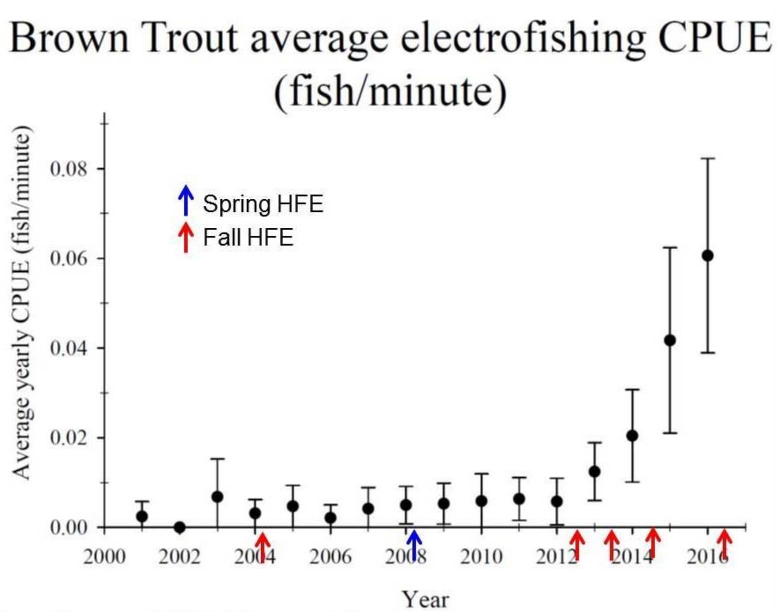

Figure 9. Graph showing catch rate of brown trout in Lees Ferry (fish/hr) from 2001-2016. Years with spring HFEs (blue arrows) and fall HFEs (red arrows) are marked. Figure courtesy of Dave Rogowski, AZGFD.

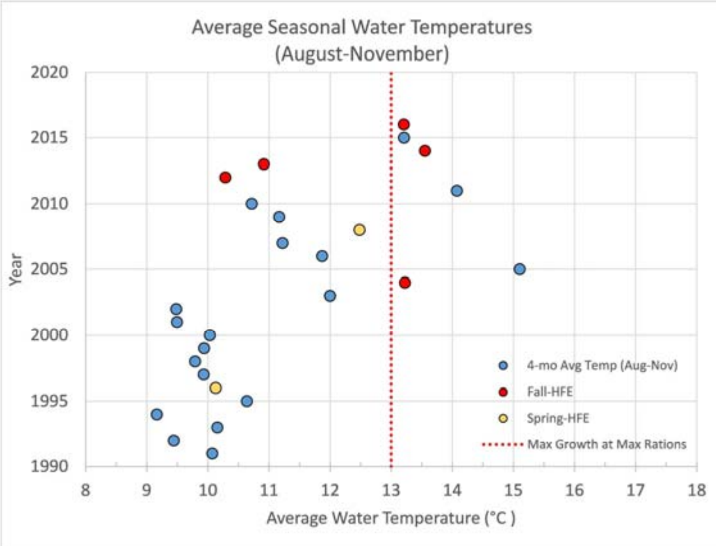

Figure 10. Graph showing average water temperature (X axis) for the months of August-November at Lees Ferry plotted against year (Y axis). The red vertical line marks 13C, the temperature at which brown trout growth efficiency is greatest (Elliott, 1994). Figure courtesy of Mike Yard, USGS.

Hypothesis 2: Recent warm water temperatures are facilitating increases in brown trout populations via increased growth and survival.

Background:

1) Maximum growth efficiency for brown trout feeding on invertebrates occurs at 13 °C (Elliott and others, 1995).

Hypothesized mechanism:

1) Recent warm water temperatures have facilitated expansion of brown trout populations by increasing egg survival, growth rates, and other vital rates for brown trout.

Evidence For:

1) August-November water temperatures (the months leading up to brown trout spawning) have exceeded this 13 °C threshold temperature value in four of the past six years (see Figure 10). During the ~20 years when brown trout populations were low and stable (i.e., 1991-2010), this 13 °C temperature threshold was only reached in two out of twenty years (2004 and 2005).

2) Al-Chokhachy and others (2016) investigated brown trout and bull trout dynamics in Montana in relation to August stream temperatures. They concluded that, “streams

warming to levels optimal for brown trout (12 to 15 °C [in August]) are the most vulnerable to future invasions and major increases in brown trout abundance."

Evidence Against:

1) The start of the brown trout increase in 2012-13 was marked by seasonal (August-November) temperatures that were below this threshold (i.e., 11°C).
2) During 2004-05 when water temperatures were also warm, brown trout CPUE declined river-wide and remained low and stable in Lees Ferry.
3) Temperature-growth relations for rainbow trout are virtually identical to those for brown trout (Elliott, 1994), and yet rainbow trout populations dramatically declined over this same period of warm water.

Hypothesis 3: Brown trout increases are associated with whirling disease in rainbow trout, which has provided abundant rainbow trout prey for brown trout.

Background:

1) Rainbow trout are highly susceptible to whirling disease while brown trout are carriers of the disease and generally resistant to deleterious negative impacts except when exposed to very high parasite doses (Sarker and others, 2015).

Hypothesized mechanism:

1) The growth potential and fitness of rainbow trout populations is appreciably lower now that whirling disease is present, and weakened rainbow trout provide abundant and highly vulnerable prey for brown trout.

Evidence For:

1) Whirling disease has contributed to declines in rainbow trout and concomitant increases in brown trout in streams and rivers throughout the Western US (Fetherman and others, 2015 and references therein).
2) Whirling disease has been present in rainbow trout from Lees Ferry since 2007 when 1 of 8 batches of rainbow trout tested positive. From 2008-2010, no samples tested positive for whirling disease, but then in 2011 samples were again positive for whirling disease (4 of 18 batches tested positive). In 2016, 12 batches of rainbow trout were collected from throughout Lees Ferry, and although no spores were detected, all 12 batches tested positive for low levels of whirling disease using PCR (Marcino, 2017, *pers. comm.* to Cantrell).[2]

[2] Joe Marcino-Fish Health Pathologist; Chris Cantrell-Chief of Fisheries; both of Arizona Game and Fish Department.

Evidence Against:

1) Observations of juvenile rainbow trout with visible signs of whirling disease are extremely rare (e.g., deformities, whirling swimming).
2) In Lees Ferry, rainbow trout populations crashed from 2012-2016 because of low adult survival (Korman and others, 2017), and survival and recruitment of juvenile rainbow trout was not considerably lower than prior years. However, in other rivers where whirling disease has negatively impacted rainbow trout populations and led to a subsequent increase in brown trout, rainbow trout populations crashed owing to recruitment failures and low survival of juveniles affected by whirling disease (Fetherman and others, 2015 and references therein).

Hypothesis 4: The current prey base improves recruitment and growth potential of brown trout

Background:

1) Since around 2012, the invertebrate prey base in Lees Ferry has been dominated by *Gammarus* and aquatic insects (i.e., midges and black flies) have been rare (Kennedy, 2017).

Hypothesized mechanism:

1) Brown trout have a wide spacing between gill rakers compared to rainbow trout (Budy and others, 2005; Langeland and Nøst, 1995) and this allows brown trout to effectively forage for large *Gammarus*, including directly from the benthos.

Evidence For:

1) Diet data demonstrate that brown trout in Lees Ferry consume predominantly *Gammarus*, while rainbow trout are primarily eating aquatic insects (i.e., midges and black Flies) and, to a lesser extent, *Gammarus* (see Figure 11). Thus, during the time of brown trout expansion their preferred prey have been relatively abundant while the preferred prey of rainbow trout have been scarce.

Evidence Against:

1) Diet data largely comes from the early years of brown trout increases and it is unclear if these feeding habits still apply (note that brown trout diet samples from 2015 and 2016 have been archived by USGS and are available for processing).

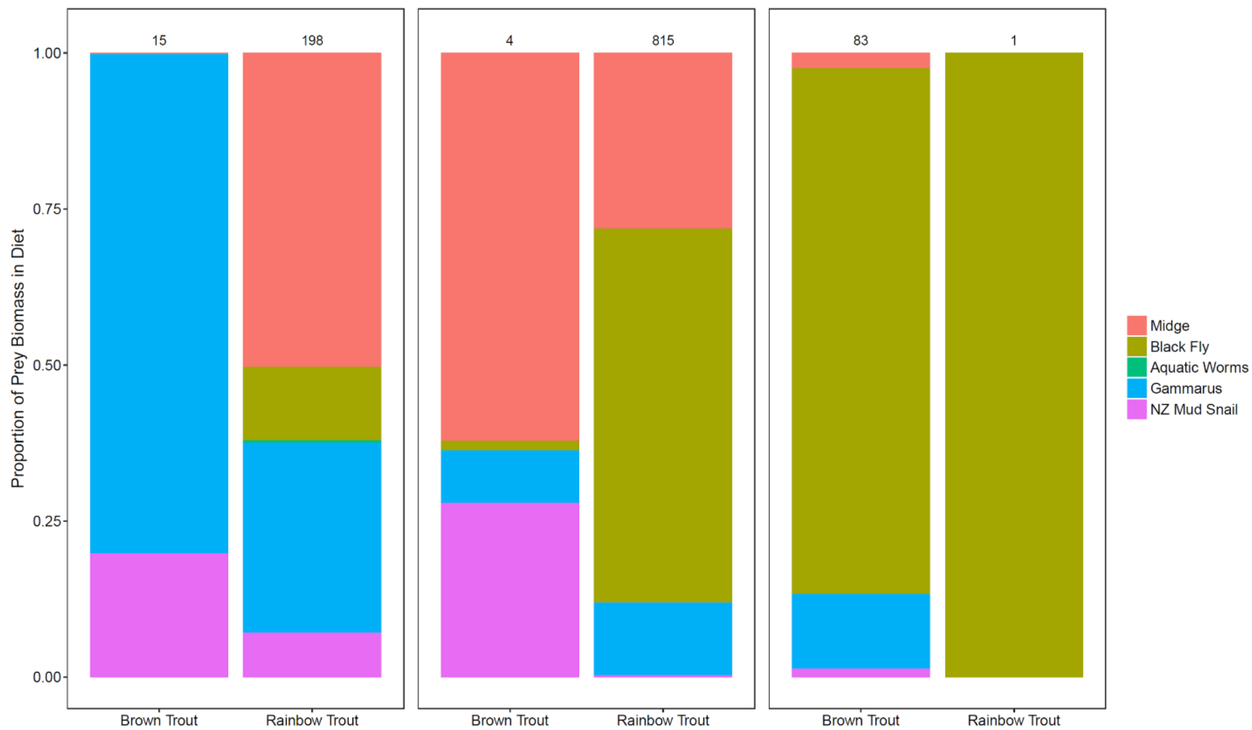

Figure 11. Figure showing proportion of different invertebrate prey items in diets of brown and rainbow trout from three different locations, Lees Ferry (left bars), Marble Canyon & Little Colorado River (center bars), and the mainstem Colorado River at Bright Angel Creek (right bars). Numbers above bars represent the sample size. Note that samples sizes for brown trout are low in comparison to rainbow trout. Diet samples for Lees Ferry are from 2012-2015 and 2017, Marble Canyon samples come from 2012-2015, and Bright Angel samples come from 2012 and 2013. Figure courtesy of Mike Dodrill, USGS.

Hypothesis 5: The weir at Bright Angel Creek led to increased migration of brown trout from Grand Canyon (i.e., increase in spawners).

<u>Background:</u>

1) Spawning season access to Bright Angel Creek has been blocked by a weir in 2002-03, 2006-07, and every winter since 2010-11 (see Figure 12).

<u>Hypothesized mechanism:</u>

1) Large numbers of ripe brown trout that historically moved into Bright Angel Creek to spawn may have migrated 100 miles upstream to Glen Canyon in search of other spawning grounds.

<u>Evidence For:</u>

1) Brown trout catch rates have declined in the vicinity of Bright Angel Creek while they have increased in Lees Ferry.

Evidence Against:

1) The first four seasons of weir operation (not all consecutive) are not correlated with detectable increases in brown trout at Lees Ferry.

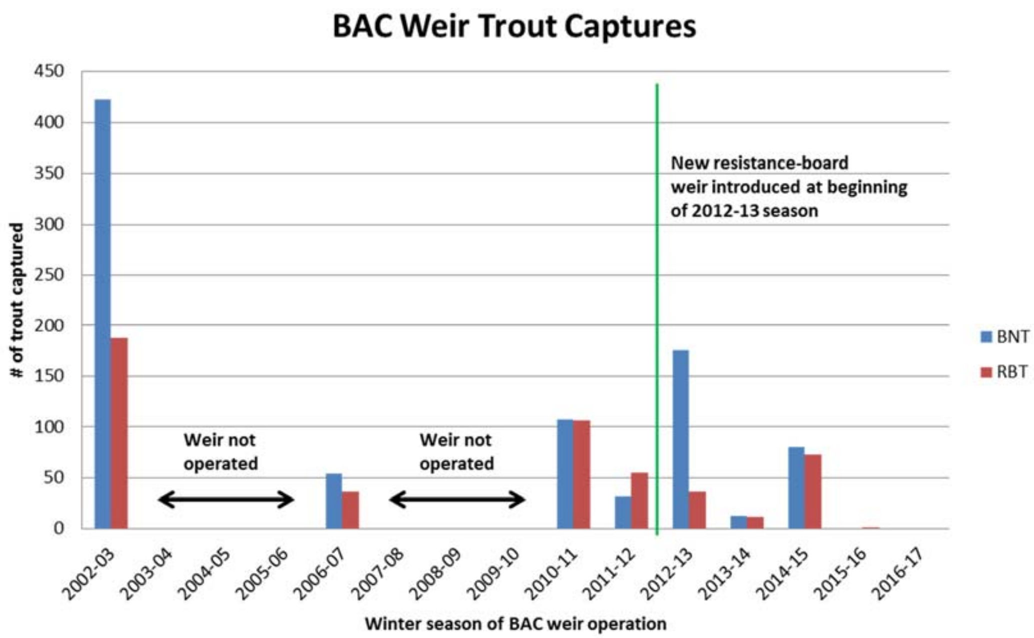

Figure 12. Graph showing years when the weir at Bright Angel Creek was operated and the number of rainbow trout and brown trout removed. Figure courtesy of Robert Schelly, NPS.

Hypothesis 6: Brown trout have increased because of declines in rainbow trout and less interference spawning.

Background:

1) Rainbow trout may compete with brown trout for spawning sites, and rainbow trout that spawn later than brown trout may superimpose eggs on top of brown trout eggs thereby reducing their survival.

Hypothesized mechanism:

1) When rainbow trout declined starting in ~2013, this reduced negative effects of interference spawning and allowed for sufficient brown trout spawning success to support population growth and recruitment.

Evidence For:

1) There is evidence in the literature that superimposition of redds or redd disturbance by rainbow trout can negatively affect other trout species, including brown trout (Nomoto and others, 2010; Scott and Irvine, 2000).

Evidence Against:

1) There was no increase in brown trout populations from 2003-2007 when rainbow trout populations were also declining and comparably low (see Figure 8).

Hypothesis 7: Brown trout have increased because of abundant rainbow trout prey.

Background:

1) Brown trout can be highly piscivorous.

Hypothesized mechanism:

1) Hyper-abundant rainbow trout in 2011 and 2012 provided the prey resources needed to support healthy and large adult brown trout that were capable of spawning.

Evidence For:

1) This is a conceptual hypothesis, but there is no evidence from the CRe or the literature supporting it.

Evidence Against:

1) Even when rainbow trout numbers are low, there are still >100,000 to be eaten.

Expert elicitation

Ideally, quantitative analyses would have been used to falsify hypotheses, but this was not possible because the data needed to rigorously evaluate many of the seven hypotheses was lacking. Thus, after group discussions, hypotheses were ranked and weighted by individual scientists based on a review of the literature, comparison with any available data, and professional judgment. For simplicity, only univariate hypotheses were considered in these evaluations. However, virtually every scientist felt that multiple root causes, acting synergistically, were responsible for the initial increase and continued growth of Lees Ferry brown trout populations.

For the expert elicitation, each scientist was asked to rank the seven hypotheses in order of credibility and then assign weights to each hypothesis. For weighting, the highest ranked hypothesis was assigned a weight of 100, and then lower ranked hypotheses were assigned lower weights (from 1-99) depending on the credibility of the hypothesis relative to the strongest hypothesis. Ties were allowed. Weights from each scientist were then standardized by dividing each individual weight by the total number of points assigned to hypotheses by each scientist. For example, if scientist X assigned 300 points in total across all the hypotheses, then the highest-weighted hypothesis for scientist X (assigned 100 points by definition) would have a standardized weight of 100 points/300 points total = 0.33.

The fall HFE hypothesis (H1) ranked consistently high in each of the four weighting exercises (eight of a possible ten 1st place ranks), and this hypothesis also had the largest weight (0.36, see Table 1 and Figure 13). Although the weight on the fall HFE hypothesis was more than double the next closest hypotheses (H2 and H4, both with weights of 0.15), the absolute weight for the fall HFE hypothesis was low (i.e., the average weight on this hypothesis was still only 0.36). Additionally, H2 (water temperature) and H4 (prey base) were consistently ranked highly, and both of these hypotheses received first place ranks in the final expert elicitation (see Table 1). Note that no other hypotheses received any 1st place ranks. Thus, there is broad agreement among scientists regarding which hypotheses are strongest (i.e., fall HFEs, water temperature, and prey base), but the absolute weights on these three hypotheses were low.

One factor that contributed to low absolute weights on the stronger hypotheses was the large number of hypotheses (7) that scientists evaluated. During discussions, scientists repeatedly attempted to falsify one or more of the weaker hypotheses so the list of hypotheses that were formally ranked and weighted was shorter, but the group was unwilling to eliminate hypotheses from future consideration because data were often lacking. For example, otolith micro-chemistry analysis of adult Brown Trout captured in Lees Ferry might have shed light on the credibility of the Bright Angel Creek weir hypothesis (H5), but no such data were available. Thus, scientist's unwillingness to eliminate hypotheses from consideration contributed to low absolute weights on the strongest hypotheses owing to dilution.

Low absolute weights on the strongest hypotheses may also reflect an awareness by scientists that such rapid and exponential increases in an animal population can only be achieved when multiple drivers align and create extremely favorable conditions for a species (Figure 14). That is, the absolute weights on the strongest hypotheses may have been low, because all three factors aligned—fall HFEs, warm water, and abundant prey—allowing for the exponential increases in brown trout populations that have been observed. Nonetheless, it is worth reemphasizing that of the seven hypotheses considered by scientists, only one hypothesis—fall HFEs—was weighted considerably higher than all others.

Table 1. List of hypotheses, ordered by the average weight of each hypothesis following evaluation by a panel of 10 scientists on September 8-11th. Larger weights and more 1st place ranks correspond to stronger hypotheses. There were eleven 1st place ranks, because ties were allowed.

Hypothesis #	Type of hypothesis	Statement of the hypothesis	Average Weight	# of 1st Place Ranks
H1	Physical driver	Fall HFEs are responsible for increases in Brown Trout, because they are a cue for ripe Brown Trout to migrate into Lees Ferry (i.e., increase in spawners), and these disturbances cleanse spawning gravels.	0.36	8
H2	Physical driver	Warmer water temperatures have increased survival and growth for Brown Trout.	0.15	2
H4	Biological driver	The current prey base improves recruitment and growth potential of Brown Trout.	0.15	1
H6	Biological driver	Brown trout have increased because of declines in Rainbow Trout and less interference spawning.	0.12	0
H5	Human driver	The weir at Bright Angel Creek led to increased migration of Brown Trout from Grand Canyon (i.e., increase in spawners).	0.11	0
H3	Physical driver	Brown Trout increases are associated with whirling disease in Rainbow Trout, which has provided abundant prey for Brown Trout.	0.07	0
H7	Biological driver	Brown Trout have increased because of abundant Rainbow Trout prey.	0.05	0

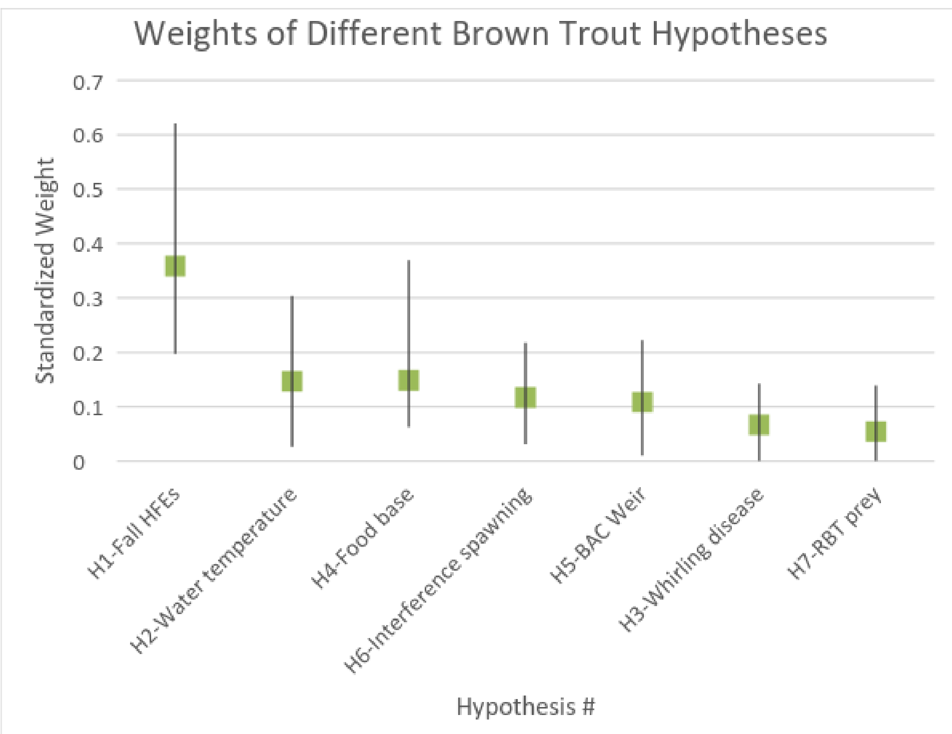

Figure 13. Plot showing weights for each of the seven hypotheses evaluated by a panel of 10 experts. The average weight (gray square), and the maximum and minimum weight (whiskers), for each hypothesis are shown.

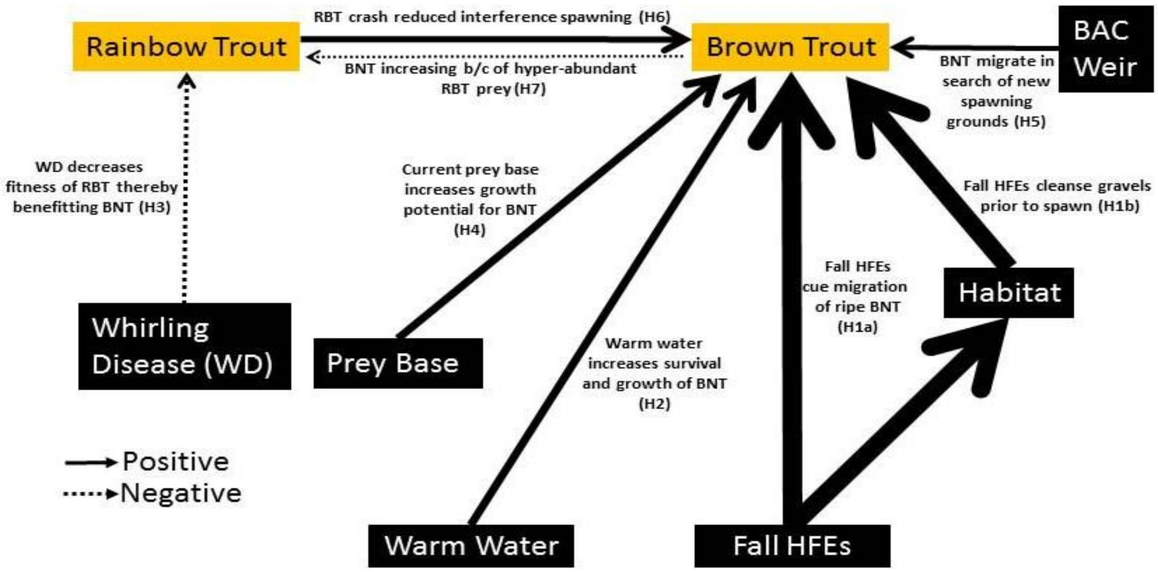

Figure 14. Conceptual diagram showing the 7 hypotheses developed to explain increasing populations of brown trout in Lees Ferry. Arrow widths correspond to the relative weight of hypotheses (i.e., stronger hypotheses are associated with wider arrows). Solid lines depict positive interactions and dotted lines depict negative interactions. WD = whirling disease, RBT = rainbow trout, HFE = High Flow Experiment, BNT = brown trout, and BAC Weir = Bright Angel Creek Weir.

Appendix to Section IV – memorandum begins next page

United States Department of the Interior

U.S. GEOLOGICAL SURVEY

SOUTHWEST BIOLOGICAL SCIENCE CENTER

GRAND CANYON MONITORING AND RESEARCH CENTER

2255 NORTH GEMINI DRIVE, MS-9394

FLAGSTAFF, ARIZONA 86001

MEMORANDUM

15 September 2017

To: Rob Billerbeck, Katrina Grantz, Mike Runge

From: Theodore Kennedy

Subject: Reducing critical uncertainties

The purpose of this memo is to summarize the one-on-one conversations I had with Melissa Trammell, David Ward, Mike Yard, Charles Yackulic, Scott VanderKooi, and Jeff Kershner regarding the question, "How much might a single additional year of data (with or without a fall HFE) allow us to distinguish the HFE hypothesis from the other 6 hypotheses for the root cause of brown trout increase?", which was posed by Mike Runge in his email dated September 12th.

The scientists I spoke with believed that a single additional year of data, with or without a fall HFE, would provide a minimal-to-modest amount of statistical power to distinguish the HFE hypothesis from the other 6 hypotheses. Scientists agreed that any distinguishing of hypotheses would primarily come in the form of potentially falsifying the other 6 hypotheses by confronting them with new or existing data. Scientists were skeptical that one additional year of data would lead to falsification of the HFE hypothesis, because the evidence in support of this hypothesis is strong, especially in comparison to the other hypotheses being considered.

Please feel free to contact me if you have any other questions or concerns.

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V. Risks to Humpback Chub and Rainbow Trout

Prepared by Charles B. Yackulic, USGS; Kimberly Dibble, USGS; Michael Yard, USGS; David Ward, USGS; and Josh Korman, ECOMETRIC.

Stakeholders have expressed interest in understanding the potential risk that establishment of a brown trout population in Lees Ferry poses both for the rainbow trout fishery in Lees Ferry and for the viability of the humpback chub population located downstream near the Little Colorado River (Figure 15). To forecast these risks (solid arrows), it was necessary to make a series of related predictions. For example, it was necessary to forecast how large the brown trout population could become in the absence of management, as well as to predict the effect of brown trout on rainbow trout, in order to determine the risk that brown trout pose to the rainbow trout population in Lees Ferry (blue solid arrow). Addressing how a brown trout population in Lees Ferry would affect humpback chub located near the Little Colorado River (yellow solid arrow) requires predicting a variety of relationships as indicated by the dotted blue arrows. These relationships include brown trout movement from Lees Ferry to the LCR and the impact of brown trout on humpback chub once they have migrated to near the LCR. At the same time, we also considered how effects of brown trout on Lees Ferry rainbow trout would potentially lessen the risk that rainbow trout pose for humpback chub. In the below sections, we derive estimates and associated uncertainty for each of these quantities and use them to derive overall estimates of risks.

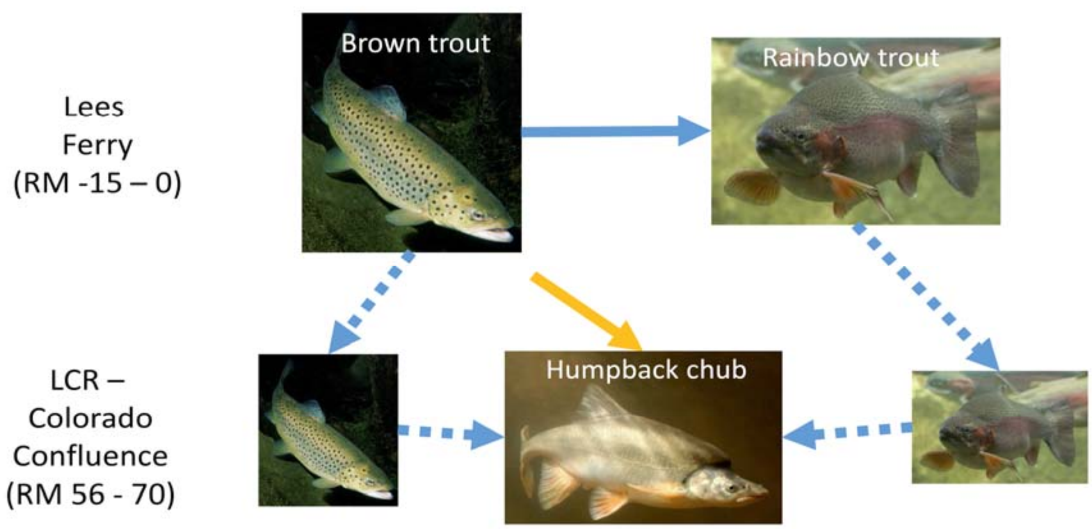

Figure 15. Conceptual model of Risks posed by a brown trout population in Lees Ferry.

Part I. Rainbow Trout Fishery in Glen Canyon

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 population abundance predictions as well as a prediction of the risk to the rainbow trout fishery.

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 tailwaters in the Western USA. Specifically, we focused on systems with six or more years of data during which stocking was not occurring and in which data for both rainbow and brown trout were present, and we focused only on adults (300 mm+ for rainbow trout; 350 mm+ for brown trout). Other tailwaters are typically sampled during the fall (i.e., Sept. / October), so we focused on this period to make comparisons to Lees Ferry 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 was removed from the analysis. We ran a random effects meta-analysis across systems, which suggests that in the average mixed fishery in the west the ratio of adult rainbow to brown trout is approximately 1.3:1, however there is substantial variation (sd of 0.59 on a log scale). Mean values for individual tailwaters that were used to fit this distribution are given by black marks on inner portion of x-axis in Figure 16. We also include the historic (i.e., 1999-2012 - orange) and present (2016 - red) ratios for Lees Ferry, which were not used in fitting this distribution. The comparison to other tailwaters illustrates the degree to which Lees Ferry has historically, and remains, exceptionally dominated by rainbow trout.

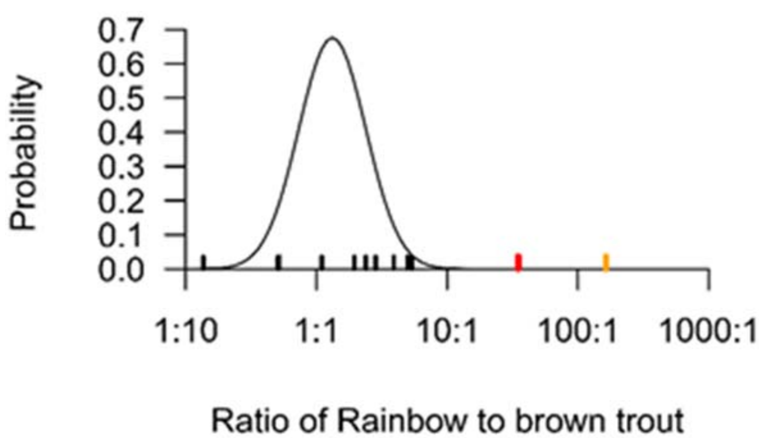

Figure 16. Ratio of rainbow trout catch to brown trout catch across western tailwaters. The red mark is the ratio at Lees Ferry in 2016, and the orange mark is the ratio at Lees Ferry from 1999-2012.

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 of systems 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 tailwater in which each additional brown trout caught was associated with 3.5 less rainbow trout caught. In two systems, rainbow trout and brown trout adult CPUE had relatively strong positive correlations. A fixed effect meta-analysis 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 (e.g., flows identified in Dibble and others, 2015). Furthermore, most other tailwaters 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 wouldn't 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 in which rainbow trout abundance decreases in response to brown trout population expansion (e.g., Chitose River, Japan – Hasegawa and others, 2017; Hasegawa, 2016; Hasegawa and others, 2014) and other instances in which rainbow trout invasion into new habitats has been limited by native brown trout population presence (e.g., Europe – Fausch and others, 2001). Therefore, we instead forced positive estimates to a very weakly 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 (i.e., an increase in the adult brown trout population of 100 individuals will be associated with 44 less adult rainbow trout), but with large uncertainty and a large probability that brown trout will not substantially suppress rainbow trout.

Synthesis: How big could the brown trout population become and what is the risk to the rainbow trout fishery.

Models developed for LTEMP predicted that the average adult rainbow trout population under alternatives that most resemble the selected alternative was approximately 100,000. Using this as a baseline, we can estimate brown trout and rainbow trout populations according to two equations: RBT = 100,000*R/(R-C) and BNT = 100,000 / (R-C) where R and C are defined by the distributions derived in the following sections. Under these equations the median rainbow trout population size, $N_{RBT, LF}$, is 99,000 (80% CI: 50,000 - 100,000) and the median brown trout population, $N_{BNT, LCR}$, is 63,000 (80% CI: 27,000 – 138,000).

Part II. Humpback Chub near the Little Colorado River.

How does the rate of movement of brown trout, M, from Lees Ferry to the Little Colorado River compare to rates of rainbow trout movement?

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. For context, a rainbow trout produced in Lees Ferry in 2011 had roughly a 1% chance of surviving and emigrating to somewhere in the Little Colorado River aggregation (i.e., RM 56 – 70) at some point in its life time (derived from survival and abundance of rainbow trout near the LCR in 2014 reported in Korman and others (2015), implied immigration to maintain abundance, and assumption that immigrants in 2014 were primarily fish produced from the extremely large 2011 cohort of approximately 800,000 juveniles in Lees Ferry). The available sparse information (a few recaps from Natal Origins and a fish detected on the LCR mux antennae) 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. Based on available evidence, we hypothesize that brown trout may migrate to the Little Colorado River aggregation at either a rate half of rainbow trout or up to two times as frequently with a uniform distribution within these bounds.

How many rainbow and brown trout should we expect near the LCR based on estimates of the Lees Ferry populations and the movement rate?

The relative number of rainbow trout near the LCR, $RN_{RBT,LCR}$, can be calculated as ($N_{RBT,LF}$/100000), since we assume a constant proportion of rainbow trout move from Lees Ferry to the LCR. The relative number of brown trout near the LCR that arrived from Lees Ferry, $RN_{BNT,LCR}$, can be calculated as ($M*N_{BNT,LF}$/100000) where M is the movement rate of brown trout relative to rainbow trout calculated in the last step. Importantly, we are modelling the additive effect of brown trout derived from Lees Ferry assuming that the number of brown trout arriving from other sources (e.g., Bright Angel) remains similar to levels observed during the period 2009 – 2016.

How does the per capita impact of brown trout, B, on humpback chub populations compare to the per capita impact of rainbow trout?

Field observations suggests that brown trout eat approximately 17 times as many humpback chub as rainbow trout (e.g., based on averaging of Yard and others (2011)'s rates above and below the LCR). On the other hand, many fish biologists have hypothesized that rainbow trout may have greater competitive, than predatory, effects on humpback chub 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 are three times as important as predatory effects of rainbow trout, and if brown trout have the same competitive effect as rainbows, then we might expect the overall effect of a brown trout to be only 5 times as great ((17+3)/(1+3) = 5). On the other hand, if competitive and predatory are equal for rainbow trout and 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 hypothesized that brown trout will have anywhere from 5 times as much to 9 times as much impact on humpback chub per capita as rainbow trout with a uniform distribution between these values.

Synthesizing results to estimate potential risk of an established brown trout population in Lees Ferry to humpback chub present near the Little Colorado River.

To synthesize these results, we modified models previously developed for LTEMP and recently updated with newer estimates to predict whether equilibrium adult abundances of humpback chub would be maintained at greater than 7,000 adults under estimates derived above. (It is important to keep in mind that even if the equilibrium estimates of adult humpback chub is greater than 7,000, we would still expect abundances in some years to potentially fall below 7,000.) We assumed 19,000 juvenile chub recruits annually in the LCR each June – a number used in previous modelling that is somewhat higher than recent direct estimates. Humpback chub vital rates for different location- and size-defined states and associated uncertainty were derived from Yackulic and others (2014) and effects of rainbow trout on juvenile survival were based on estimates from Yackulic and others (*in review*). To calculate the combined impacts of brown and rainbow trout, we calculated the effective number of rainbow trout, effRBT, using the following equation

$$\text{effRBT} = (RN_{RBT,\,LCR} + B^{*}\, RN_{BNT,LCR}) * \underline{N},$$

where $\underline{N}$ is the average number of rainbow trout in the LCR reach over the last seven years. To calculate risk, we compared the frequency with which the equilibrium abundance was calculated to be less than 7000 using $\underline{N}$ to the frequency when we substituted effRBT. We estimated a 0 % chance of an equilibrium adult humpback chub population being below 7,000 using $\underline{N}$, but a 54% chance of an equilibrium below 7,000 using effRBT.

Part III. Overall Summary and Caveats

The present brown trout population likely represent a relatively minor risk to both rainbow trout and humpback chub populations, however, if the brown trout population continues to expand at the current rate this situation could soon change. An established larger brown trout population likely represents a modest risk to rainbow trout in Lees Ferry, and a substantial risk to humpback chub populations located downstream. There is substantial uncertainty in estimating risk, much of which is ultimately related to uncertainty in the ultimate size that the Lees Ferry population of brown trout would grow to in the absence of management.

The estimates reported here rest on a number of assumptions, some stated and others implicit. For simplicity, our analysis relied on crude equilibrium estimates as opposed to dynamic simulations as used in LTEMP simulations (U.S. Department of Interior, 2016a). Furthermore, we assumed vital rates based on recent warm years (i.e., we ignored the potential for significantly cooler or warmer temperatures such as are expected under current management if water levels in Lake Powell either increase or decrease – and which were one of the dominant drivers of humpback chub population predictions used for LTEMP). In general, the equilibrium assumptions made here should lead to more optimistic estimates of adult humpback chub population size than expectations from dynamic simulations, however this should affect the reference estimates of humpback chub population size (i.e., using $\underline{N}$) as well as the estimates that included brown trout effects, so we expect the relative effect would not differ substantially in a more thorough simulation study. On the other hand, the relative risk posed by brown and rainbow trout may depend on environmental conditions. Laboratory studies indicate brown trout are able to feed more effectively than rainbow trout under high turbidity conditions (Ward and others, 2016) and under a wider range of water temperatures (Ward and Morton-Starner, 2015). In addition, the effects of whirling disease are expected to depend on water temperature. Even if whirling disease is not a root cause of recent increases in brown trout, it could nonetheless facilitate future invasion by brown trout if warmer temperatures lead to increased impacts of whirling disease.

Our analyses of rainbow and brown trout ratios assume equal capture probabilities for both species, and are limited to systems/years in which stocking was not occurring which may have biased our samples. We looked at other systems to determine the potential size of the brown trout population (i.e., the carrying capacity) because it is difficult to predict with available information from our system, however, we also know that our tailwater is unique, particularly with respect to its food base and the magnitude of interannual variation in rainbow trout recruitment. Furthermore, our analysis did not consider multiple life stages for rainbow or brown trout, or other measures of the quality of the rainbow trout fishery (e.g., average adult size). It is entirely plausible that brown trout may lessen rainbow trout recruitment and outmigration without affecting the size of the adult population. Moreover, decreased competition with juvenile rainbow trout could lead to larger sized adult rainbow trout. On the other hand, we reran our risk analysis and removed the impacts of rainbow trout on humpback chub (an extreme example in which rainbow trout outmigration is eliminated by brown trout) focusing solely on the impact of brown trout and still found a 44% chance that the equilibrium abundance would be below 7,000. This suggests that even if outmigration by rainbow trout is lessened by brown trout, the direct threat posed by brown trout still outweighs this indirect benefit.

VI. Comparison of Management Options

Prepared by Lucas Bair, USGS; Jeff Kershner, USGS; Chris Cantrell, AZGFD; Craig Ellsworth, WAPA; Jessica Gwinn, FWS; Theodore Kennedy, USGS; Scott Rogers, AZGFD; James Peterson, USGS; and Melissa Trammell, NPS.

This section identifies management and experimental actions that are possibly relevant to brown trout in the Colorado River (mainstem) below Glen Canyon Dam (GCD). Options for brown trout management are defined and evaluated against efficacy, over-arching management objectives as defined in Section 3, impacts to other downstream resources, and consistency with stakeholder (e.g., Tribal) values. Each option contains assumptions, uncertainties and additional factors that could affect results of implementation. There are management actions possibly relevant to brown trout that are included in the LTEMP, including the timing of high-flow experiments (HFEs) and mechanical removal of brown trout. There are also a number of additional management and experimental actions described in this section that are not included in the LTEMP and have not been reviewed under NEPA or ESA.

Management objectives

The evaluation of management options related to brown trout considers existing management activities and management objectives, as defined in Section 3, impacts to other downstream resources, and stakeholder (e.g., Tribal) values. See Section 3 for a description of management objectives. No quantitative management objectives have been set specifically for brown trout. The purpose of the workshop is to promote discussion and dialogue about the potential risks brown trout represent to existing resources, to evaluate the potential management actions that may be used to reduce or control the population, and to minimize negative impacts to other resources resulting from the brown trout, or actions taken to control them. Specific management targets for brown trout will be developed after the workshop. However, with regard to other management objectives, each of the proposed management and experimental actions are expected to reduce brown trout densities to a level that is consistent with management objectives designed to allow for the recovery of humpback chub.

Management Options

A suite of management options possibly relevant to brown trout management exist. These include options such as, but not limited to mechanical removal, TMFs, YY (diploid strain, or non-viable with respect to reproduction) brown or rainbow trout stocking, timing of HFEs, and control of mainstem temperature. Management actions are organized in accordance to their ability to directly influence brown trout populations in the mainstem or if they are experimental actions addressing hypotheses defined in Section 4. Management and experimental actions are also grouped in relation to meeting resource objectives.

Management actions

Management actions are options that specifically address brown trout abundance by direct or indirect manipulation of population abundance. Management actions could be used to reduce brown trout abundance in the Lees Ferry or Little Colorado River (LCR) reach of the mainstem to meet objectives identified in Section 3. For the purposes of evaluating management action options, actions are grouped in general categories. There is significant uncertainty in the efficacy of many of the proposed management actions and several actions have not yet been reviewed under NEPA or the ESA.

Brown trout mechanical removal

Mechanical removal of brown trout in Lees Ferry or the LCR is potentially an effective tool for management of brown trout populations. In the absence of eradication, significant reductions in densities and recruitment of 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), and even when removal efforts have failed to reduce total abundance, as in the case of 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 (Meyer and others, 2017; Peterson and others, 2008; 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 (Meyer and others, 2017; Saunders and others, 2015), but this effect may not currently apply in the Lees Ferry brown trout population if it is assumed to be far from density-dependent equilibrium, with rainbow trout still comprising approximately 95 percent of the fish community. Some factors contributing to diminished effectiveness of mechanical removal efforts include a well-established and abundant target species and failure to target source populations or areas of reproduction that sustain high levels of recruitment and immigration (Zelasko and others, 2016).

Mechanical removal could be implemented using various strategies. For example, a short-term emergency removal effort in Lees Ferry could occur under the Comprehensive Fisheries Management Plan’s rapid response and emergency compliance protocol (National Park Service, 2013a). Long-term mechanical removal at Lees Ferry could also occur, likely in the November through February timeframe, however, would need appropriate environmental compliance and permitting. Mechanical removal could also be more targeted in the Lees Ferry reach at certain times and locations, for example targeting spawning beds. Long-term mechanical removal in other reaches in Marble Canyon or at the confluence of the LCR could also occur, with compliance required for any mechanical removal actions that fell outside of the LTEMP BO humpback chub related triggers. In the LTEMP, mechanical removal is implemented with “boat-mounted electrofishing equipment to remove all nonnative fish captured.” Electrofishing is likely to occur during the night and the level of effort (number of trips or ‘passes’) would be determined by a predetermined objective. Removals with no option for stocking elsewhere would be euthanized and frozen for later beneficial use. Whirling disease prohibits live removal of trout due to the risk of spreading the disease to other waters (U.S. Department of Interior, 2016b). Management actions other than mechanical removal are possible. For example, disrupting spawning beds (e.g., redds) or behavior may be effective forms of brown trout management. Disruption of spawning would likely require appropriate environmental compliance and permitting.

The efficacy of mechanical removal of brown trout is less uncertain than other management options. There may be uncertainty in specific brown trout removal strategies but effectiveness in many cases corresponds to effort. However, while mechanical removal is frequently successful at removing a large portion of a fish population, this success is generally short lived as the new recruits rapidly replace those removed (Peterson and others, 2008). Most populations recover to pre-treatment levels soon after the mechanical removal is concluded. Long-term mechanical removal has higher economic costs than short-term strategies and therefore long-term removal strategies through electroshocking may not be an efficient solution to manage brown trout at Lees Ferry. Targeted electrofishing over known brown trout spawning bars could be considered to potentially improve efficiency. The economic cost of removing brown trout at Lees Ferry, to maintain abundance at existing levels, is estimated to be $500,000 per year (Yard M., USGS 2017, *pers. comm.*). The level of effort required (e.g., number of passes, expected fish handling) under different mechanical removal strategies will be detailed in subsequent drafts. Targeted brown trout removal at high-concentration spawning bars and other possible combination of mechanical removal could have a much lower cost.

It is anticipated that mechanical removal in the Lees Ferry reach could meet humpback chub compliance with ESA, reducing abundances of brown trout at the LCR below the predator index defined in the LTEMP. However, it is unknown at this time what the out-migration rate of brown trout is, therefore, mechanical removals of brown trout in Lees Ferry may not have a measurable effect on the predator index where humpback chub population aggregates exist at the LCR reach. Mechanical removal in the Lees Ferry reach has the potential to negatively affect the condition of the rainbow trout fishery through bycatch. Therefore, monitoring of the rainbow trout fishery would be necessary in any mechanical removal actions. Mechanical removal is species specific and could be accomplished with relative precision and may have limited impact to the rainbow trout fishery, Sand Load Index or other resources of concern.

Mechanical removal of brown trout in the Lees Ferry or LCR reaches of the mainstem would have a significant impact on the ‘Tribal concerns with the taking of life’ objective. The number of removal trips, brown trout removed, the processing of brown trout for beneficial use, and the objective of mechanical removal actions are potential metrics that may need to be addressed when considering Tribal concerns.

Brown trout angling regulations

Angling regulations may be an effective tool for management of brown trout populations. 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. Unintended outcomes (stemming from “perverse incentives”) must be considered in harvest incentive programs, and may include increased value placed on continued presence of the target species and intentional introductions. Must-kill regulations are another means of communicating to anglers the undesirability of certain nonnative species and potentially affecting target populations. Currently, the Arizona Game and Fish Commission has removed all harvest limits on brown trout in Lees Ferry. Brown trout removal in Lees Ferry would likely have a negative impact on the angling community.

The efficacy of angling regulations in reducing brown trout is unknown, but the value in the message may be important. Variation in angling regulations are not expected to have an effect on downstream resources. Tribal concerns may be less with these methods because all fish taken in this way would be consumed by humans. Enacting new regulations would require coordination between AZGFD and NPS, but would be very low cost. Additional funding may be needed to support the cash harvest incentives.

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 describes rainbow trout TMFs as 2 or 3 days of elevated flows followed by a very sharp drop in flows, to a minimum level, to strand young-of-year rainbow trout (U.S. Department of Interior, 2016a). In the LTEMP the elevated flows are proposed to be conducted in the spring and summer months (May-July) and consist of relatively high flows (e.g., 20,000 cfs) followed by low flows that are within the minimum flow level (e.g., 5,000 cfs to 8,000 cfs) and maintained for less than 12 hours. Ramp up rates are consistent with normal operations (i.e., 4,000 cfs/hour) while the down ramp rate would be 15,000 cfs/hour (U.S. Department of Interior, 2016a). Brown trout TMFs would target either young-of-year in February through April or target spawning to dry out redds in December or January. TMFs that target brown trout could mimic the design of LTEMP rainbow trout TMFs. Flow management actions that target redds may be ineffective because of location too deep in channel as well as compensatory responses of surviving fish, however, this method may be a way to disrupt spawning.

The efficacy of TMFs is uncertain. Timing and variation of specific strategies to strand young-of-year have yet to be determined. The economic cost (i.e., foregone hydropower value) of brown trout TMFs would likely be comparable to the costs of TMFs in the LTEMP (e.g., $400,000 – 1 million per experiment) (U.S. Department of Interior, 2016a). It is anticipated that TMFs could meet humpback chub compliance with ESA, reducing abundances of brown trout below the predator index defined in the LTEMP. However, if brown trout TMFs are proposed outside of the time specified and considered under the LTEMP EIS and BO, further consultation may be needed. Brown trout TMFs have the potential to negatively affect the condition of the rainbow trout fishery. Therefore, monitoring of the rainbow trout fishery would be necessary in any mechanical removal actions. TMFs could also have a negative interaction with HFEs and minimum flows limits may need to be specified to minimize the impact on the food base (U.S. Department of Interior, 2016a).

Brown trout TMFs would have a significant impact on the 'Tribal concerns with the taking of life' objective. The number of flow experiments, the life-stage of brown trout targeted, and intention of the flow action are some of the considerations that may need to addressed when considering Tribal concerns.

Brown trout stocking

Experimental stocking with YY male brown trout in Lees Ferry is potentially an effective tool for management of brown trout populations. This management action would result in brown trout offspring that are all XY male. Brown trout stocking is experimental and the efficacy is highly uncertain. This method is only being tested elsewhere for brook trout, but modeling of impacts shows promise, particularly when coupled with concurrent removal of existing trout (Schill and others, 2017). The economic cost of brown trout stocking would likely be comparable to other low cost management action to control abundance. It is uncertain but imperative to determine if brown trout stocking would have impacts on other downstream resources, such as humpback chub. Even if brown trout stocking was able to achieve management goals, this method of management focuses on multi-generational declines, is a longer-term solution, and in the short-run increased brown trout abundance may cause outmigration of brown trout into Marble Canyon. Stocking of brown trout YY males would require initial development of a broodstock of YY males, as well as appropriate environmental compliance and permitting.

Experimental actions

Other experimental management actions are listed below. Experimental management actions are options that are potentially an effective tool for management of brown trout populations and specifically address one or more of the hypotheses identified in Section 4. These experimental options potentially have a higher level of uncertainty in both efficacy and impact on other downstream resources. Not all the experimental actions have appropriate environmental compliance and permitting.

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 hydrology, 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 is short in duration, and is restricted to the period immediately prior to and surrounding 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 hydrology 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 differential 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). It is hypothesized that fall-timed HFEs cleanse spawning gravels immediately prior to brown trout spawning thereby improving egg survival and recruitment. Fall-timed HFEs may cue migration of ripe brown trout into Glen Canyon thereby augmenting the number of spawners. Suspending or moving HFEs to spring would alter these seasonal outcomes, possibly disadvantaging brown trout and favoring rainbow trout. It is also a potential that spring HFEs could leave emerging brown trout vulnerable to predation and other threats.

High-flow experiments that potentially address brown trout management could take on a variety of strategies to address one or more of the hypotheses identified in Section 2. Fall HFEs, typically in October or November, are included in the current LTEMP HFE protocol, with spring HFEs to be implemented beginning in 2020 (U.S. Department of Interior, 2016a). Options under existing compliance include experimental short-term suspension of fall HFEs or long-term altered fall HFEs, including shifting the frequency, timing and duration. A change in timing or sediment accounting outside of the LTEMP EIS protocol would require appropriate environmental compliance and permits.

Suspension or alteration of fall high-flow experiments

Suspension or altered timing of fall HFEs may affect brown trout recruitment to an extent that compliance with the ESA is feasible, reducing abundance of brown trout below the predator index defined in the LTEMP. The suspension or alteration of fall HFEs may not require new environmental compliance and permitting. The efficacy of altered HFE protocol is uncertain. A short-term suspension of fall HFEs of a sufficient interval to test hypotheses about the increased brown trout abundance would likely have a negative effect on the Sand Load Index and a positive effect on the condition of the rainbow trout fishery.

Sediment triggered spring high-flow experiments

Sediment triggered spring HFEs are potentially an effective tool for the management of brown trout populations. Variation on LTEMP protocol could include implementation of sediment-triggered spring HFEs beginning in 2018 or 2019. Another variation in the LTEMP protocol is to include fall sediment inputs in the spring HFE account period, either including or suspending fall HFEs. Spring HFEs may disadvantaging brown trout recruitment. Spring HFEs may also disadvantage brown trout and favor rainbow trout through shifts in the food base. For example, the 2008 spring HFE reduced the abundance of scuds (*Gammarus lacustris*) (Cross and others, 2011), an aquatic amphipod that may promote growth and survival of brown trout (Section 4). In contrast, the 2008 spring HFE stimulated production of aquatic insects (midges and black flies) that are the preferred prey of rainbow trout (Cross and others, 2011). Spring HFEs might also improve the health of rainbow trout populations by greatly reducing the abundance of sludge worms (*Tubifex tubifex*; Cross and others, 2011) which are the vector for whirling disease affecting rainbow trout populations. The efficacy of altered HFE protocol is uncertain. Although impacts of an altered HFE protocol would depend on the ultimate design, a short-term suspension of fall HFEs and/or more emphasis on spring HFEs could have neutral-to-negative effects on the Sand Load Index but a positive effect on the condition of the rainbow trout fishery.

Annual spring high-flow experiments

Annual spring HFEs are potentially an effective tool for the management of brown trout populations. Annual spring HFEs would be implemented independent of sediment triggers. Spring HFEs could have a similar impact on brown trout as the sediment-triggered spring HFEs. As with the sediment triggered HFEs, the efficacy of an altered HFE protocol is uncertain. Annual spring HFEs would need appropriate environmental compliance and permitting. Annual spring HFEs could result in negative impacts to the value of hydropower generation and the Load Index, and potentially a positive impact to the condition of the rainbow trout fishery.

Rainbow trout stocking

Experimental stocking of rainbow trout in Lees Ferry is potentially an effective tool for management of brown trout populations. Stocking the rainbow trout fishery with individuals that potentially could out-compete brown trout or are less vulnerable to whirling disease may put downward pressure on the brown trout population in Lees Ferry. Hofer cross rainbow trout have been stocked in other western states and have reversed trends in whirling disease. Some areas also saw a decrease in brown trout as rainbow trout populations recovered (Nehring, B., 2017, *pers. comm.*). This action is experimental and the efficacy of stocking is highly uncertain. The economic cost of rainbow trout stocking would likely be comparable to other low cost management action to control abundance. It is not anticipated that rainbow trout stocking would have impacts on downstream resources except possibly for humpback chub. Given the strong correlation observed between high rainbow trout recruitment at Lees Ferry and increased outmigration into Marble Canyon (Korman and others, 2012), a density-dependent increase in downstream movements by rainbows out of the Lees Ferry reach might be expected as a result of stocking. Rainbow trout stocking may require appropriate environmental compliance.

Temperature control device

Temperature is potentially an effective tool for the management of brown trout populations. The LTEMP BO contains a conservation measure to explore the efficacy and efficiency of a temperature control devise (TCD) to address conditions that could lead to the establishment of nonnative fishes. It is hypothesized that recent warm water temperatures may have facilitated expansion of brown trout populations by increasing egg survival, growth rates, and other vital rates for brown trout, and these growth requirements were not being met by previous cold-water temperatures. Installation of a TCD would allow resource managers to control the withdrawal depth of water from Lake Powell to assist in the control of temperature in the mainstem. Reducing mainstem temperature could also have an impact on the life cycle of whirling disease. The efficacy of altering temperature in the mainstem is uncertain. The cost of a TCD could range from $15-150 million, in 2006 dollars (Bureau of Reclamation, 1999). The rainbow trout fishery, humpback chub, and other native and nonnative species could be affected by changes in mainstem temperature for the management of brown trout populations. Monitoring of these aquatic species, along with other potential impacted downstream resources, would need to occur. Installation of a TCD would need appropriate environmental compliance and permitting. In addition, the Arizona Game & Fish Department's management plan supported the TCD as an experimental approach for managing the rainbow trout and humpback chub populations.

No action

If no action is taken, the brown trout population may continue increasing in abundance. Impacts on the rainbow trout fishery and humpback chub downstream may increase as the abundance of brown trout increase. See Section 5 for an assessment of brown trout and risks to the rainbow trout fishery and humpback chub.

Multiple management and experimental actions

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 draft. Combinations of management and experimental actions, the sequence of implementation considering efficacy, risk and compliance issues may be discussed in subsequent drafts.

Comparison of Management Actions

To compare management actions each individual management and experimental action is evaluated based on efficacy, economic cost, and potential effect on management objectives (Table 2).

Efficacy

The efficacy of both management and experimental options is relatively unknown. The outcomes of mechanical removal actions have been demonstrated in previous work and are generally viewed as more certain than the potential outcomes of habitat management and experimental flow, temperature manipulation, and trout stocking. While mechanical removal actions may increase the likelihood of brown trout removal, it is uncertain if the outcome associated with mechanical removal would improve compliance with the ESA; reducing the abundance of brown trout near the LCR below the predator index as defined in the LTEMP. Management and experimental actions will need to be monitored to assess the efficacy of brown trout management and the effect on management objectives. A review of the results of previous trout control efforts in other similar situations will be necessary to understand the relative merits and costs of each of the proposed methods. An initial step in determining the efficacy of downstream options would be to elicit expert opinion and a review of the literature. Quantitative modeling of efficacy may be possible for mechanical removal efforts and certain flow experiments (TMFs, Spring HFEs, altered timing of fall HFEs), but was not completed for this white paper.

Economic costs

The potential economic cost of actions range from personnel and logistics costs of mechanical removal to foregone hydropower revenue involved with flow actions, to cost associated with the construction of a TCD. In addition, the cost of a monitoring program that will determine the success or failure of these measures and effects on downstream resources must be considered. In general, mechanical removal would cost approximately $500,000 per year to implement at Lees Ferry or the LCR (Yard, M., USGS 2017, *pers. comm.*). This is comparable to rainbow trout TMFs in the LTEMP and is what would be expected to implement brown trout TMFs (U.S. Department of Interior, 2016a). Cost is also associated with flow actions that change the Sand Load Index or value of hydropower generated at GCD and could have a low to moderate levels of cost. For example, sediment triggered spring HFEs may have a low cost of implementation, negative effect on the Sand Load Index and a positive effect on the value of hydropower generated at GCD. Suspension of fall HFEs (negative effect on Sand Load Index) or annual spring HFEs (negative effect on Sand Load Index and value of hydropower generated at GCD) may incur moderate economic costs. A TCD would potentially have the largest economic cost. Planning documents estimate the total costs of temperature control at $15-150 million in 2016 dollars (Bureau of Reclamation, 1999).

Resource Outcomes

Compliance with the ESA

The proposed management and experimental actions are expected to reduce brown trout densities to a level that is consistent with management goals designed to allow for the recovery of humpback chub, reducing abundances of brown trout below the predator index defined in the LTEMP. There are a number of uncertainties with each management and experimental action described in this section and many of the options do not have appropriate environmental compliance and permitting. This includes evaluation of the potential management and experimental actions that could be effective tools for management of brown trout populations as they affect ESA species.

The condition of the rainbow trout fishery

The condition of the rainbow trout fishery may be negatively affected by any mechanical removal effort in the Lees Ferry reach of the mainstem, although such removal passes might be similar to or even less intensive than recent electrofishing projects targeting rainbow trout in that reach. Mechanical removal in the LCR reach of the mainstem would not affect the rainbow trout fishery. The impact of brown trout TMFs on the rainbow trout fishery is uncertain but potentially negative. Suspension of fall HFEs or more emphasis being place on spring HFEs may have a positive impact on the rainbow trout fishery.

Potential interactions with high-flow experiments

Management and experimental flow actions would affect fine-sediment budgets on the mainstem. Brown trout TMFs may have a negative effect on the delivery of fine sediment while suspension of fall HFEs and annual spring HFEs would likely have a definitive negative effect on the delivery of fine sediment. While uncertain, sediment triggered spring HFEs may have a neutral to slight negative effect on the long-run delivery of fine sediment by reducing the probability of HFE events.

Tribal concerns with the taking of life

As identified in the "Management Objectives" section, the Pueblo of Zuni, Hopi Tribe, and Navajo Nation, have expressed concern for the removal of fish, including nonnative trout, if such removal constitutes what they believe is an unwarranted or unnecessary taking of life. The mechanical removal and flow actions to reduce brown trout abundance would have a significant impact on the 'Tribal concerns with the taking of life' objective. The implementation of management and experimental actions, number of nonnative fish removed from the mainstem, the processing of nonnative fish for beneficial use, and objective of management and experimental actions are aspects of brown trout management that could be addressed to consider Tribal concerns. These considerations would not be limited to management actions that are aimed to reduce brown trout abundance but also experimental actions that address one or more of the hypothesis defined in Section 4.

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 changes in hydropower production, effects on other native fish, and effects on recreation (especially, boating and rafting as well as use of recreational camping beaches along the river segments of interest). The evaluation of economic cost associated with management options (e.g., foregone hydropower value), the Sand Load Index or the condition of the rainbow trout fishery, does consider some of these downstream resources. However, every management and experimental action would have a complex interaction with downstream resources and further evaluation of management options would need to occur.

Ease of implementation

The speed at which management options could be implemented largely depends on appropriate environmental compliance and permitting. Management options have been reviewed under NEPA and Section 7 of the ESA and include mechanical removal of brown trout, triggered by a predator index in the LTEMP, and suspension or alteration of fall HFEs, as long as the altered protocol fall within the LTEMP bounds. Management options that have not been considered under appropriate environmental compliance and permitting include brown trout TMFs, altered HFE protocols placing more emphasis on spring HFEs, stocking, and a TCD. These actions could take longer to implement and may be more effective or efficient in combination with management options that have already been reviewed in past planning documents. If any of the options are predicted to take wildlife, appropriate consultation may be required.

Table 2: Comparison of individual brown trout management and experimental actions[1]

Management and experimental actions	Relative efficacy[2]	Relative economic cost[3]	The condition of the rainbow trout fishery	Potential interactions with high-flow experiments	Tribal concerns with the taking of life
Brown trout removal at Lees Ferry	Moderate	Low	0	NA	Need input from tribes
Brown trout removal at the Little Colorado River	Moderate	Low	0	NA	Need input from tribes
Brown trout angling regulations	Not yet analyzed	Low	0	NA	Need input from tribes
Brown trout management flows	Not yet analyzed	Low	0	-	Need input from tribes
Brown trout YY stocking in Lees Ferry	Not yet analyzed	Low	0	NA	Need input from tribes
Rainbow trout stocking in Lees Ferry	Not yet analyzed	Low	+	NA	Need input from tribes
Suspension of fall high-flow experiments	Not yet analyzed	Moderate	+	-	Need input from tribes
Sediment triggered spring high-flow experiments	Not yet analyzed	Low	+	0/-	Need input from tribes
Annual spring high-flow experiments	Not yet analyzed	Moderate	+	-	Need input from tribes

Temperature control device	Not yet analyzed	High	+	0	Need input from tribes

Notes: NA (not applicable), + (positive outcome), - (negative outcome), 0 (neutral outcome)

[1] Multiple or a sequence of multiple management actions and experiments may be more effective and efficient at managing brown trout populations than an individual management or experimental action.

[2] Management and experimental actions are evaluated based on ability to manage brown trout in a way that effectively meets recovery goals of humpback chub.

[3] Low cost are anticipated to be <$500,000 per year, moderate costs between $500K and $1.5 million per year, and high costs greater than $1.5 million per year

DISCLAIMER

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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