VERSION 1.1
April 2022

Species Status Assessment Report for the Colorado pikeminnow *Ptychocheilus lucius*

U.S. Fish and Wildlife Service
Mountain-Prairie Region
Denver, CO

PREFACE

This Species Status Assessment provides an integrated, scientifically sound assessment of the biological status of the endangered Colorado pikeminnow *Ptychocheilus lucius*. This document was prepared by the U.S. Fish and Wildlife Service (USFWS), with assistance from state, federal, and private researchers currently working with Colorado pikeminnow. The writing team would like to acknowledge the substantial contribution of time and effort by those that participated in the Science Team. This SSA report is Version 1.1, which includes updates to current condition scoring and thresholds based on input from a Recovery Team convened in 2021. These revisions represent minor changes to current condition categories based on updated information since the 2002 Recovery Goals were written. The subsequent analysis resulted in minor changes that are consistent with findings in the 2020 5-year status review.

Writing Team

Tildon Jones (Coordinator, Upper Colorado River Recovery Program)
Eliza Gilbert (Program Biologist, San Juan River Basin Recovery Implementation Program)
Tom Chart (former Director, retired, Upper Colorado River Recovery Program)

U.S. Fish and Wildlife Service Species Status Assessment Advisory Group

Craig Hansen (U.S. Fish and Wildlife Service, Region 6)

Reviewers and Collaborators

Upper Colorado River Recovery Program Directors Office: Donald Anderson, Katie Busch, Melanie Fischer, Kevin McAbee, Cheyenne Owens, Julie Stahli

Science Team: Paul Badame, Kevin Bestgen, Jim Brooks, Kelly Cambridge. Harry Crockett, Scott Durst, Darek Elverud, Eliza Gilbert, Jacob Mazzone, Bill Miller, Steven Platania, Dale Ryden, Matt Zeigler, Tom Chart

Peer Reviewers: Keith Gido, Wayne Hubert

Upper Colorado River Recovery Program Biology Committee Members: Paul Badame, Pete Cavalli, Harry Crockett, Bill Davis, Derek Fryer, Tom Pitts, Dale Ryden, Dave Speas, Melissa Trammell

San Juan River Basin Recovery Implementation Program Biology Committee: Ryan Besser, Harry Crockett, Stephen Davenport, Vincent Lamarra, Jacob Mazzone, Mark McKinstry, William Miller, Benjamin Schleicher, Tom Wesche, Brian Westfall, and Matthew Ziegler

San Juan River Program Office Staff: Melissa Mata, Nate Franssen, Scott Durst

Federal, State, and Private Collaborators and Other Interested Parties: Doug Osmundson

Cover Photograph Credits

a) Colorado River, Grand Canyon 1911 (National Park Service), b) upper Colorado River subbasin (U.S. Fish and Wildlife Service), and c) Green River subbasin (Utah Division of Wildlife Resources)

Recommended Reference

U.S. Fish and Wildlife Service. 2022. Species status assessment report for the Colorado pikeminnow *Ptychocheilus lucius*. Mountain-Prairie Region, Denver, Colorado. Version 1.1

Species Status Assessment Report for
Colorado pikeminnow *Ptychocheilus lucius*

Prepared by the
U.S. Fish and Wildlife Service

EXECUTIVE SUMMARY

This species status assessment (SSA) is a comprehensive review of demographic and habitat factors for the Colorado pikeminnow *Ptychocheilus lucius* (Girard 1856) and provides a thorough account of the species' overall viability. The SSA analyzes the viability of the species across three extant populations, and considers resource conditions for the lower Colorado River basin where the species is currently extirpated. The SSA provides an overview of the species' taxonomy, life cycle, historical distribution, and listing status under the Endangered Species Act. Species needs are described at the individual, population, and species level, and needs are organized into the concepts of resiliency, redundancy, and representation. Next, the SSA provides an overview of factors that can negatively influence the species or its habitat (stressors), followed by a description of conservation measures intended to mitigate those stressors. Current condition of demographic and habitat factors for each analysis unit is summarized, providing an overall ranking of current condition for each unit. The final section summarizes projections of future conditions for each analysis unit, based on model results from a recently completed population viability analysis.

Species Background

The Colorado pikeminnow is the largest member of the family Cyprinidae native to North America and a species endemic to warmwater reaches of large rivers in the Colorado River basin. It was the apex predator within these reaches, and is believed to be almost entirely piscivorous as an adult. The species can grow to a large size (>1.5 m [5 ft]) and live over fifty years. Colorado pikeminnow are known to make long distance migrations for spawning and return to their home range where they inhabit deep runs, pools, and eddies. Eggs hatch within the river substrate as spring peak flows decline, with the larvae carried potentially long distances by river flows to low velocity nursery habitats downstream of the cobble spawning bars. In these reaches, larvae and juveniles seek low to zero velocity backwaters that provide warm temperatures for growth and abundant food supply in the form of macroinvertebrates and small fish prey. Individuals become sexually mature between seven and ten years of age and can spawn repeatedly as adults. Both adult and nursery habitats, as well as spawning bars, are formed and maintained by high spring peak flows that move sediment, clean cobble substrates, and maintain channel complexity to provide a diversity of habitats. Colorado pikeminnow inhabit river reaches that historically experienced extremes in both flow and temperature on an annual basis, in addition to high turbidity from sediment inputs as a result of spring snow melt or flash floods.

Historically, Colorado pikeminnow occurred throughout the warmwater reaches of the Colorado River basin, including the Green, Colorado, and San Juan subbasins of Wyoming, Colorado, Utah, and New Mexico; downstream through the Colorado River mainstem in Arizona, Nevada, California, and Mexico; and the Gila River subbasin in Arizona and New Mexico. In the lower Colorado River basin (LCRB or 'lower basin') downstream of Glen Canyon Dam, the construction of dams and water projects diverted river flows, fragmented river reaches, reduced peak flows, dewatered some reaches, and channelized the river starting in the early 20th century. As a result of extensive water development and modified hydrology and resultant habitats, Colorado pikeminnow were extirpated from the LCRB by the 1960s. In the upper Colorado River basin (UCRB or 'upper basin'), including Lake Powell and its tributaries, the construction of large dams and diversions was more diffuse, leaving longer reaches of river available in downstream areas. Dams converted sections of rivers to coldwater tailraces, altered hydrology through reduced spring peaks, and presented barriers to migration. Nonnative sport fishes were also introduced into reservoirs and riverine habitats throughout the entire Colorado River basin; these species both compete with and prey upon Colorado pikeminnow. In the UCRB, Colorado pikeminnow populations exhibit contracted ranges and reduced abundances in the Green and upper Colorado river subbasins, and were functionally extirpated from the San Juan River subbasin. Population declines and extirpation from the LCRB, resulting from flow and habitat modifications and the impacts of nonnative species, led to Colorado pikeminnow being included in the 1967 List of Endangered Species and the original 1973 Endangered Species Act.

Two recovery programs were established to enhance populations of the Colorado pikeminnow, one for the Green and upper Colorado subbasins, and one for the San Juan River subbasin. The Upper Colorado River Endangered Fish Recovery Program (UCREFRP) was established to maintain and recover wild, self-sustaining populations of Colorado pikeminnow in the Green and upper Colorado rivers and their major tributaries. The San Juan River Basin Recovery Implementation Program (SJRIP) has reintroduced Colorado pikeminnow through an augmentation program, with the goal of establishing a wild, self-sustaining population that is not dependent on stocking. An experimental, non-essential population of Colorado pikeminnow was also designated in the Salt and Verde rivers of the Gila River subbasin, but individuals stocked into these two tributaries since the 1980s do not appear to have established a population. The SSA examines the current and future status of Colorado pikeminnow analysis units and their habitats in the Green, upper Colorado, and San Juan river subbasins. The SSA also describes and summarizes habitat conditions in the LCRB reaches of the Grand Canyon, lower Colorado River mainstem, and the Gila River subbasin, but no demographic information is available for these extirpated populations to make an assessment of future viability in these reaches. Despite potentially suitable habitat factors, any analysis unit where the species is extirpated was considered to be in an overall extirpated condition.

Species Needs

The SSA considers the species' needs during discrete life stages: spawning adults, egg and larvae within spawning substrates, age-0 and juvenile fish in nursery habitats, sub-adults, and adults. Because of Colorado pikeminnow's complex life history, each life stage has specific and often unique resource needs. The SSA summarizes the following resources which were considered to most influence species viability:

1. Variable flow regimes, specifically peak flows to maintain channel complexity and spawning habitats
2. Base flows to provide suitable nursery habitats
3. Suitable water temperatures for spawning and growth

4. Complex, redundant riverine habitats that provide a combination of the necessary elements of spawning, nursery, and foraging areas
5. Abundant, suitable forage base
6. Population size and demographic rates
7. Multiple naturally recruiting and resilient populations
8. Genetic and behavioral diversity

Stressors and Conservation Measures

The SSA also identifies and describes ecological stressors that impact the species, as well as conservation measures that mitigate those stressors. The stressors identified are reductions to natural flow regimes, water temperature depression as a result of hypolimnetic releases from large dams, physical barriers to movement and the resultant loss of habitat and connectivity, entrainment into water diversion facilities, nonnative fish competition and predation, contaminants, channel simplification, and climate change. Conservation measures that mitigate these stressors are the implementation of flow and temperature recommendations, installation and operation of fish passages, exclusions from entrainment into water infrastructure, nonnative fish management, and population augmentation.

Current Condition

The SSA determines the current condition for Colorado pikeminnow by examining the individual, population, and species needs, and analyzing their availability and suitability within the context of current stressors and conservation measures mitigating those stressors. The SSA assesses current condition for six analysis units based on geographic subbasins. Analysis units are delineated by dams and reservoirs, and further refined by reaches where population size is estimated and demographic processes are thought to be largely independent. These analysis units are the Green, upper Colorado, and San Juan river subbasins in the UCRB, and the Grand Canyon, Gila River, and lower Colorado River mainstem reaches in the LCRB. The SSA summarizes current condition of demographic variables as a measure of species resiliency, and assesses habitat factors that provide for the species' needs. Rankings of current conditions are a result of compiling recent data and measuring those summary data against criteria developed by a technical team of experts from each of the three subbasins where Colorado pikeminnow still occur. The ranking system categorizes demographic and habitat factors into high, medium, low, or functionally extirpated rankings based on the pre-determined criteria. A high ranking indicates the factor either met delisting criteria (demographic factors) or represented the best condition to support species viability based on available data. A functionally extirpated ranking indicates a factor was not suitable or available to support a resilient, viable population. Low and medium categories are intermediate rankings indicating incremental conditions between high and extirpated.

For subbasins in the upper Colorado River basin, overall current conditions for demographic factors were low in all three analysis units (Table EX1). Since the initiation of robust monitoring, approximately the last two decades, the Green River subbasin has had the largest population of adult Colorado pikeminnow consisting of wild fish that have not been supplemented by stocking, except in isolated instances for experimental purposes. Spawning has been documented annually at two sites in the Green and Yampa rivers, with variable larval production and transport linked to river conditions. Recruitment to the age-0 juvenile stage has been low compared to the period before 2000 in the middle Green River and variable in the lower Green River, with the declining adult trend attributed to a lack of recruitment. While adult abundance has been relatively high, exceeding downlisting criteria in some years, population estimates have been declining since about 2000. Based on low adult numbers in the most recent abundance estimates (2016-2018), efforts to collect and develop a broodstock for possible future augmentation have been initiated.

In the upper Colorado River subbasin, the wild adult population consists of several hundred individuals, but this population has also been declining in recent years. Captures of age-0 fish indicate spawning occurs annually, but recruitment is generally low with at least one infrequent "spawning spike" documented where juvenile abundance was an order of magnitude higher than previously collected data. While broodstock development is also underway for this population, the need for augmentation is not clear at this time.

The San Juan River subbasin consists of adult fish resulting from augmentation efforts after the wild population of Colorado pikeminnow was nearly extirpated in the late 1990s. Adult abundance has only recently been estimated; estimates indicate a relatively small adult population comprised of stocked individuals, which appears to be increasing in the last few years. Reproduction has been documented annually since 2013, with increasing catch rates of larval fish, but recruitment of wild fish beyond their first year appears to be limited. Currently, the available data suggest persistence of Colorado pikeminnow in the San Juan River is reliant on stocking.

Since their extirpation in the 1970s, Colorado pikeminnow in the lower Colorado River basin have only been reintroduced as a nonessential, experimental population in the Gila River subbasin, specifically in the Verde River. Fish were stocked in the upper reaches of the Gila River subbasin starting in the mid-1980s, but survival of these fish has been low and of limited duration. As a result, Arizona Game and Fish Department stocked the remaining Colorado pikeminnow from their Bubbling Ponds Hatchery in 2018, and has no plans to continue stocking in the future. With the low survival of stocked fish and lack of subsequent captures, this population is considered to be functionally extirpated. No Colorado pikeminnow have been documented downstream of Glen Canyon Dam since the mid-1970s.

Table EX1. Current condition of demographic factors for six analysis units of Colorado pikeminnow. Ø denotes functionally extirpated. Definitions and rating criteria are described in detail in Table 20 and Section 5.1.

Analysis unit	**Wild reproduction**	**Wild recruitment to sexual maturity**	**Adult Abundance**	**Long-term Population Trajectory**
Green River subbasin	MODERATE	LOW	LOW	LOW
Upper Colorado River subbasin	HIGH	HIGH	LOW	LOW
San Juan River subbasin	LOW	**Ø**	LOW	MODERATE
Colorado River, Grand Canyon	**Ø**	**Ø**	**Ø**	**Ø**
Lower Colorado River mainstem	**Ø**	**Ø**	**Ø**	**Ø**
Gila River subbasin	**Ø**	**Ø**	**Ø**	**Ø**

This SSA also assesses habitat factors to determine if the resource needs of Colorado pikeminnow are being met and the effects of conservation measures in addressing those needs. The assessment includes a summary of habitat factors for both the UCRB, where the species still occurs, and the unoccupied LCRB to determine if the remaining reaches of river could potentially support Colorado pikeminnow (Table EX2). The Green River subbasin ranks high for habitat conditions. As a result of being the least regulated subbasin, the Green River subbasin maintains variable peak flows from tributary inputs, and provides prescribed peak and base flows through the U.S. Bureau of Reclamation's reoperation of Flaming Gorge Dam (as per their 2006 Record of Decision). The Green River subbasin also possesses complex habitats, encompasses two major tributaries with a large extent of connected, warmwater riverine habitat, and provides at least two independent spawning sites located upstream of corresponding nursery reaches with extensive backwater habitat. Despite these habitat attributes, the Green River subbasin also has multiple problematic nonnative fish species in high densities that pose competitive and predatory risks to Colorado pikeminnow of various ages from larvae to adults. For the upper Colorado River subbasin, the overall habitat factor condition is moderate. This rating resulted from peak flows, water temperatures, the extent of available riverine habitat, and forage base being suitable to some extent, but not provided consistently in recent years. Base flows that provide nursery habitat and larval transport are suitable to support recruitment in most years. The San Juan River subbasin also has an overall moderate rating for habitat factors. Water temperatures and nonnative fish impacts are generally considered to be conducive to Colorado pikeminnow population resilience, but peak flows sufficient to maintain channel morphology and the extent of connected, complex riverine habitat have occurred less frequently than anticipated over the last 20 years. These high flows are also associated with creating and maintaining backwater habitats that are important nursery habitats of the species. As a result, this factor is considered to be in a moderate condition.

In the LCRB, extensive modification of the Colorado River and its tributaries during a dam construction period in the 1930s to 1960s led to drastic changes in flow, water temperature, and connected riverine habitats. Both the lower Colorado River mainstem and the Gila River subbasin are considered unsuitable for Colorado pikeminnow in several key habitat features. Peak and base flows are highly regulated and do not resemble historical flow regimes that were variable and functioned to maintain and create key habitats. These reaches are also characterized by shorter lengths of riverine habitat separated by dams and their impoundments, which frequently create cold, tailwater reaches that do not provide suitable water temperatures for spawning or growth of young Colorado pikeminnow. In addition, multiple species of nonnative fishes inhabit the river in sufficient densities to pose significant threats to Colorado pikeminnow and reduce densities of all native fishes. In the Gila River subbasin, these nonnative species are implicated as an impediment to re-establishing Colorado pikeminnow, and similar effects have been observed for razorback sucker in the lower Colorado River. Finally, large reaches of the lower Colorado River are channelized and armored, all but eliminating nursery habitats for young Colorado pikeminnow. These two rivers may provide suitably warm water temperatures in some reaches, but the lack of other key habitat features makes their overall suitability low. The Grand Canyon reach of the Colorado River ranked moderate for habitat factors. While peak flows and base flows are not managed in consideration of Colorado pikeminnow needs, recent warming of water temperatures and large increases in native fish abundance, particularly in the western Grand Canyon, have improved the suitability of this river reach. This segment of river is also relatively long, and has some tributary habitat, but the upstream extent is likely cold for most life stages of Colorado pikeminnow, and it is not clear to what extent spawning and nursery habitats might be available.

Table EX2. Current condition of habitat factors for six analysis units of Colorado pikeminnow. Green represents a high condition, yellow denotes moderate, and orange indicates low condition. Ø denotes functionally extirpated. Definitions and rating criteria are described in detail in Table 28 and Section 5.4.

Analysis Unit	Peak flows	Base flows	Water temperature	Complex, redundant habitat	Forage base
Green River subbasin	HIGH	MODERATE	HIGH	HIGH	LOW
Upper Colorado River subbasin	MODERATE	HIGH	MODERATE	MODERATE	MODERATE
San Juan River subbasin	LOW	MODERATE	HIGH	LOW	HIGH
Colorado River, Grand Canyon	LOW	LOW	MODERATE	LOW	HIGH
Lower Colorado River mainstem	Ø	Ø	HIGH	Ø	Ø
Gila River subbasin	Ø	Ø	HIGH	LOW	Ø

When demographic and habitat factors are combined, the overall condition scores are similar to those based on averaging demographic factors alone. The Green and upper Colorado river subbasins still ranked “moderate” with the San Juan River subbasin ranking “low,” despite generally higher habitat factor rankings for all three units (Figure EX1).

The species is spread across three populations in the upper basin, contributing to redundancy, although extirpation in the lower basin limits the species’ geographic distribution compared to its historic range. Genetic data indicate Colorado pikeminnow are genetically similar in the Green and upper Colorado rivers. The San Juan River population is augmented with offspring produced by fish collected from the Colorado River, and the genetic composition of that river basin reflects that origin. In short, Colorado pikeminnow from the San Juan River are closely related to the upper Colorado River broodstock. The species also exhibits some diversity in behavior, with both migratory and localized spawning displayed across the three remaining populations. The Green River basin fish display more migratory behavior, moving to specific spawning reaches each year, whereas individuals in the upper Colorado River spawn in more diffuse areas closer to their home ranges. Adults in the San Juan River basin exhibited both types of spawning behavior before the species declined in that system. Fish in the Green and upper Colorado subbasins can move freely between the two units as evidenced by recapture data, and genetic studies suggest this occurs frequently enough that the two populations do not exhibit significant genetic differentiation. The San Juan River subbasin is largely isolated from the other units by long distances of reservoir habitat and the presence of an impassable waterfall near its downstream inflow into Lake Powell.

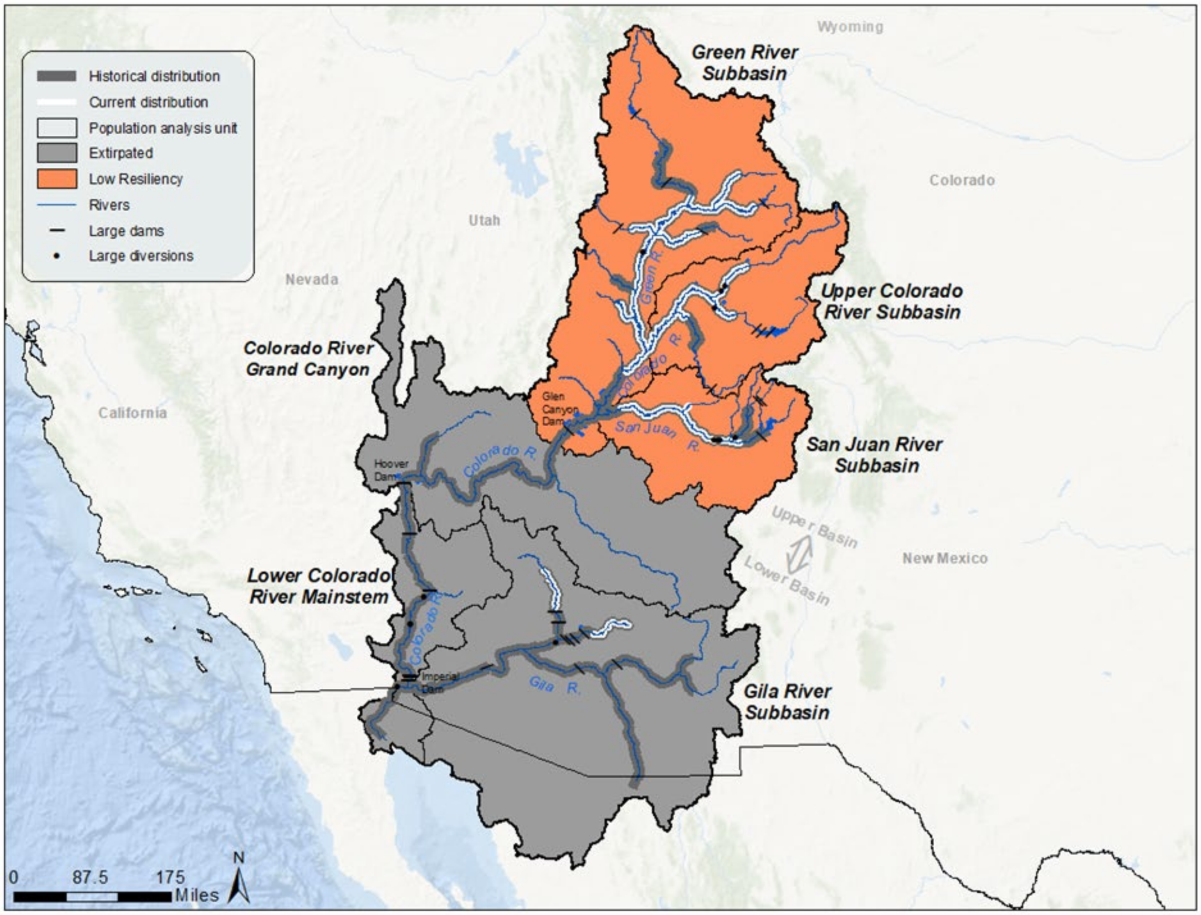


Figure EX1. Historical and current distribution of Colorado pikeminnow in the Colorado River basin. Analysis units are colored based on overall condition derived by averaging condition ratings.

Future condition

Future conditions for Colorado pikeminnow were evaluated using population viability analysis (PVA) projections for the occupied units (i.e. upper basin) utilizing input from a panel of experts. The PVA analyzed past adult abundances, and their relationship to underlying demographic rates, to project future adult abundances under multiple future scenarios (Miller, P. S. 2018). While these models did not explicitly include habitat factors, they did change demographic rates based on relationships observed for specific habitat conditions. For example, the PVA modeled a reduction in reproduction and recruitment based on observed relationships between base flow management and age-0 fish densities in nursery habitats, and the projections incremented demographic parameters based on the frequency of achieving base flows that improved age-0 densities. In other instances, relationships between a habitat factor and demographic rates were not known (i.e. nonnative fish reduction), so demographic rates were adjusted to reflect a presumed response to conservation actions. Models for the Green and upper Colorado river subbasins included what was termed “single” and “dual” phase dynamics based on observed abundances of adults, which showed an increasing trend in early years, followed by a decline in the recent period. The single-phase models treated annual fluctuations in adult abundance as variability around a long-term decline. The dual phase dynamic assumed the initial population growth followed by subsequent decline reflected actual population trends and a corresponding change in underlying demographic rates. The SSA examines population responses over a forty-year period, based on an average generation time of thirteen years and extending the analysis over three generations to detect trends in abundance. The PVA models extended to 100 years into the future, which the SSA briefly summarizes, but predicting habitat changes and conservation measures that far into the future produced a high level of uncertainty in the projections. Based on the extent and magnitude of water development in the lower basin, and recent decision documents related to the management of that system, the assessment concludes habitat conditions in the lower basin will largely persist unchanged, and those analysis units will remain extirpated.

For this SSA, models from the PVA are selected to include a range of future scenarios. The scenarios include a status quo projection (Scenario 1), a reduction in conservation (Scenario 2), a slight increase in conservation based on the effective implementation of current management actions (Scenario 3), and a significant increase in conservation where multiple management actions occur in concert with success (Scenario 4). The SSA predicts future conditions based on the 40-year projections from the PVA, and the condition of underlying demographic factors that would produce predicted trends. The overall future condition for each scenario resulted from averaging ratings across the demographic factor conditions.

- Scenario 1: Recently observed trends in adult abundance and the underlying demographic rates that produce them continue into the future— For the Green and upper Colorado river subbasins this scenario assumed the frequency of recent base flow management and the resulting reproductive output observed for those flows would continue. Therefore, age-specific mortality rates remain the same as those derived from observed trends in adult abundance. Carrying capacity, which was estimated from the highest observed adult estimates in each basin, remains constant. Although the PVA identified specific management actions or stressors that could influence these demographic rates, changes in reproduction, mortality, or carrying capacity could be the result of any of the factors discussed as stressors or actions intended to reduce their impacts. The upper Colorado River subbasin models included varying levels of "spawning spikes" occurring into the future. The "spawning spikes" were based on an event observed in 2015 where age-0 abundance was significantly higher than previously documented. For the San Juan River projections, stocking continues at current levels (400,000 age-0 fish annually), and age-specific mortality rates do not change. For this scenario, all of the extant analysis units in the upper basin are predicted to rate as a low condition, with reduced representation and redundancy similar to current conditions.

- Scenario 2: Conservation measures for Colorado pikeminnow are reduced in their implementation or effectiveness— This could result from a new stressor emerging or increasing effects from existing stressors, a lapse in authorizing legislation or reduced funding for recovery programs, or a reduction in the implementation or effectiveness of management actions. Scenario 2 was not modeled in the PVA, but assumes lower abundance for adults and lower demographic rates than the status quo scenario. The status quo projections incorporated generally low demographic rates and predicted long-term declines. A reduction in these rates would be expected to exacerbate those declines and lead to the functional extirpation of all three upper basin analysis units. This scenario predicts that individuals will persist in the three extant units, but the processes necessary to support viable populations would diminish to ineffective levels. Redundancy and representation would also be reduced for this scenario.

- Scenario 3: Slight increases in the implementation or effectiveness of existing management actions improve underlying demographic rates— This scenario incorporates pairs of actions currently being implemented throughout the basin, and assumes these actions result in a population response. For the Green River subbasin, the PVA modeled improved reproduction and recruitment to age-0 as a result of preferred base flows being implemented more frequently. The Green River projection also increased survival for all age classes as a result of more effective nonnative fish management and reduced entrainment into an irrigation canal system. The upper Colorado River subbasin models maintained current base flow regimes, which appear to be within the preferred range for age-0 recruitment, and improved survival for ages 0-4. This projection also increased carrying capacity based on more effective fish use of passages to expand the currently occupied range. Models for the San Juan River subbasin included increased reproduction, improved survival through age-4, and continued stocking at current rates. While the PVA attributed changes in demographic rates to specific management actions based on observed relationships, it is important to note that increased reproduction, recruitment, and survival could be the result of many management actions or improved resource conditions. In some cases it is not clear to what extent a management action may need to occur to produce the modeled demographic response. The result of these improvements in demographic rates is a high rating for the Green and upper Colorado units' condition, and a low condition for the San Juan River subbasin unit, largely due to the reliance on stocking to maintain a population. Redundancy for this scenario would remain unchanged from the current condition, and representation would improve with more individuals throughout the current range.

- Scenario 4: Significant increases in conservation result from the successful implementation of multiple management actions in concert— For the Green River subbasin, this included higher rates of reproduction and recruitment to age-0 at more frequent intervals, and improved survival across all age classes. Models for the upper Colorado River subbasin included the continuation of occasional "spawning spikes" where age-0 abundance is significantly higher than the mean densities typically observed. The upper Colorado River models also increased survival of ages 0-4 and increased carrying capacity. San Juan River projections were based on estimates of demographic rates that would be necessary to maintain the population in the absence of stocking. These changes included increased reproduction, higher rates of recruitment to age-0, and improved survival for juvenile through sub-adult fish, but as noted above for Scenario 3, it is not clear exactly what level of management actions would produce the modeled demographic rates. Given the assumptions described above, the projections for this scenario resulted in a high condition for all three analysis units in the upper basin. Under this scenario, representation would improve across the upper basin with more individuals in all three populations. Redundancy would also improve with a larger, more viable San Juan River population in addition to those in the Green and upper Colorado rivers.

In summary, the assessment of potential future scenarios produced a wide range of possible outcomes for Colorado pikeminnow within its current range, from improvement in condition for all extant populations to functional extirpation of the species (Figure EX2). Despite ongoing efforts to recover the species in rivers of the upper basin, populations in the Green and upper Colorado rivers have declined in recent years. Augmentation efforts in the San Juan River have prevented the extirpation of Colorado pikeminnow in that basin, but the current population appears to rely on continued stocking of large numbers of fish. A continuation of these recent trends and underlying demographic parameters suggest the species will be in a low condition across the upper basin, which represents approximately one-third of its former range. Reductions in conservation activities or elimination of current recovery programs are likely to result in the species becoming functionally extirpated across its range. Successful implementation of additional management actions could improve the condition of at least two populations in the Green and upper Colorado rivers, with even further improvements in the San Juan River if underlying demographic rates respond to those activities. It is not clear, however, the magnitude or extent of specific management actions that would be required to elicit such population responses.

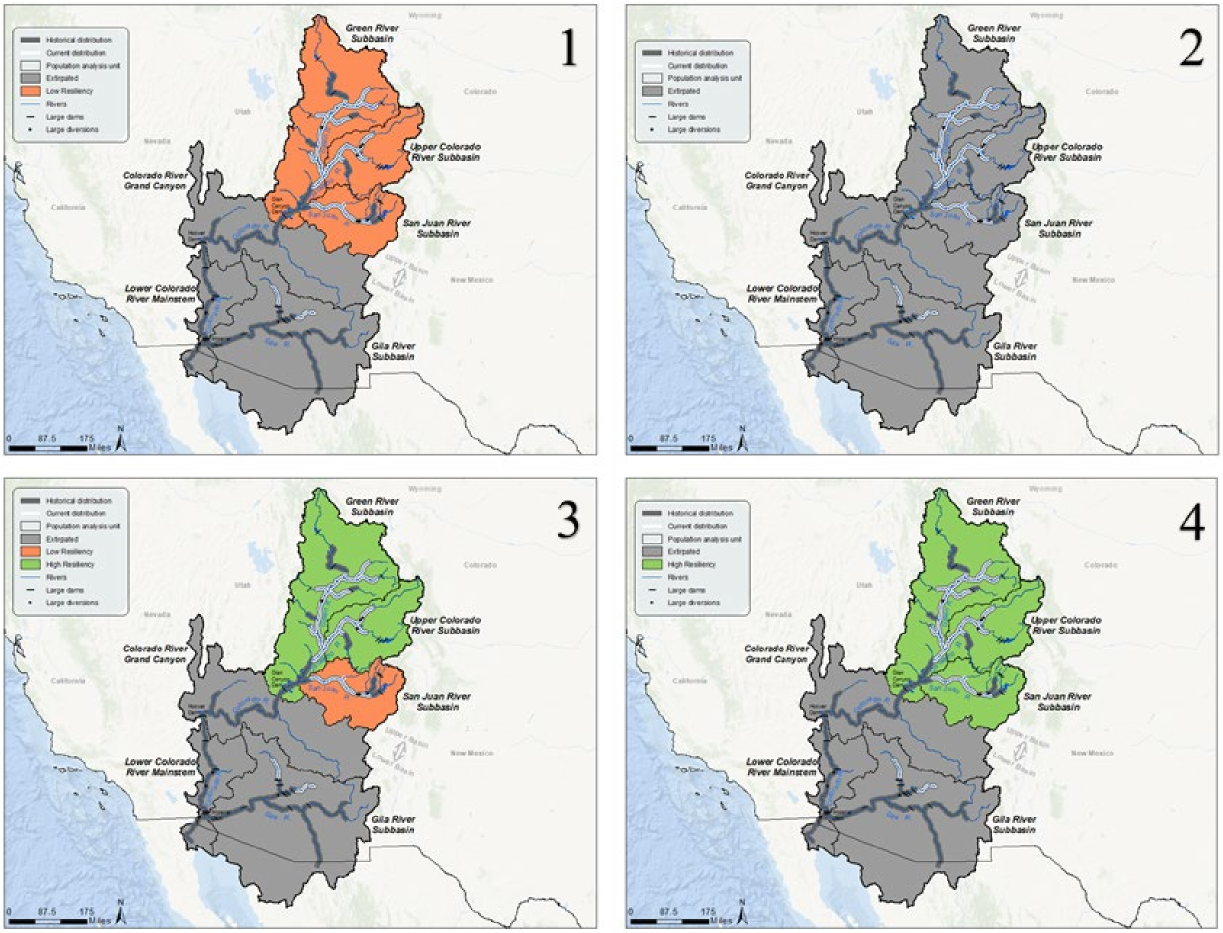


Figure EX2. Overall demographic condition of Colorado pikeminnow analysis units for four future scenarios modeled in a PVA: 1) status quo 2) conservation reduction 3) slight increase in conservation and 4) significant increase in conservation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 – INTRODUCTION

This Species Status Assessment (SSA) was written to support future policy decisions for Colorado pikeminnow *Ptychocheilus lucius* including the next 5-year review and revision to the species' recovery plan. As with all SSAs, this document is intended to provide a clear, in-depth characterization of the species' biology and ecology; the influence of environmental stressors and conservation management actions; current biological status; and projected plausible future scenarios (Smith, D. R. *et al.* 2018). Through a summary of these scenarios, the SSA concludes with a range of potential long-term viability trajectories, while also considering key uncertainties (U.S. Fish and Wildlife Service 2016). This SSA is designed to be a living document and intended to be easily updated as new information becomes available. It is within that context that this SSA is being revised based on input from a panel of species experts convened in 2021. The first version of this SSA relied on demographic criteria from the 2002 Recovery Goals (U.S. Fish and Wildlife Service 2002) to evaluate resiliency within each population. The science panel provided input to refine the metrics being used to evaluate populations, using insights from research and monitoring that has occurred since the Recovery Goals were drafted.

SSAs are structured to inform a variety of policy decisions and documents under the Endangered Species Act of 1973, as amended (16 U.S.C. 35; hereafter ESA) such as recovery plans, 5-year reviews, Section 7 consultations, and classification decisions. Importantly, an SSA itself does not result in a policy decision by the U.S. Fish and Wildlife Service (Service), such as whether a species' status should be changed or what criteria should be in a recovery plan. Thus, this SSA is a stand-alone, science-based document produced independently from the application of policy or regulation and is intended to provide a review of the available information strictly related to the current and future biological status of Colorado pikeminnow throughout its range.

To assess the current and future biological status of Colorado pikeminnow, this SSA first reviews the ecological needs of Colorado pikeminnow at the individual, population, and species level. Population and species ecological needs are expressed using the conservation biological principles of **Resiliency, Redundancy,** and **Representation**, or the 3 Rs (Smith, D. R. *et al.* 2018).

- Resiliency is the species' ability to endure stochastic disturbance, and can be described by abundance and population growth rate. The degree of connectivity between populations can also influence resiliency.
- Redundancy captures the species' ability to withstand catastrophic disturbances by spreading risk over a large area or across multiple populations. A species that is redundant would be comprised of multiple resilient populations spread over the species' range.
- Representation describes a species' ability to adapt to environmental conditions over time, and includes the extent of genetic, behavioral, and/or ecological diversity within and among populations.

We use the 3 Rs together to characterize the species' viability (Figure 1). According to the SSA framework, after assessing species needs, we then evaluate the current and future condition of these needs, again using the 3Rs to describe condition. Using the SSA framework, this SSA report:

- First describes the species, its evolutionary history, life-cycle, and historical distribution (Chapter 2);
- Then identifies the resource needs of Colorado pikeminnow, defines the geographic unit for each population's resiliency assessment, and describes how the species' redundancy and representation will be assessed (Chapter 3);
- Then identifies and describes stressors influencing Colorado pikeminnow viability and conservation management actions implemented to mitigate those stressors (Chapter 4);
- Then assesses the current condition of each Colorado pikeminnow population's resiliency and the species' redundancy and representation (Chapter 5); and
- Finally, concludes by identifying plausible future scenarios with projections of each populations' resiliency and the species' redundancy and representation under each future scenario (Chapter 6).

This SSA forecasts the ability of the species to sustain populations in the wild over the next 40 years. We considered 40 years a time frame for which we could predict viability (i.e., 3 Rs) with a reasonable degree of certainty, based on the likelihood of future stressors, conservation measures, and estimates of demographic parameters. We acknowledge that for a long-lived species such as Colorado pikeminnow, forty years represents only three generations and population responses may occur slowly over a longer period. We also present 100-year trends predicted by population viability analyses, but longer future timeframes are inherently more uncertain, particularly in regards to future management actions and potential stressors.

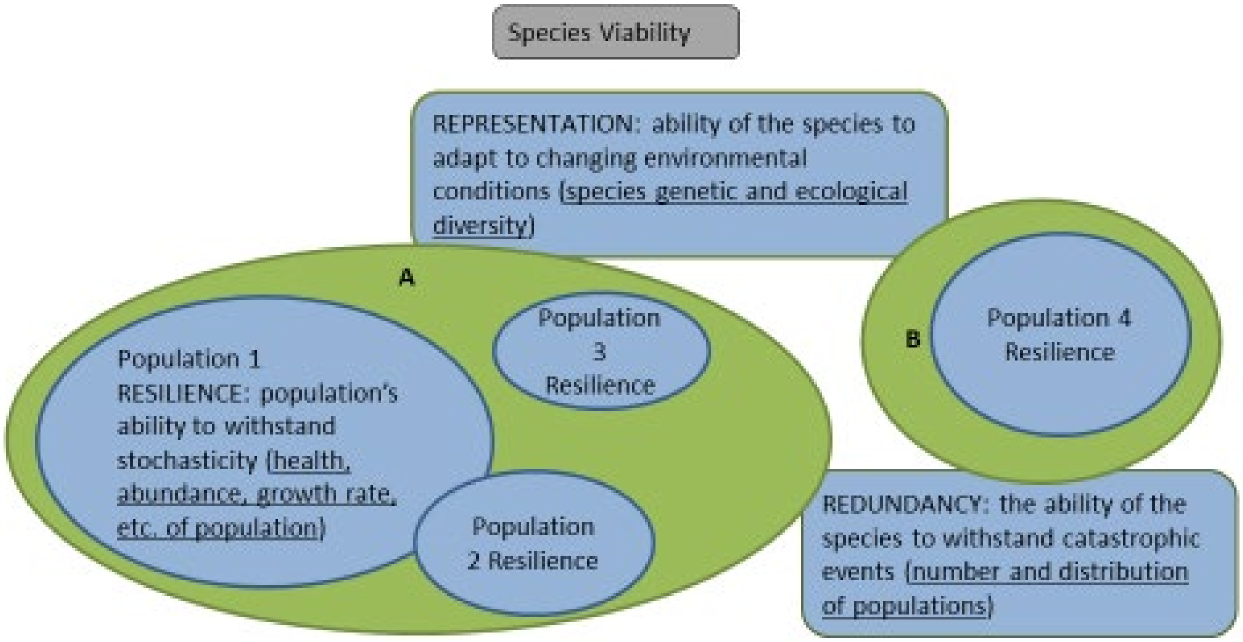


Figure 1. A conceptual model illustration of species viability as a relationship among population resiliency, species redundancy (encompassing metapopulation A and single population B), and representation.

CHAPTER 2 – SPECIES OVERVIEW

2.1 Taxonomy and description

Colorado pikeminnow is a large fish in the family Cyprinidae, commonly referred to as the minnow family. This family is wide ranging, is the most species-rich of the freshwater fish families, and is the second most numerous vertebrate family (Nelson *et al.* 2016). Cyprinidae contains approximately 3,000 species within 367 genera (Nelson *et al.* 2016). Of these species, Colorado pikeminnow is distinguishable as the largest minnow native to North America (Tyus 1991). Within the warmwater reaches of its historical range it likely attained sizes of approximately 1.8 meters (6 feet) in total length (TL) and a mass of 40 kilograms (88 pounds; Miller, R. R. 1961).

Colorado pikeminnow is endemic to the Colorado River Basin of the southwestern United States (Miller, R. R. 1961; Tyus 1991). The species was described in 1856 (Girard 1856) under the common name Colorado squawfish, a name which was revised to Colorado pikeminnow in the 1990s (Nelson *et al.* 1998). It was a source of nutrition for ancient and modern civilizations. Archaeological sites, which date back more than 500 years, contain this fish's bones (Gobalet *et al.* 2005) and the fish was sold commercially in California and Arizona (Minckley 1973; Mueller and Marsh 2002) as "salmon," "white salmon," or "whitefish" (Evermann and Rutter 1894).

This large fish is long and fusiform, or tapered at both ends. Its head can comprise approximately 25 percent of the fish's standard length[1] (SL) and is dorso-ventrally flattened with a long snout that can be approximately 10 percent of the head's length (Girard 1856; Snyder *et al.* 2016). The mouth is terminal with thickened lips and both the lower and upper jaw extend past the middle of the eye. As a member of the cyprinid family, Colorado pikeminnow have teeth behind their mouth on the pharyngeal arch (or gill arch in the throat) rather than in the front on the jaws. The pharyngeal teeth are spaced apart and barely hooked in a typical pattern of 2,5-4,2, meaning there are two teeth in the outer and five in the inner row of the left arch, and four teeth in the inner and two teeth in the outer row of the right arch. Large adults are silvery-white colored with a creamy-white belly and adults in spawning condition may have a light rosy-red tinge on the head. The caudal peduncle, or region between the tail fin and body, is thick with a triangular black patch at the base of the caudal fin in juveniles. The dorsal and anal fins typically have 9 principal rays each. Scales are small, cycloid, and silvery with the lateral line composed of 83–87 scales. Although this is the largest cyprinid in the Colorado River Basin, the average diameter of its eggs (range = 1.9–2.2 mm [0.08 – 0.09 in]) and larvae at emergence (7–9 mm [0.3 - 0.4 in] SL) are relatively small (Snyder *et al.* 2016).

2.2 Evolutionary history

Colorado pikeminnow is a member of a unique assemblage of warmwater fishes. In the Colorado River Basin, it is part of a native fish community which includes 36 species in 20 genera and 9 families. Endemic fish species in this basin account for 64 percent of native species and 35 percent of native genera, comprising one of the highest levels of endemism in North America (Carlson and Muth 1989). Colorado pikeminnow is unusual among cyprinids as adults are thought to be almost entirely piscivorous (feed on other fish species; Vanicek and Kramer 1969),

---

[1] Standard length is measured from a fishes head to the base of the caudal fin.

although some studies do suggest opportunistic feeding on other prey (Tyus and Minckley 1988). For example, roundtail chub *Gila robusta* and humpback chub *Gila cypha*, two sympatric large-bodied Colorado River basin cyprinids, have much more omnivorous and variable diets than Colorado pikeminnow (Vanicek 1967; Vanicek and Kramer 1969; Jacobi and Jacobi 1981).

In general, cyprinids seem poorly adapted for piscivory. With their lack of jaw teeth, relatively small pharyngeal cavity, and lack of a true stomach (de Graaf *et al.* 2010), their morphology potentially makes a predatory existence more difficult. These morphological constraints may explain why, in this highly abundant and geographically wide-ranging family of fishes, specialization in piscivory is rare (de Graaf *et al.* 2010; Vejrík *et al.* 2016). However, Colorado pikeminnow appears to have overcome these morphological limitations, as it was the top native predator in the Colorado River Basin (Minckley 1973; Holden and Wick 1982). Indeed, the predatory pressure that Colorado pikeminnow exerted may have been so great as to drive the evolution of large, nuchal humps (humps behind the head) in two Colorado River basin prey species, humpback chub and razorback sucker *Xyrauchen texanus* (Portz and Tyus 2004).

2.3 Life-cycle

As a fish native to the Colorado River Basin, the life history of Colorado pikeminnow (Table 1 and Figure 2) is intrinsically connected to this snowmelt-driven hydrologic system. In response to large spring peak flows, Colorado pikeminnow can make spawning migrations of hundreds of kilometers to and from spawning areas (Tyus 1990; Irving and Modde 2000). Some individuals may have a strong level of spawning site fidelity as shown by the return of adults to distinct spawning areas identified in the Green and San Juan river subbasins (Tyus 1990; Ryden and Ahlm 1996; Irving and Modde 2000). However, some adults appear to be less specific as spawning sites may vary across years as suggested by observations in the upper Colorado River subbasin (McAda and Kaeding 1991) and by increased longitudinal spawning by stocked fish documented in the San Juan River subbasin (Farrington *et al.* 2018) .

Table 1. Annual seasonal life-cycle by life-stage for Colorado pikeminnow.

<table>
<tr><th>Life stage</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td rowspan="2">Adult</td><td colspan="2"></td><td colspan="4">Migrate</td><td colspan="2"></td><td colspan="3">Migrate</td><td></td></tr>
<tr><td colspan="5"></td><td colspan="3">Spawn</td><td colspan="4"></td></tr>
<tr><td>Egg</td><td colspan="5"></td><td colspan="3">Incubate</td><td colspan="4"></td></tr>
<tr><td>Larvae</td><td colspan="6"></td><td colspan="2">Drift</td><td colspan="4"></td></tr>
<tr><td>Juvenile (age 0)</td><td colspan="8"></td><td colspan="4">Forage</td></tr>
<tr><td>Juvenile (age 1 to <3)</td><td colspan="12">Transition to piscivory and increase forage range</td></tr>
<tr><td>Sub-adult (age 3 to ~6+)</td><td colspan="12">Move between forage areas and establish home range</td></tr>
</table>

Colorado pikeminnow spawn in groups in the summer over areas composed of cobble and gravel that have been recently cleaned by spring peak flows. Males do not control territories or participate in male-male contests (Osmundson, D. B. 2006), and adults do not prepare spawning bars, or build or guard nests (Snyder *et al.* 2016). Colorado pikeminnow broadcast adhesive, demersal eggs, meaning they remain on the river bottom and adhere to the substrate. In appropriate conditions, eggs will settle within the substrate's interstitial spaces where they remain until hatch (Bestgen and Hill 2016a). Given warm water temperatures (18-30°C [64-86°F]) eggs hatch within four to seven days, and recently hatched larvae linger within the interstitial spaces between gravel and cobble for another 4-8 days before emerging into the current. Thus, the incubation period from egg deposition until emergence is relatively long (8–15 days). Larvae at this stage begin to disperse, mediated by the slower summer current. As larvae drift, grow, and develop stronger swimming ability, they tend to occupy low velocity nursery habitat, created and maintained by the river's spring peak flow and inundated by moderate volumes of summer base flow. In these nursery habitats, the larvae prey upon small invertebrates until they transform into juveniles, which is a distinct morphological transition (Figure 2; Snyder *et al.* 2016).

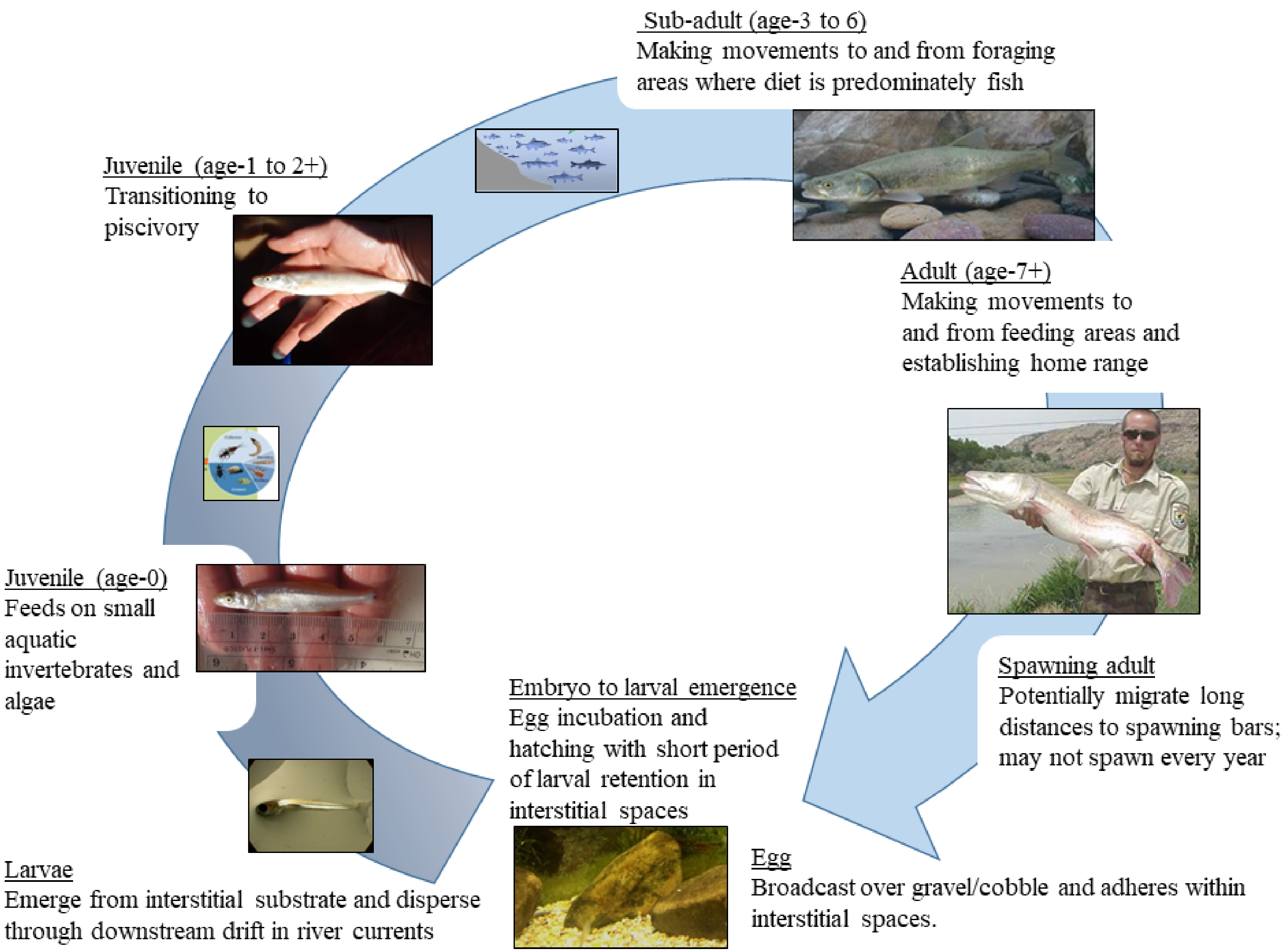


Figure 2. The general life cycle of Colorado pikeminnow (adapted from Bestgen *et al.* 2006).

By the time Colorado pikeminnow larvae transform into juveniles, snowmelt flows have decreased and lower, more stable summer base flows typically dominate, with periodic flash floods from summer thunderstorms. Optimal summer flows will inundate backwater and other low velocity habitats providing these juvenile (age-0) Colorado pikeminnow nursery habitat where they progress to foraging upon large aquatic invertebrates (Vanicek 1967; Jacobi and Jacobi 1981). Because the Colorado pikeminnow is highly piscivorous, age-0 Colorado pikeminnow can transition to consuming fish at an early age (Muth and Snyder 1995). By convention, all age-0 fish are considered age-1 on 1 January. Young Colorado pikeminnow predominantly consume aquatic invertebrates until they are approximately 100 –150 mm (4 - 6 in) TL (Vanicek and Kramer 1969) after which they begin a transition to piscivory. As shown in Table 2, Colorado pikeminnow from the San Juan River appear to attain larger sizes at the same age. This is either due to age-0 fish being stocked at a larger size than their wild counterparts, or warmer water temperatures in the San Juan River (Durst and Franssen 2014). In addition, the transition to becoming fully piscivorous may happen more slowly in the San Juan River and not until after age-2 (Franssen *et al.* 2019).

Table 2. Estimated mean length by age (1–7) for Colorado pikeminnow in the upper Colorado and San Juan river subbasins (Durst and Franssen 2014; Osmundson, D. B. and White 2017a; Osmundson, D. B. and White 2017b).

	upper Colorado River subbasin			San Juan River subbasin		
Age (years)	*N*	Mean total length (mm)	Range	*N*	Mean total length (mm)	95% C.I.
1	73	71.2	50–103	426	177.0	175.2–178.8
2	57	147.9	114–183	247	233.7	227.9–239.5
3	3	232.7	190–259	89	313.3	303.4–323.2
4	6	314.7	267–374	8	379.3	351.4–407.1
5	19	376.2	326–453	1	464	-
6*	10	424.1	375–472	1	550	-
7*	7	456.3	430–479	NA	-	-

* As Colorado pikeminnow grow beyond age-5 assignment of age using length is less reliable (Osmundson, D. B. and White 2017a).

As they become sexually mature (as early as age-6 or 7 at approximately 450 mm (18 in.) TL) and predominantly piscivorous, Colorado pikeminnow make longer movements to foraging habitats comprised of pools, deep runs, and eddies – habitat maintained by high spring flows – and finally establish a home range (Osmundson, D. B. *et al.* 1998). Osmundson et al. (1998) analyzed patterns of Colorado pikeminnow distribution and movement in the Colorado River. They noted that larger fish were more abundant in upstream reaches, while downstream reaches contained larger numbers of juvenile and sub-adults. Other studies noted a similar pattern in both the Green and Colorado rivers (Valdez, Mangan, Smith *et al.* 1982; Tyus 1986). Osmundson et al. (1998) also observed a tendency toward upstream movements, particularly by smaller fish. Adult and sub-adult fish in the upper reach mostly exhibited localized movements less than 10 km (6 mi), and no fish from the upper reach moved downstream. These patterns of movement, in addition to lower body condition in the downstream reaches, led to the hypothesis that adults moved upstream to take advantage of more abundant prey resources. Smaller individuals, however, likely remained in lower reaches to take advantage of warmer water temperatures and abundant small prey to maximize growth.

Although Colorado pikeminnow is currently limited to a cooler portion of its historical range (upper basin rivers), which may result in reduced growth rates and increased age at sexual maturity (Kaeding and Osmundson 1988), general natural history can be surmised from extant populations. The largest female (965 mm [38 in] TL) and largest male (781 mm [31 in] TL) recently captured were both estimated to be 58 years old (Osmundson, D. B. 2006). Age at first reproduction (sexual maturity) appears to vary by sex. While females may have higher growth rates than males, males have been documented to mature earlier (Osmundson, D. B. 2006), as young as age-6 (Vanicek and Kramer 1969). However, it is probably not until age-8 (~486 mm [19 in] TL) that most males become active spawners (Osmundson, D. B. 2006). Females may become sexually mature as early as age-7 but most probably do not spawn until 9–10 years of age (Osmundson, D. B. 2006). Like many freshwater fishes, Colorado pikeminnow is relatively fecund and 9 to 10 year-old females induced to spawn can produce, on average, 77,400 eggs (Hamman 1986). Individuals likely spawn multiple times during a lifetime, and there is evidence they may spawn annually (Tyus 1990; Irving and Modde 2000; Osmundson, D. B. 2006).

2.4 Historical distribution

Colorado pikeminnow's ability to migrate long distances is likely one of the reasons this species was once found throughout warmwater reaches of the Colorado River Basin from as far north as Wyoming downstream to the Gulf of California (Figure 3). In its northern range, Colorado pikeminnow was present throughout the Green, upper Colorado, and San Juan rivers including these rivers' major tributaries (Jordan 1891; Koster 1960; Seethaler 1978; Platania 1990). The most northern documentation of the species was in the Green River at Green River, Wyoming (Ellis 1914; Baxter and Simon 1970). In the upper Colorado River basin, Colorado pikeminnow was documented as being rare to occasional (Vanicek 1967; Vanicek *et al.* 1970; Seethaler 1978), although the species may have already declined before these studies occurred. Jordan and Evermann (1896) described Colorado pikeminnow as "very abundant" in the Gunnison River near Delta, CO, and historic accounts from Quartarone and Young (1995) also suggest the species may have been more common in the early 20th century. In its southern range, individuals were also reported as common to abundant (late 1800s and early 1900s) in the mainstem Colorado River and the Gila River and its tributaries (Kirsch 1889; Jordan 1891; Evermann and Rutter 1894; Gilbert, C. H. and Scofield 1898; Quartarone and Young 1995). In neither the northern or southern range was the species documented in colder headwater reaches.

Colorado pikeminnow abundance and distribution contracted as early as the 1930s because of the construction of large mainstem dams and water diversions (Miller, R. R. 1961; Mueller and Marsh 2002). Most of the species' decline was documented in the lower Colorado River basin[2] (Figure 3), and the period 1935-1938 brought the construction of Hoover, Imperial, and Parker Dams, which created a series of impoundments in the lower reach. By the 1960s, few Colorado pikeminnow were caught in the lower Colorado River basin (Minckley and Deacon 1968; Minckley 1973) and the 1963 construction of Glen Canyon Dam, which created Lake Powell,

---

[2] The Colorado River Compact of 1922 divides the Colorado River into the Upper and Lower basins demarcated at Lees Ferry, Arizona.

prevented movement between the upper and lower Colorado River basins. In the mid-1970s few Colorado pikeminnow were reported from the lower Colorado River basin at which time the species was considered extirpated from this portion of the Colorado River (Moyle 1976; Seethaler *et al.* 1979; Smith, G. R. *et al.* 1979; Suttkus and Clemmer 1979; Minckley 1985; Minckley 1991; Mueller and Marsh 2002). However, since the mid-1990s the Verde River, a tributary in the Gila River subbasin, has been stocked with Colorado pikeminnow (greater than 300 mm [12 in]); these hatchery-reared fish represent the only documented Colorado pikeminnow in the lower Colorado River basin since they were considered extirpated in the late 1970s.

Populations of Colorado pikeminnow in the upper Colorado River basin persist, and wild populations are present in the Green and upper Colorado river subbasins. The Green River subbasin supports the largest population of Colorado pikeminnow (Bestgen *et al.* 2018), and supports two distinct spawning sites and corresponding nursery reaches. The upper Colorado River subbasin also supports a smaller population of wild-spawning fish (Osmundson, D. B. and White 2017b). There is evidence of enough movement between the Green and upper Colorado river subbasins that these populations likely function as a metapopulation and are not considered genetically distinct (Osmundson, D. B. and White 2017b).

In the San Juan River subbasin, Colorado pikeminnow declined concurrently with the construction of Navajo Dam and Lake Powell on the upstream and downstream reaches of this river, and the species was considered nearly extirpated in this subbasin by the late 1980s (Platania *et al.* 1991). Colorado pikeminnow have been repatriated to this subbasin through annual stocking, and the resulting adult population has maintained spawning in the wild. These wild-spawned larvae recently resulted in recruitment to juvenile size (2016–2017; Farrington *et al.* 2018; Zeigler *et al.* 2018). However, because untagged age-0 fish are stocked into the San Juan River each autumn it is not possible to discern between stocked and wild fish. Thus, recruitment of wild-spawned fish to age-1 has yet to be documented in the San Juan River subbasin.

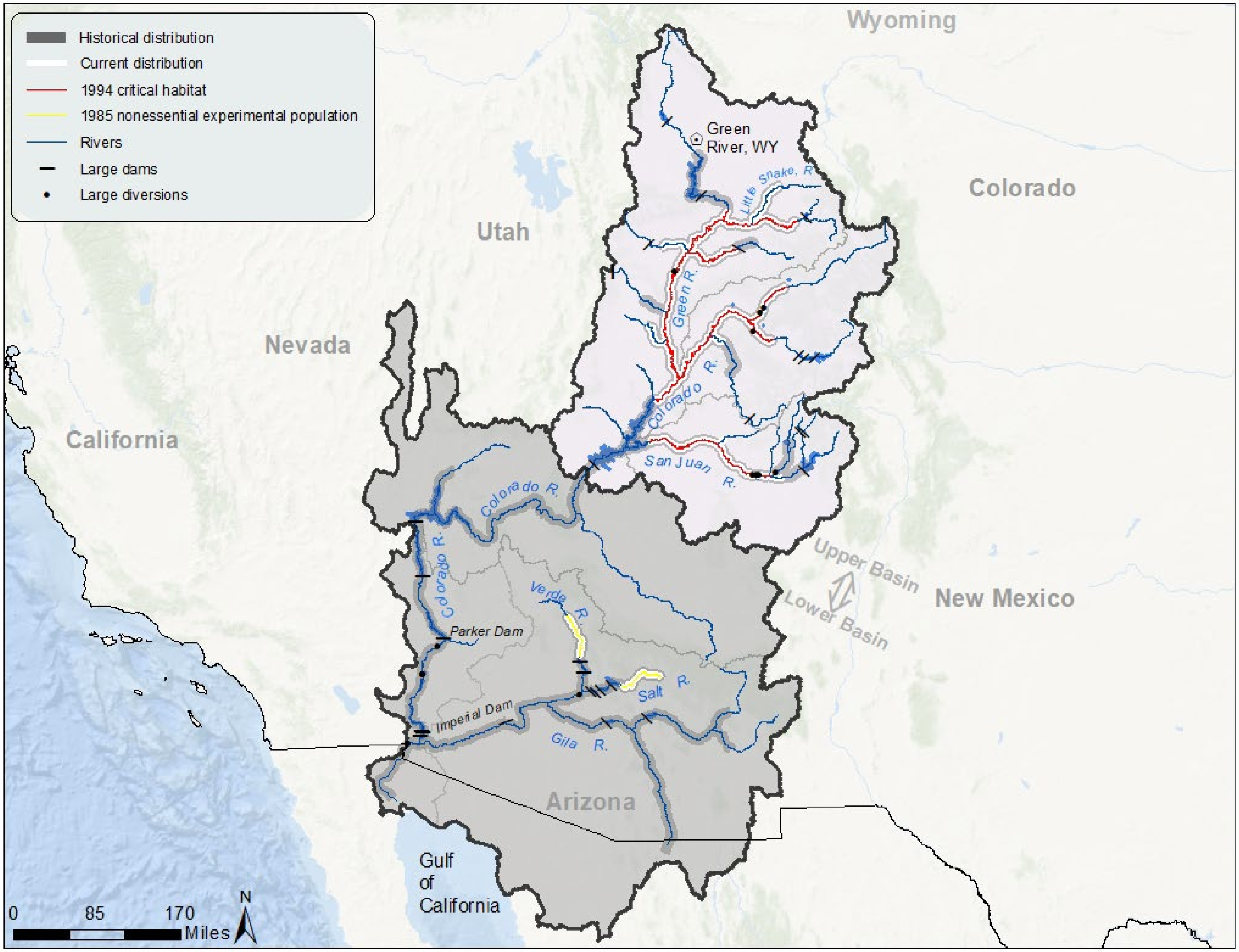


Figure 3. Historical and current Colorado pikeminnow distribution with designated critical habitat and nonessential experimental populations.

2.5 Listing status and recovery planning

Because of range contraction and population declines, Colorado pikeminnow (as Colorado squawfish) was included in the 1967 List of Endangered Species (32 FR 4001; March 11, 1967). Colorado pikeminnow's status remained listed as "endangered" under the Endangered Species Act of 1973, as amended, throughout its historical range in Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming. In the mid-1980s, two experimental, nonessential populations were proposed in the lower Colorado River basin. One was designated for two rivers (Salt and Verde) in the Gila River subbasin (50 FR 30188; July 24, 1985) and another was proposed but not finalized for the mainstem lower Colorado River between Parker and Imperial dams (50 FR 32143; August 26, 1987). In 1994 a total of 1,848 km (1148 mi) of river were designated as critical habitat in three Upper Colorado River subbasins: the Green, upper Colorado, and San Juan (59 FR 13374; March 21, 1994). Critical habitat has not been designated for Colorado pikeminnow in the lower basin. A recovery plan for the species was approved in 1991 and amended by the 2002 Colorado Pikeminnow Recovery Goals (U.S. Fish and Wildlife Service 2002). The most recent 5-year status review was completed in 2020 and recommended that Colorado pikeminnow remain listed as an endangered species (U.S. Fish and Wildlife Service 2020).

CHAPTER 3 – INDIVIDUAL, POPULATION, AND SPECIES NEEDS

The needs of a species can be evaluated hierarchically, starting at the lowest level with an individual animal's basic resource needs for breeding, feeding, and sheltering. These are described in the first section (3.1) of this chapter and include life-stage specific resource needs, such as water temperature required for eggs to hatch and habitat individuals need to be able to access and secure suitable prey. In the next sections, we describe population (3.2) and then species-level (3.3) needs within the context of populations' resiliency and the species' redundancy and representation. Our understanding of individual, population, and species need(s) presented in this chapter were derived from monitoring of and empirical research on Colorado pikeminnow in the upper Colorado River basin since the early 1990s. We do not know if or how these needs deviate from historical condition, and we acknowledge this as an uncertainty (Dayton *et al.* 1998; Pinnegar and Engelhard 2008).

3.1 Individual level needs - resources

3.1.1 Warm water temperatures

Colorado pikeminnow is considered a warmwater species, and temperature thresholds are tied to reproductive phenology and success. Both water temperature and peak spring discharge are predictive of the annual initiation of spawning (Tyus 1990; Bestgen and Hill 2016a) because adults require water temperatures that reach and exceed 16–18°C (61 - 64°F) to develop gametes and successfully spawn (Table 3; Tyus 1990; Bestgen and Hill 2016a). Spring increases in water temperature and declining river flows following the spring peak cue adults to begin spawning migrations (Tyus and McAda 1984; Tyus 1990; Irving and Modde 2000; Bestgen *et al.* 2007; Bestgen and Hill 2016a). As with initiation of adult spawning migrations, warm water is also required for an egg to incubate and hatch: water temperatures between 18-26°C (64 – 70°F) provide the highest likelihood a Colorado pikeminnow egg will successfully hatch (Bestgen and Williams 1994). Age-0 juvenile fish also require warm water temperatures for growth (22-30°C [72 - 86°F]; Bestgen 1996) and a high abundance of prey items (Vanicek and Kramer 1969). Without sufficiently warm water temperatures, survival and growth may be reduced (Kaeding and Osmundson 1988; Bestgen *et al.* 2006) affecting overall recruitment. Given warm water, food, and refuge from river currents, a larval fish may transition into an age-0 fish within two to three months (Bestgen 1996; Snyder *et al.* 2016). Survival from an age-0 to age-1 fish, which occurs over an individual's first winter, depends on the growth rate during its first summer. If an age-0 fish can reach sufficient length prior to winter, it has a higher likelihood of surviving harsh winter conditions than a smaller sized fish (Tyus and Haines 1991; Thompson *et al.* 1991; Haines *et al.* 1998; McAda and Ryel 1999; Kitcheyan and Haines 2004; Bestgen *et al.* 2006). While these studies found some evidence for size-dependent mortality, the relationship was not consistent across years or reaches. Data from the Green and Colorado rivers indicate that backwaters are preferred nursery habitats for age-0 Colorado pikeminnow because they provide the warmer water temperatures necessary for growth, as well as food and refuge from swift river currents.

3.1.2 Peak and base flows—nursery habitat

Once a larval Colorado pikeminnow emerges from the substrate it is transported downstream by river currents. The distance a larval fish drifts is positively related to river flow and thus, for a larval fish to find refuge from the river's flow, it must encounter low-velocity nursery habitats such as channel margins, backwaters, or embayments (shoreline depressions similar to backwaters but facing upstream; Bestgen and Hill 2016a). Low velocity areas of rivers provide important nursery habitat for Colorado pikeminnow because they offer warmer, food-rich environments, and previous studies have shown a preference for backwaters in particular (Tyus and Haines 1991; Day, K. S. *et al.* 1999; Trammell and Chart 1999a; Trammell and Chart 1999b; Day, K. S. *et al.* 2000; Archer *et al.* 2000). A larval Colorado pikeminnow may not remain in a specific nursery habitat and can continue to move in and out of nursery habitats, drifting as far downstream as 160 km (99 mi; Tyus and Haines 1991; Diver and Wilson 2018). Muth *et al.* (2000) specifically described backwaters as one of these habitats and defined them as a "generally shallow area within the river channel with little or no flow that is situated downstream of an obstruction, such as a sand or gravel bar, and that has some direct surface water connection with the river." Bank-attached backwaters form as flows drop from the spring peak and one end of a side channel (usually the upstream end) becomes disconnected from the river flow, but the other end remains connected. This isolation from the flowing water of the river's main channel allows water temperature in the backwater habitat to warm.

Spring peak flows are considered the primary driver in creating backwater nursery habitats in the Colorado River basin (Grippo *et al.* 2017), and strongly influence interannual changes in backwater morphology (Rakowski and Schmidt 1999; Muth *et al.* 2000). Results from testing this hypothesis indicate annual peak flow and duration are predictive of backwater surface area and volume, respectively (Grippo *et al.* 2017; Lamarra, V. A. *et al.* 2018). In the Green River, the annual magnitude and duration of peak flow explained between 48–52 percent of the variation in flows which maximize backwater surface area and volume with a positive but nonlinear relationship (Figure 4; Grippo *et al.* 2017). In other words, as the magnitude or duration of peak flows increased, the flow required to maximize backwater area and volume also increased. In this system, flows that reached approximately 566 m^3/s (20,000 cfs) for approximately 15 days require the highest base flows to maximize both area and volume of backwaters. These data suggest that higher and longer duration peak flows produce larger backwaters since increased base flows are needed to maximize backwater area and depth. This is implied because lower base flows leave some amount of backwater habitat unfilled. Several studies have concluded that decreased peak flow magnitude has resulted in channel narrowing and loss of complexity in the Green River (Allred and Schmidt 1999; Rakowski and Schmidt 1999; Walker *et al.* 2019). A series of low peak flow years can decrease backwater habitat as sediment transport decreases and existing backwaters fill with sediment (Rakowski and Schmidt 1999; Bliesner *et al.* 2009).

Osmundson et al. (1995) recommended peak flows for the 15-Mile Reach of the Colorado River >665 m^3/s (>23,500 cfs) in at least five of every 20 years, based on studies that showed this flow magnitude mobilized sediment to maintain spawning cobble and channel complexity. They also found a peak flow >1133 m^3/s (>40,000 cfs) at the Colorado-Utah state line gage would accomplish similar habitat maintenance functions downstream of the confluence with the Gunnison River and maintain backwaters for juvenile fish. The flow magnitudes identified in Osmundson et al. (1995) were consistent with those identified by Pitlick and van Steeter (1998) as being capable of mobilizing the bed load.

The main stem of the San Juan River has experienced reduced peak flows since the construction of Navajo Dam in 1962. Studies conducted after the construction of Navajo Dam suggest peak flows greater than 227 m^3/s (8,000 cfs) result in an overall increase in backwater areas (San Juan River Basin Recovery Implementation Program 2006; Lamarra, V. A. *et al.* 2018; U.S. Fish and Wildlife Service 2018b). Although the highest peak flows in the San Juan River did not consistently produce the greatest area of backwaters, in some years they resulted in > 80,000 m^2 (> 861,113 ft^2) of backwaters, substantially greater than that associated with lower peak flows (Figure 5; Lamarra, V. A. *et al.* 2018). Also, while higher flows do not guarantee increased total area of backwaters, in general, larger backwaters occurred after higher peak flows.

Peak flows are also important in maintaining channel complexity, which influences the distribution and number of backwaters and other habitat features. If a river channel loses complexity, it becomes characterized by a single channel that lacks backwaters, side channels, islands, and other habitat features important to Colorado pikeminnow. These various habitats contribute to specific life stages at different times.

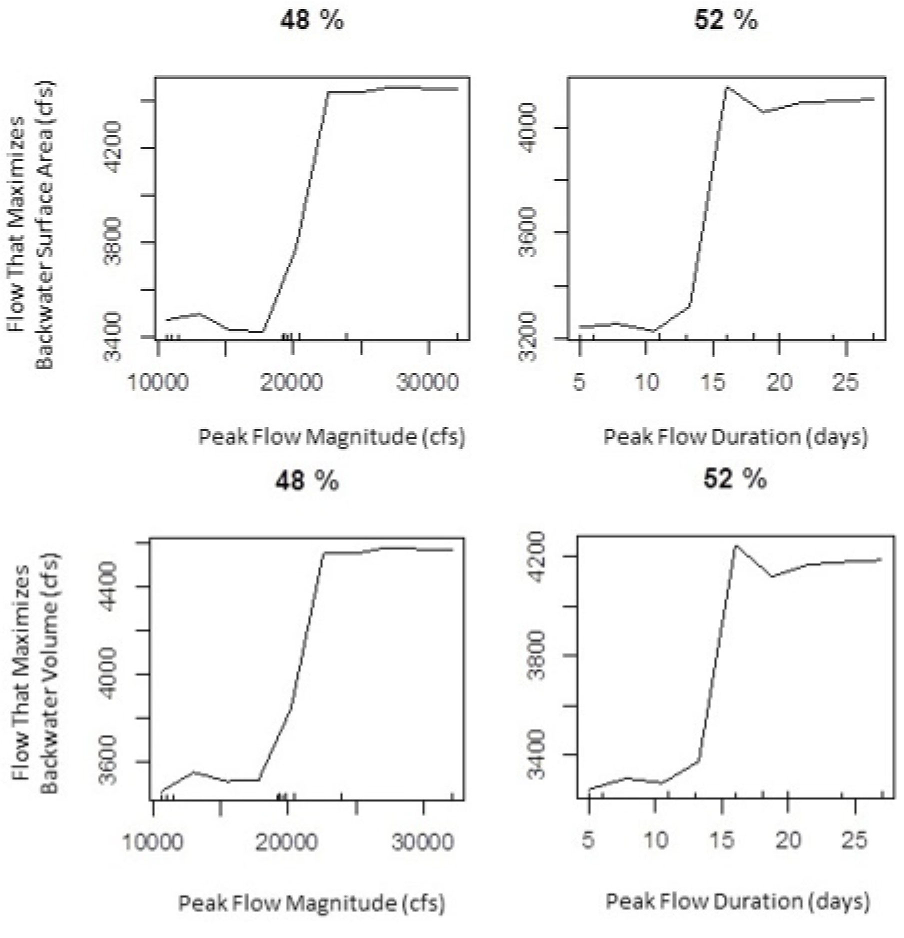


Figure 4. Relationship between peak flow (magnitude and duration) and base flow required to maximize backwater surface area and volume in the Green River (Grippo *et al.* 2017). Percentages above the graphs indicate the relative contribution of peak flow magnitude and duration to the model used.

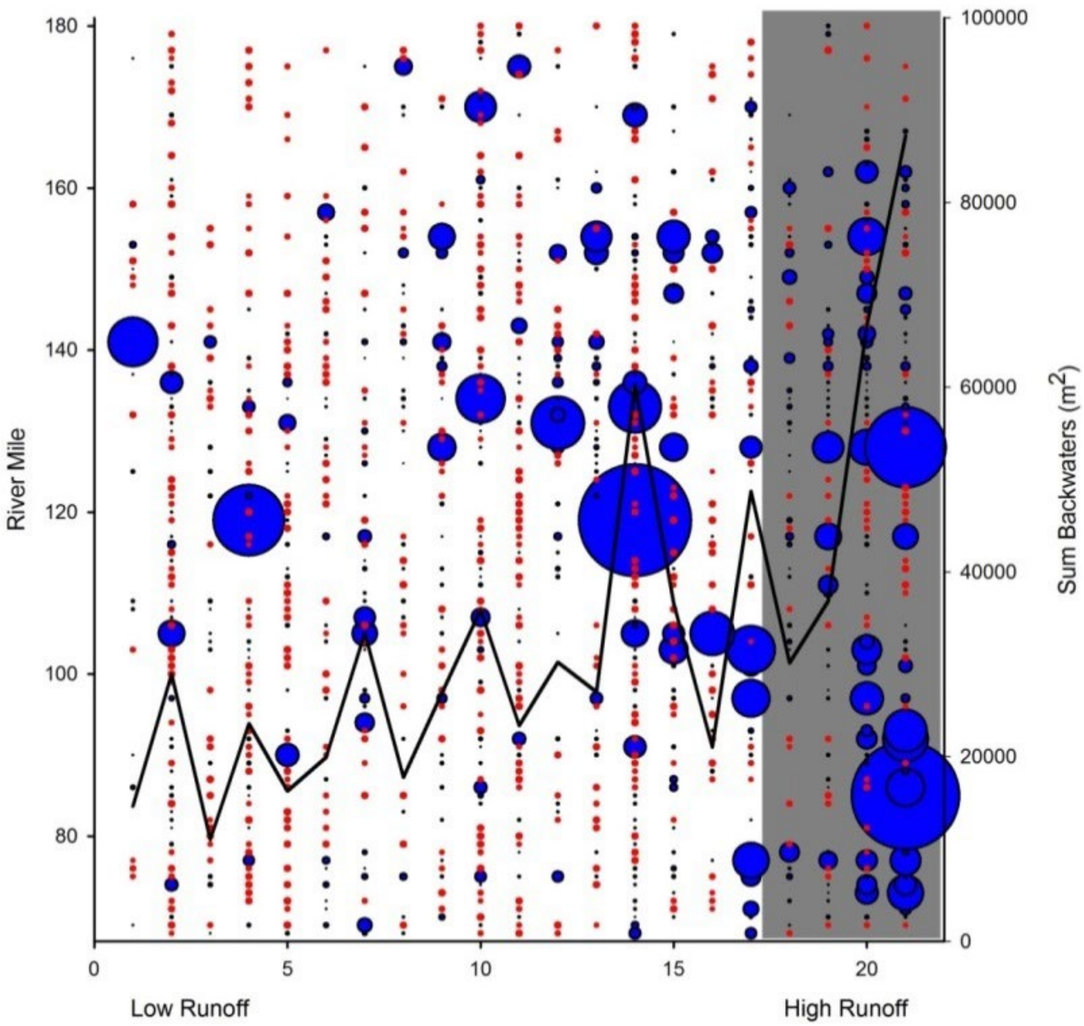


Figure 5. Location (circles) and total area of backwaters (black line) in the San Juan River (1995–2016) ranked by magnitude of spring runoff. Grey bar indicates the four highest spring run off years (i.e., years with >227 m³/s [>8,000 cfs]). Backwaters identified in red are smaller than the average size and those in blue are above average (figure from Lamarra, V. A. *et al.* 2018).

Moderate summer base flows provide backwater nursery habitats (Grippo *et al.* 2017; Lamarra, V. A. *et al.* 2018) and are positively correlated to age-0 Colorado pikeminnow abundance (Figure 6; Bestgen and Hill 2016a). With reduced flows, backwaters can lose water volume and decrease in size. Higher flows often overtop the sandbar margin separating the backwater from the main channel, converting low velocity backwater habitat into a higher velocity channel margin. In the middle Green River, summer flows >28 m³/s (>1,000 cfs) but >85 m³/s (<3,000 cfs) resulted in the highest density of backwaters (Figure 7; Grippo *et al.* 2017), and flows 48 – 85 m³/s (1,700–3,000 cfs) are associated with the greatest density of age-0 Colorado pikeminnow in autumn (Figure 6; Bestgen and Hill 2016a). In the San Juan River, increasing summer base flows from 12 to 42 m³/s (431 to 1,500 cfs; 2002–2013) resulted in a significant increase in the size of backwaters associated with secondary channels as well as an overall increase in the number of flowing secondary channels (Lamarra, V. A. *et al.* 2018). This channel type may be important as it is thought to contain a higher proportion of low velocity habitat than the mainstem. The work by Lamarra (2015) also showed a relationship with increasing base flow and backwater area, with more backwater area produced at flows above 21 m^3/s (750 cfs). These moderate and higher base flows may also support early life-stages of Colorado pikeminnow by reducing the frequency of lower flows that appear to establish conditions more favorable for nonnative species (i.e., smallmouth bass *Micropterus dolomieu* (Bestgen and Hill 2016b) and channel catfish *Ictalurus punctatus*, common carp *Cyprinus carpio*, and red shiner *Cyprinella lutrensis* (Gido and Propst 2012). Base flows are important for maintaining connectivity between river reaches, allowing Colorado pikeminnow to return to their home ranges after spawning and to move between different habitats for foraging. Burdick (1997) used 30 cm (11.8 in) as a minimum water depth required for adult Colorado pikeminnow to pass through shallow riffles and for designing fish passages. Several flow recommendation studies have used this 30 cm (11.8 in) threshold for determining minimum flows to allow passage of adult fish within rivers (Modde *et al.* 1999; Haines *et al.* 2004).

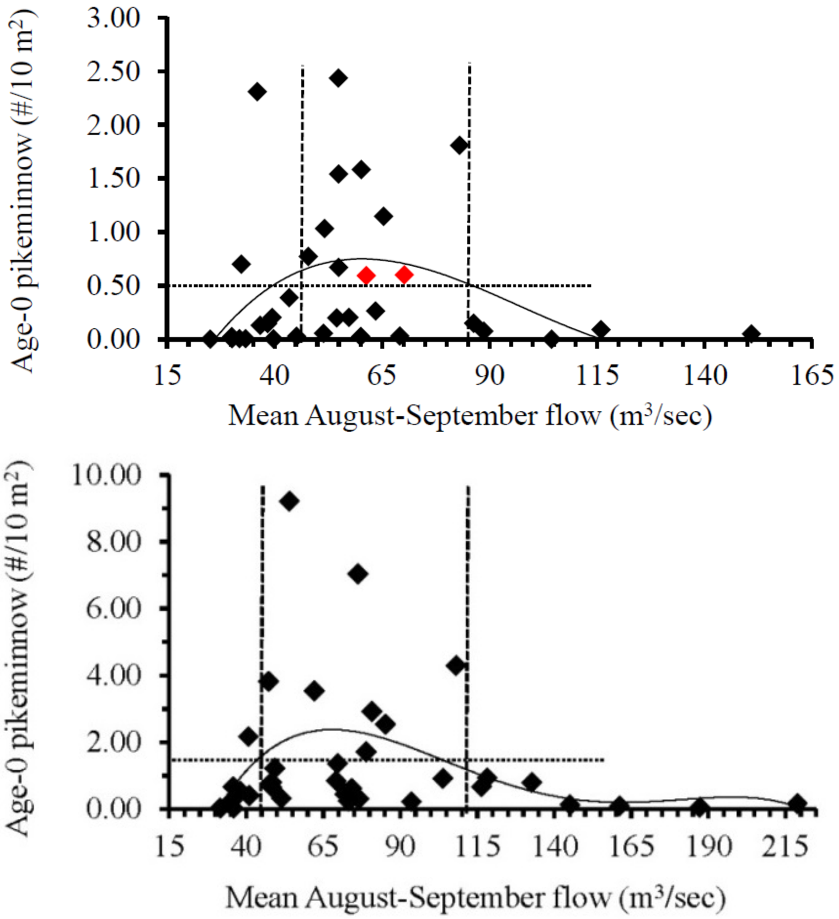


Figure 6. Relationship between summer flow and Colorado pikeminnow age-0 density in the middle (upper panel) and lower (lower panel) Green River from 1979–2012, from Bestgen and Hill (2016a). Red diamonds indicate two more recent years (2009 and 2010) where age-0 densities were above average. Horizontal dashed line indicates long term mean density. Vertical dashed lines bound the range of flows where age-0 densities were more frequently observed to be higher than average.

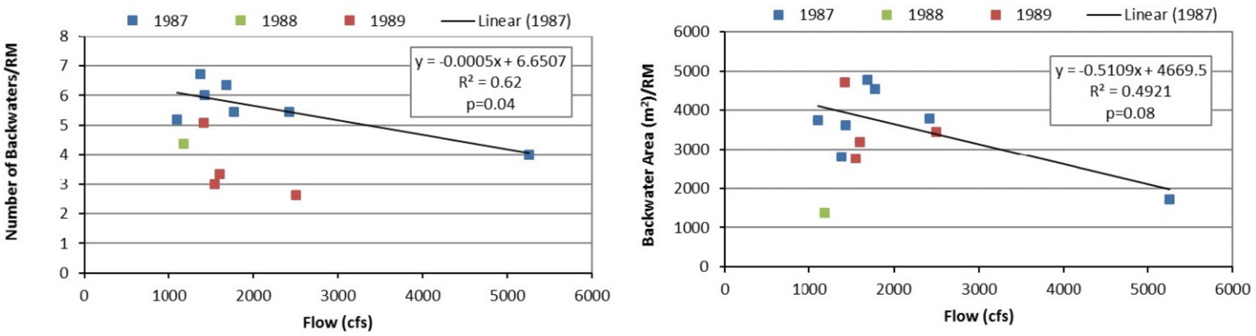


Figure 7. Relationship between summer flow in the Green River (at Ouray), Green River subbasin, and backwater density and area per river mile. Figures from Grippo et al. (2017).

3.1.3 Spring peak flows—spawning habitat and reproduction

High spring flows support reproduction and early life-stage recruitment by cueing spawning and producing adequate spawning habitat (Bestgen and Hill 2016a). Colorado pikeminnow spawn on the descending limb (decreasing later portion) of the peak spring flow, and the timing of the first spawn and peak spawning activity is correlated with the magnitude of the spring peak flow (Nesler *et al.* 1988; Bestgen and Hill 2016a). The detailed processes through which peak flows, as well as other environmental variables such as temperature and photoperiod, regulate the timing of spawning are not fully understood, however, the relationship between peak flow and larval fish abundance is positively correlated (Figure 8; Bestgen and Hill 2016a). The precise mechanism behind this relationship is unclear but is believed to result from the following hypotheses: (1) High spring flows clean and reshape gravel and cobble deposits creating high quality spawning substrate for eggs to adhere (Harvey and Wick 1993); (2) the peak flow's descending limb and base flow transport water through the newly created interstitial spaces, providing oxygen to support embryo incubation and survival; and (3) the descending limb may provide sufficient flow to transport larvae downstream to suitable nursery habitat (Bestgen and Hill 2016a).

Clean cobble and gravel, warm water, and suitable flows are required for a Colorado pikeminnow egg to establish, incubate, hatch, and survive to a drifting larval fish (Table 3). The adhesive property of the egg requires a clean, hard substrate; if an egg cannot attach it is likely lost downstream to die or be consumed by other fish (Bestgen and Hill 2016a). Incubating eggs and pre-emergent larvae also require clean cobble and gravel that allow water to flow through interstitial spaces and provide aeration. Given the aforementioned factors, spawning and hatching require suitable water temperatures, spring peak flows to clean and maintain cobble bars, base flows sufficient to provide water for incubating eggs and larval transport, and river segments of sufficient length and connectivity to provide suitable substrate and access between these sites and home ranges.

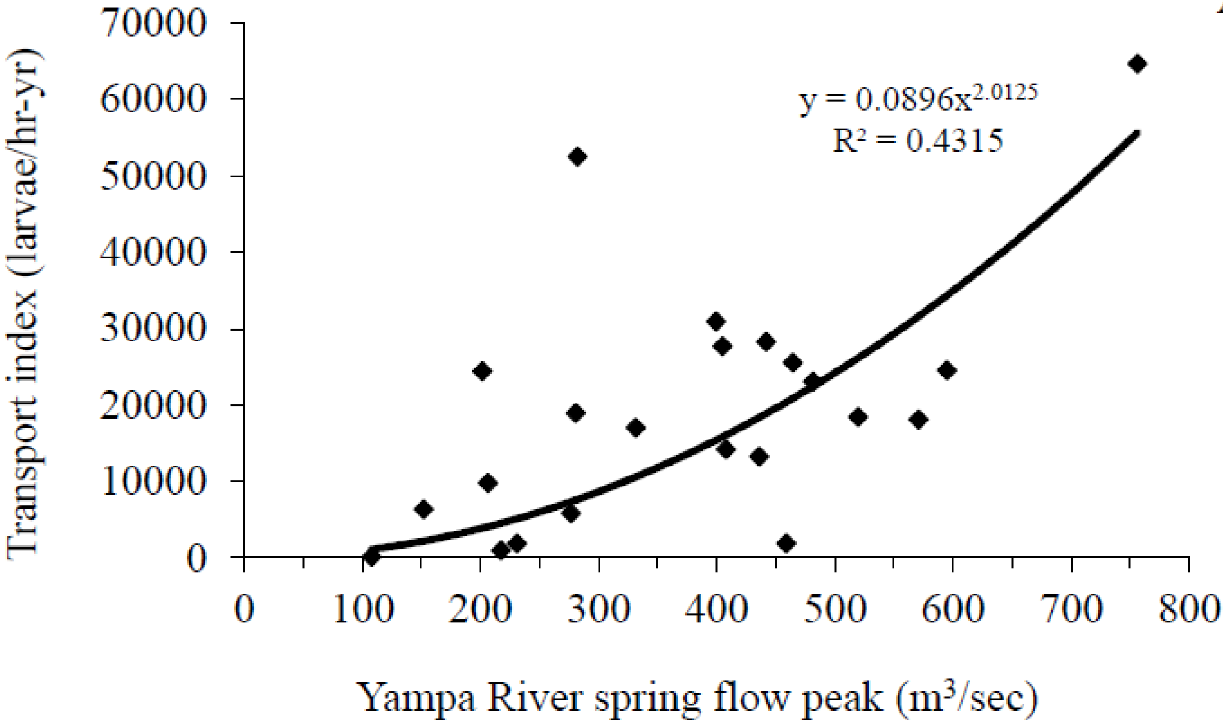


Figure 8. Relationship between peak flow and Colorado pikeminnow larval transport (Yampa River 1990–2012 from Bestgen and Hill 2016a).

Table 3. Individual Colorado pikeminnow life-stage specific resource needs (adapted from Bestgen *et al.* 2006).

Life Stage	Resources and/or circumstances needed for individuals to complete each life stage	Reference
Spawning adult	• Water temperature in late spring/early summer consistently reaches and exceeds 16–18°C (60-65°F) • Free movement to reach spawning areas	• Tyus 1990; Bestgen and Hill 2016a
Egg	• Clean cobble and/or gravel substrate on which to adhere.	• Bestgen and Hill 2016a
Embryo and larva in substrate	• Clean cobble and/or gravel substrate that provide interstitial spaces of moderate water velocities and flow-through of oxygenated water. • Incubation and growing temperature of 18–26°C (65-79°F).	• Bestgen and Hill 2016a • Bestgen and Williams 1994; Bestgen 1996
Larva	• Refuge from main river currents (low-velocity habitat). • Growing temperature of 22–26°C (72-79°F). • Abundant food supply (diatoms, algae, aquatic invertebrates).	• Bestgen and Hill 2016a • Vanicek and Kramer 1969
Juvenile (age-0)	• Stable low-velocity habitat. • Suitable water temperature for growth (22-26°C [72-79°F) • Growth to ~39–44 mm (1.5 in) TL prior to winter (overwinter length-dependent mortality). • Abundant food supply (aquatic invertebrates).	• Bestgen and Hill 2016a • Haines et al. 1998 • Thompson et al. 1991 • Vanicek and Kramer 1969; Muth and Snyder 1995; Bestgen 1996
Juvenile (age 1–2+)	• Abundant food supply (aquatic invertebrates and fish). • Suitable habitats, mainly low-velocity areas	• Vanicek and Kramer 1969
Sub-adult and adult	• Abundant food supply (primarily fish, but also other prey). • Free movement to access food supply and establish home range. • Pools and/or deep, slow-moving water for foraging.	• Osmundson et al. 1998 • Tyus and Minckley 1988

3.1.4 Base flows—extent of connected habitat available

For Colorado pikeminnow, the extent of available riverine habitat can influence adult abundance and maximum carrying capacity. The distribution of Colorado pikeminnow throughout its range is likely a function of the extent of available riverine habitat (frequently measured as river length) and its ability to support different life stages. This is because, in general, an organism's population abundance is positively correlated to habitat size (Gaston and Blackburn 2000), and for Colorado River basin fishes, localized extirpation risk increases as the length of occupied river decreases (Fagan *et al.* 2002). The relationship between adult abundance and river length is likely a function of the river's ability to provide multiple suitable spawning sites, an abundance of suitable nursery habitat for drifting larvae and age-0 fish (Bestgen *et al.* 2006), foraging habitat for juvenile through adult life-stages, and enough area for adults to establish home ranges (Osmundson, D. B. *et al.* 1998). Foraging area and adult habitats can include areas such as tributaries that do not offer the appropriate age-0 habitats (Fresques *et al.* 2013; Bottcher *et al.* 2013; Cathcart *et al.* 2019). As a result, the Green River subbasin, with its tributaries the White and Yampa rivers, has had the largest population of Colorado pikeminnow in recent years (Osmundson, D. B. and White 2017b; Bestgen *et al.* 2018) and represents the largest contiguous reach of riverine habitat in the upper Colorado River basin (Valdez 2018).

There is evidence that Colorado pikeminnow can be highly migratory and spawn in specific river reaches across years (Green and San Juan river subbasins; Ryden and Ahlm 1996; Irving and Modde 2000), or that spawning is more dispersed and occurs in areas near an individual's home range (upper Colorado River subbasin). In either case, adults must have continued access to suitable spawning sites to successfully reproduce, which can require unimpeded access over long stretches of river. Adult Colorado pikeminnow home ranges and foraging areas can be a long distance from spawning reaches, and are often different habitats. As described above, this species requires clean cobble substrates with flowing water to keep eggs and larvae well-oxygenated. These areas occur in higher gradient reaches where adequate flow velocity can maintain cobble bars and provide water circulation through the substrate. Larvae then drift into nursery reaches, which are often characterized by low gradients that allow for sediment deposition and the creation of zero or low velocity habitats, such as backwaters, flooded tributary mouths, and side channels. Adult home ranges must have sufficient prey densities to support individual fish, thus a population would require adequate home range habitat to support a given population size.

As a result of this species' life history requirements for different habitats during various life stages, these habitats typically occur in different geomorphic reaches separated by long river distances and arranged in a particular pattern (Osmundson, D. B. *et al.* 1998). Maximum carrying capacities for Colorado pikeminnow in the Green and upper Colorado river subbasins have been estimated (Miller, P. S. 2018), and using these estimates, a minimum number of river miles would be required under ideal conditions to support the number of adults required to meet recovery criteria (U.S. Fish and Wildlife Service 2002) and to maintain resilient, self-sustaining populations. To illustrate this concept, the PVA used a carrying capacity of 4.6 adults/km (7.4 adults/mi) to model the Green River subbasin population (Miller, P. S. 2018; Valdez 2018). Using this value for carrying capacity, the Green River subbasin would have to provide a minimum of 565 km (351 mi) of adult habitat to reach the Recovery Goal of 2,600 adults. If this adult habitat does not include spawning or nursery habitats, additional river reaches would be required to support a functioning population. For Colorado pikeminnow, more spawning habitat translates to greater reproductive output. Likewise, the more nursery habitat that is available, the greater early life-stage survival rates (Bestgen and Hill 2016a; Grippo *et al.* 2017). These relationships between the extent of available habitat and demographics affect population growth rates and abundance.

3.1.5 Abundant and suitable food resources

Aquatic insects are important prey for juvenile Colorado pikeminnow up to ~100 mm (4 in) TL (Vanicek and Kramer 1969). At this life-stage, access to low-velocity habitat is important, as these habitats are most likely to have a high abundance of aquatic insects. As Colorado pikeminnow become more piscivorous, access to pools and deep slow water becomes more important (Tyus and McAda 1984; Muth *et al.* 2000). Colorado pikeminnow evolved within a native fish assemblage dominated by soft-rayed fishes, which are more suitable for consumption than spiny fishes (Pimental *et al.* 1985; Osmundson, D. B. 1999). Prey consumption is constrained by morphology including gape relative to body size (Burnette and Gibb 2013; Gilbert, E. *et al.* 2018). Not only do Colorado pikeminnow require suitable prey but also suitably-sized prey (Osmundson, D. B. *et al.* 1998). Current studies have not suggested Colorado pikeminnow populations are limited by food availability, although nonnative fishes can compete with them for forage (Muth and Snyder 1995; McGarvey *et al.* 2010).

3.2 Population level needs - resiliency

For the purpose of this SSA, viability is defined as the ability of Colorado pikeminnow to persist in the wild over a biologically meaningful time frame. We use the 3 Rs (Resiliency, Redundancy, and Representation) to describe viability (U.S. Fish and Wildlife Service 2016). Within the SSA framework, a population's resiliency is measured through the concept of population health defined by demographic factors. In addition, a population's health is regulated by biotic and abiotic environmental conditions and thus we incorporated this into an overall assessment of a population's resiliency. Resiliency refers to a population's ability to withstand stochastic events arising from random factors and is based on demographic factors, such as abundance and recruitment, which are in turn influenced by the ecological characteristics, or habitat factors, or needs of individuals (Figure 9). A highly resilient Colorado pikeminnow population would be able to withstand temporary demographic stochasticity, such as poor reproductive success or low recruitment, environmental stochasticity such as short-term drought, variability in prey densities and availability of nursery habitat, or altered environmental flows. As a result, a resilient Colorado pikeminnow population would have: 1) sufficient numbers of adults to reproduce and to withstand variability in river conditions, 2) adult abundance would be stable or increasing over several years, 3) reproduction would occur consistently each year, 4) age-0 fish would survive their first summer and recruit to juveniles, and 5) abundance of sub-adult recruits (fish that will become adults the next year) would be high enough to replace adult mortalities.

As mentioned above, Colorado pikeminnow reproductive success and recruitment can be correlated to available spawning and nursery habitats created by spring peak and base flows, which were historically highly variable in the Colorado River basin. It is believed that the species' long life span and high fecundity are adaptations to this natural variability within the system (Osmundson, D. B. *et al.* 1997; Osmundson, D. B. and Burnham 1998). Despite such adaptations, environmental stochasticity can be exacerbated by human alterations. For example, water withdrawals can increase the frequency and magnitude of low water conditions within river reaches. Alternately, human activities such as the construction of dams can diminish environmental stochasticity by reducing the variability between peak and base flows.

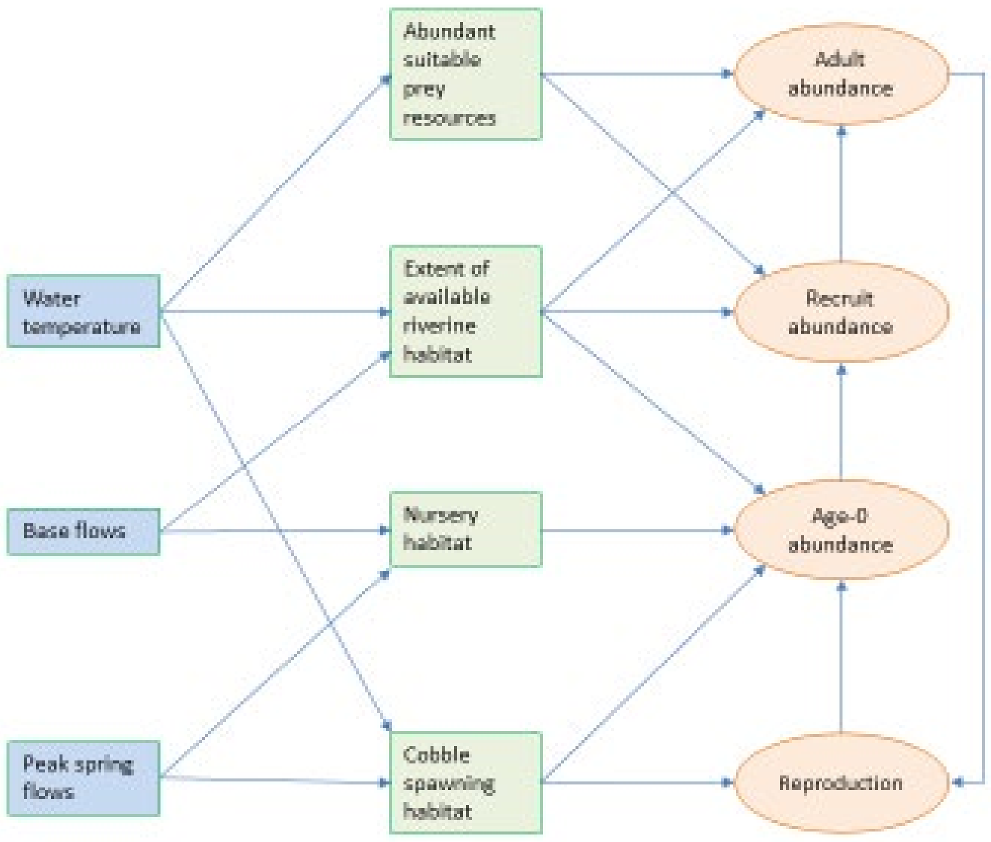


Figure 9. Colorado pikeminnow population ecology influencing each population's resiliency. Blue boxes represent abiotic factors, green denotes habitat factors, and orange indicates demographic factors (adapted from Bestgen *et al.* 2006).

Although the distribution of Colorado pikeminnow has contracted compared to its historical range, we assessed resiliency over the species' entire historical range so that we could assess overall redundancy. This allows us to assess future species conditions under potential management scenarios, including conservation efforts such as reintroduction of the species to currently unoccupied areas that were historically part of its range. As a result, six analysis units were defined and examined for their potential to support Colorado pikeminnow populations (Figure 10). Four resiliency analysis units were defined based on hydrologic subbasins where the species has persisted or has been reintroduced (Green, upper Colorado, San Juan, and Gila river subbasins). The Green and upper Colorado River subbasin units are based on reaches where Colorado pikeminnow adult abundance estimates are generated, and these estimates are used in measuring progress towards recovery criteria. Both of these subbasins function as independent units in terms of spawning and recruitment, and previous data show that exchange of adults between the two rivers is low (Osmundson, D. B. and White 2017b). Both subbasins are also bounded upstream by dams or the known extent of Colorado pikeminnow range, and Lake Powell forms the downstream limit to suitable habitat. The San Juan River subbasin unit is separated from the Green and Colorado rivers by Lake Powell and is further isolated by the presence of a waterfall near its inflow to the reservoir. Movement of Colorado pikeminnow between the San Juan River and the rest of the upper basin has not been documented since the formation of Lake Powell. This unit is heavily influenced by stocking of Colorado pikeminnow, has independent demographic rates from the other rivers, and is affected by the operation of Navajo Dam, which forms the upstream boundary of this unit. The Gila River subbasin unit was determined based on the experimental stocking of fish into the drainage, and its isolation from other rivers of the Colorado River system due to the presence of dams and dewatering of the lower river reaches. The other two analysis units were geographic reaches delineated by the presence of large dams: the Colorado River in the Grand Canyon (bounded upstream by Glen Canyon Dam and downstream by Hoover Dam/Lake Mead) and the lower Colorado River mainstem (bounded upstream by Hoover Dam and downstream by Imperial Dam, but also encompassing several other impoundments). Although Colorado pikeminnow are not present in either the Grand Canyon or the lower Colorado River mainstem, these reaches would function independently of other populations because of their isolation and the nature of flow management within them. If Colorado pikeminnow were reintroduced into these reaches, any resulting population would reside within the confines of these reaches and demographic rates would be a result of habitat conditions within the specified reach.

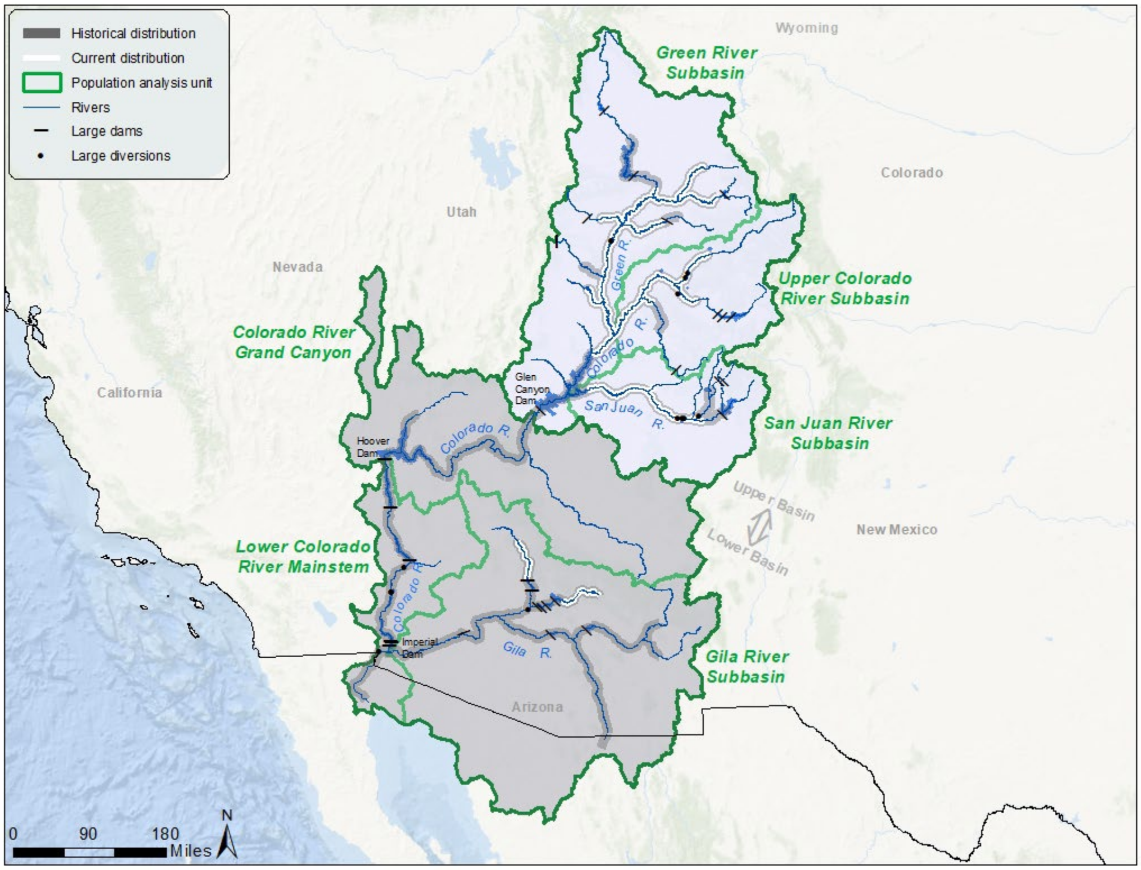


Figure 10. Colorado pikeminnow population resiliency analysis units.

3.3 Species level needs – redundancy and representation

Colorado pikeminnow can migrate long distances between home ranges and spawning areas (Wick *et al.* 1983; Tyus and McAda 1984; Irving and Modde 2000; Osmundson, D. B. 2011). In addition, fish have been documented moving between the Green and upper Colorado river subbasins at a rate estimated at 6.5 adults per year (Osmundson, D. B. and White 2017b). This likely represents a rate of movement that prevents genetic differentiation at a population level. Range and connectivity become important species needs in the context of the natural variability present in the Colorado River basin, where habitat conditions can be limited in reaches of river as a result of drought. This effect is further compounded if fish are restricted in their ability to move to more suitable habitat because of habitat fragmentation or flows altered by water development.

Redundancy describes the ability of a species to withstand catastrophic events. Redundancy gauges the likelihood that Colorado pikeminnow can withstand or "bounce back" from catastrophic events such as rare destructive natural events or episodes involving multiple or large portions of extant populations. Species that are well distributed across their historical range are considered more redundant than species confined to a small portion of their range (Carroll *et al.* 2010; Redford *et al.* 2011). Redundancy helps "spread the risk" and ensures not all populations are extirpated. To be considered redundant, Colorado pikeminnow needs multiple populations distributed across its range. Colorado pikeminnow is currently distributed across three populations in the upper basin, and the science panel agreed that these three populations, at minimum, should be maintained to support the species' viability. In this SSA, we characterize redundancy by the number of viable populations and the spatial scale of their distribution.

Representation describes the ability of a species to adapt to changing environmental conditions. The breadth of genetic diversity within and among populations can be a measure of representation. Ultimately genetic diversity provides for morphological and behavioral plasticity that allows a species to respond to various environments (i.e., inhabit and thrive in various habitat types). Species representation gauges the probability that Colorado pikeminnow is capable of using different habitats in response to a change in environment. The more representation or diversity a species has (genetic, morphological, and/or behavioral), the more capable it is of adapting to changes (natural or human caused) in its environment. In this SSA, we characterize Colorado pikeminnow representation by summarizing genetic and behavioral diversity. For behavioral diversity, we consider migratory versus more localized spawning activity. It is unclear to what extent the species has exhibited other types of variability.

3.4 Summary of species needs:

Colorado pikeminnow need warm water temperatures for spawning, hatching, and growth; peak flows to clean spawning bars, transport drifting larvae, and form backwater nursery habitats; base flows to maintain nursery habitats through summer and provide access between spawning areas and home ranges; and complex riverine habitats that provide sites for spawning, feeding, and rearing. These features of flow, temperature, and availability of habitats influence the ability of Colorado pikeminnow to reproduce, grow, and survive at different life stages, particularly during a fish's first summer. When these features are available and suitable, they provide the resources to support resilient populations, which are characterized by adult abundances that are sufficient to withstand environmental variation, reproduce, and exhibit stable or increasing trends over longer timeframes. Resilient populations also demonstrate consistent annual reproduction, survival, and recruitment of age-0 fish, and recruit abundances sufficient to replace adult mortalities.

The species needs multiple populations distributed across its historic range in order to be redundant and withstand catastrophic events. These populations would need to include individuals with diverse genetic composition and behavioral traits, such as migratory and localized spawning, in order to preserve the variation present in current populations and to allow the species to adapt to changing conditions.

CHAPTER 4 –INFLUENCES OF STRESSORS AND CONSERVATION MEASURES ON VIABILITY

This chapter evaluates stressors (change in resource need) that have and will continue to influence Colorado pikeminnow viability as well as conservation management actions that have been implemented to reduce these stressors. Some of the stressors directly influence demographics through mortality of individuals (e.g. entrainment into water infrastructure), while others affect habitat factors that can indirectly influence demographic rates. All of the stressors described in this chapter impact population resiliency (Figure 11). While these stressors primarily have an impact on population resiliency, species redundancy and representation will be discussed and evaluated when applicable.

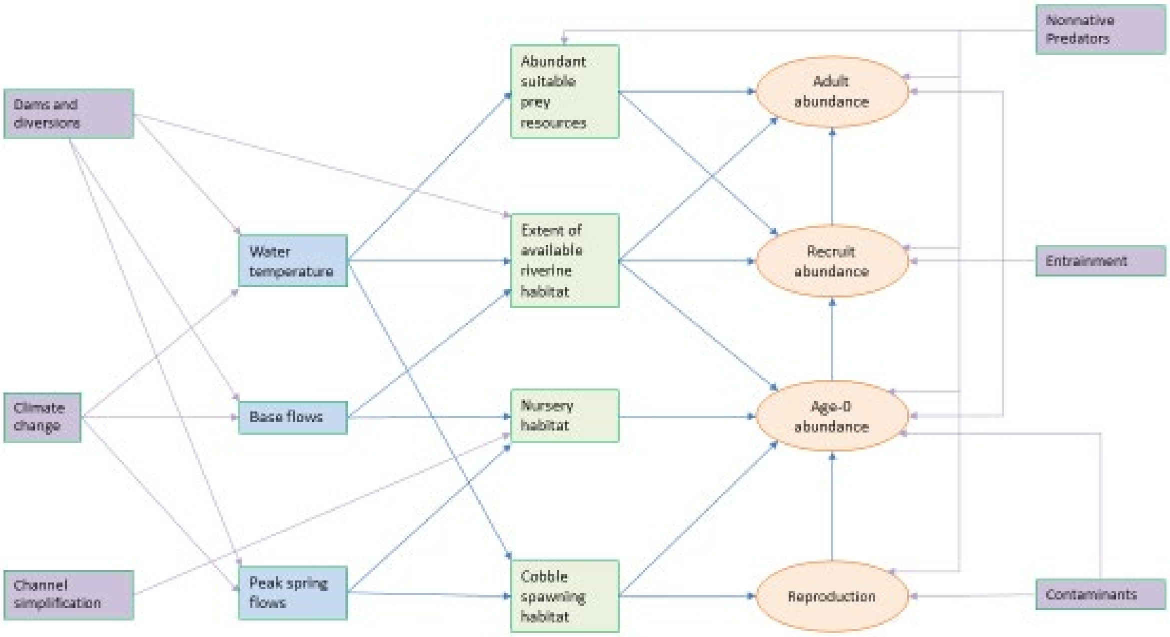


Figure 11. Factors influencing resiliency of Colorado pikeminnow populations. Purple boxes indicate potential stressors and arrows show the habitat or demographic factors they influence.

4.1 Stressors

4.1.1 Reduced peak and base flows

Spring peak flows and summer base flows function to create and maintain multiple, essential habitats used by different life stages of Colorado pikeminnow. Spring peak flows transport sediment and clean cobble spawning bars to maintain the interstitial spaces where eggs are deposited and hatch. As larvae emerge from those cobble bars, declining peak flows transport them downstream to nursery habitats. These nursery habitats are also created and maintained by peak flows through scouring of the channel and the movement of sediment. This process removes encroaching vegetation that can simplify the channel, and helps to form backwater habitats that larvae and juveniles prefer. Base flows maintain nursery habitats by stabilizing backwater depth and persistence through the summer growing period, and data suggest that there is a range of base flows that maximize the survival of age-0 Colorado pikeminnow. Base flows also provide riverine habitats with sufficient depth to allow adult Colorado pikeminnow free movement between foraging areas and spawning areas.

Colorado River basin water is heavily used and intensively managed, which affects the river flows needed by the Colorado pikeminnow. The states in the upper Colorado River basin have yet to fully develop the 7.5 million acre-feet (maf) of their apportioned total consumptive use established in the 1922 compact (U.S. Bureau of Reclamation 2012a). Nevertheless, water apportioned for municipal, industrial, agricultural, and hydropower uses under current compacts and agreements exceeds the 100-year record of availability. The current volume of consumptive use and other depletions of water in the basin have been estimated at approximately 15.3 maf annually in recent years, compared to the approximately 100-year basin-wide historical annual average natural flow of about 16.4 maf (U.S. Bureau of Reclamation 2012a). For Colorado pikeminnow, these water depletions mean a reduction in water available to create and maintain suitable habitat and alterations in the quantity and timing of flow. More specifically, since the 1960s dams and diversions have altered flow regimes by reducing mean spring peak flows and increasing mean base flows in the summer through winter period (U.S. Fish and Wildlife Service 2018c), as described below:

- Green River: spring peaks decreased 34%, base flows increased 76%
- Upper Colorado River: spring peaks decreased 33%, base flows increased 37%
- Yampa River: spring peaks decreased 4%, base flows increased 5%
- San Juan River: spring peaks decreased 46%, base flows increased 168% (Holden 1999)
- Colorado River in Grand Canyon: spring peaks decreased 80%, base flows increased 67%
- Lower Colorado River: spring peaks decreased 70%, base flows increased 258%

Reductions in peak flows can result in spawning bars becoming filled with fine sediments that eliminate the interstitial spaces required for egg incubation and early larval development. Eggs deposited in such habitats can be washed away or lost to predation, with the result being a reduction in reproductive success. Lower magnitude peak flows are also less effective in scouring river channels to remove encroaching vegetation, moving sediment to create backwater and low velocity habitats, and maintaining channel complexity by keeping side channels and other off channel habitats inundated. Complex channel morphology sustains nursery habitats, particularly backwaters, and provides foraging and resting habitats for juveniles and adults. A reduction in channel complexity would lead to decreases in nursery habitat and lower survival and recruitment of age-0 fish to the population.

Elevated base flows have the potential to inundate backwaters and other low velocity habitats, converting them into flowing portions of the main channel. These low velocity habitats are important for age-0 Colorado pikeminnow because they provide refuge from swift river currents and warmer water temperatures for faster growth. Negative effects to nursery habitat quantity and quality can result in lower survival of juvenile fish. Conversely, while base flows have increased in many mainstem river reaches, many of the smaller tributaries have experienced lower base flows. In many cases, water depletions have left smaller tributaries essentially dewatered during portions of the year (e.g. Duchesne, Price, Salt, Animas, LaPlata rivers). In reaches where water depletions have significantly reduced flows, the resulting conditions may not be adequate to create or maintain spawning and nursery habitats, and adult fish may not be able to navigate reaches of shallow water to establish new populations. This reduces the amount of habitat for all life stages, and shrinks the potential range the species can occupy. Finally, lower peak and base flows tend to favor some species of nonnative fishes (e.g., smallmouth bass) that compete with and prey upon Colorado pikeminnow. Competition for prey results in less forage available to adults and juveniles, while predation directly results in fewer individuals.

4.1.2 Decreases in water temperature

Cold-water reservoir releases below large dams can result in thermally unsuitable habitat for Colorado pikeminnow, which reduces survival and affects spawning behavior (Kaeding and Osmundson 1988; Bestgen and Williams 1994; Muth *et al.* 2000; Osmundson, D. B. 2011; Bestgen and Hill 2016a). Reservoir releases occur for a variety of reasons including hydroelectric generation, water delivery, flood mitigation, and environmental flows. These releases tend to be from the bottom (hypolimnetic) layer of the reservoir that is typically colder than water at higher reservoir elevations during summer. Release of this cold water can cause portions of downstream river reaches to fail to reach or exceed 18°C (64°F), reducing the likelihood Colorado pikeminnow will spawn within those portions of the river (Bestgen and Hill 2016a). Consistently cold water temperatures can also render river reaches unsuitable for fish to establish home ranges, and growth for the species appears to cease at 13°C (55°F; Kaeding and Osmundson 1988; Osmundson, D. B. 2011). A reduction in recruitment and the quantity of thermally suitable habitat to support spawning and adult abundance can limit the number of individuals in a population and ultimately the population's resiliency. The spatial extent to which cold hypolimnetic releases result in unsuitable habitat may include entire river reaches. If this precludes Colorado pikeminnow from establishing a population, hypolimnetic releases can result in reducing the species' redundancy. In addition, sudden exposure to cold water temperatures can cause cold shock in larval Colorado pikeminnow (Berry 1988). An example of where this could be a concern is the confluence of the Green and Yampa rivers, where hypolimnetic releases from Flaming Gorge Dam meet warmer waters and drifting larvae from the Yampa River (Muth *et al.* 2000).

In the Colorado River basin, the effect of hypolimnetic releases on the overall thermal suitability of habitat is not only a function of the warming of water as it moves downstream, and the temporal effect of seasons, but also thermal characteristics of tributary inflows (Figure 12). For example, tributaries such as the Animas River (San Juan River subbasin) and the Yampa River (Green River subbasin) help to warm water temperatures in the summer below their confluences. These tributary inputs can help maintain thermal suitability in reaches downstream.

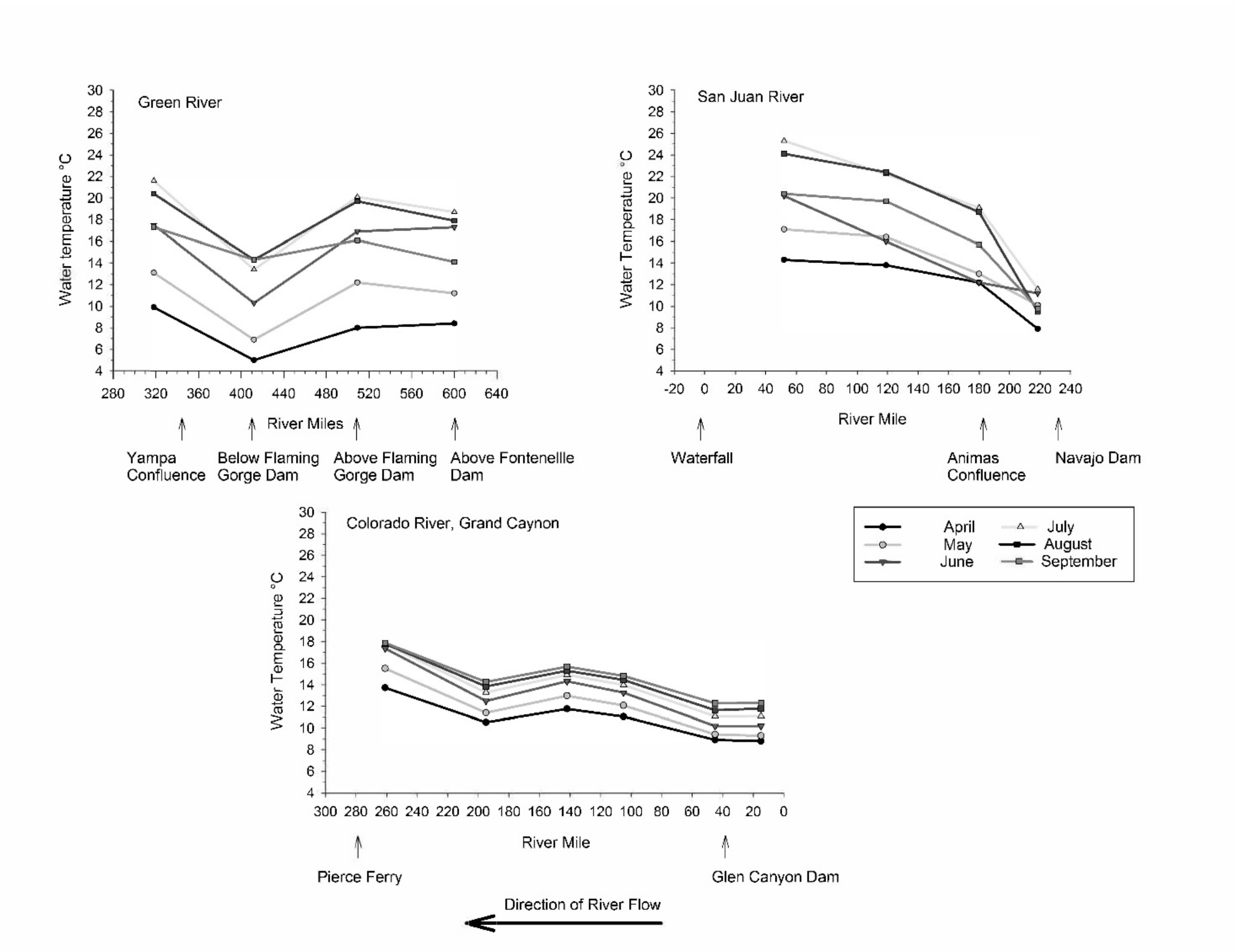


Figure 12. Mean monthly (April – September) water temperature measured at indicated river miles and downstream warming in the Colorado River basin: Green, San Juan, and Colorado rivers (2010–2016).

4.1.3 Physical barriers to movement and amount of available riverine habitat

Colorado pikeminnow adults can move long distances annually between foraging home ranges and spawning habitats. In addition, the species requires sufficient adult foraging habitat to support a minimum viable population. Finally, the ability to move between different river reaches allows individuals to find suitable water temperatures and flow conditions with variable hydrology, particularly in periods of drought and reduced flows. Physical barriers to Colorado pikeminnow movement affect the species' resiliency by limiting access to feeding, spawning, or nursery habitats, redundancy by limiting the distribution of populations across the range, and representation by limiting genetic exchange between populations. The physical fragmentation of Colorado pikeminnow's range into smaller disconnected segments is the result of large dams and their reservoirs as well as smaller, but impassable, low head diversion structures (Figure 3, Figure 13, and Figure 14). Large dams not only create physical barriers to movement, but they often create thermal barriers for warmwater fishes by releasing colder waters in their tailraces (Section 4.1.2). Since flows in the Colorado River Basin are regulated throughout most of the current and historical range of Colorado pikeminnow, large dams and management of their flows may preclude occupation of the species in some areas.

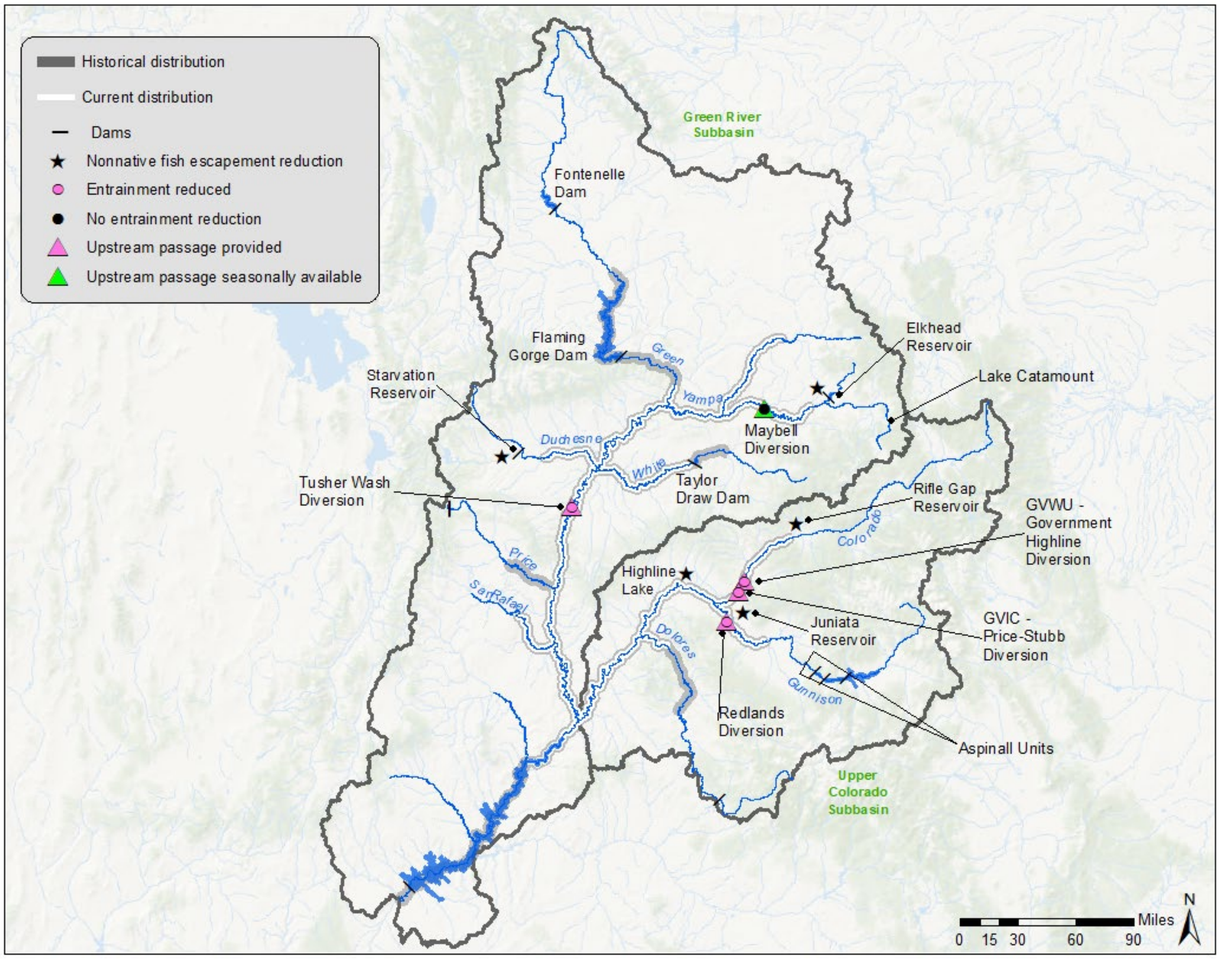


Figure 13. Location of nonnative fish escapement reduction, entrainment, and upstream fish passage devices in the Green and upper Colorado River subbasins.

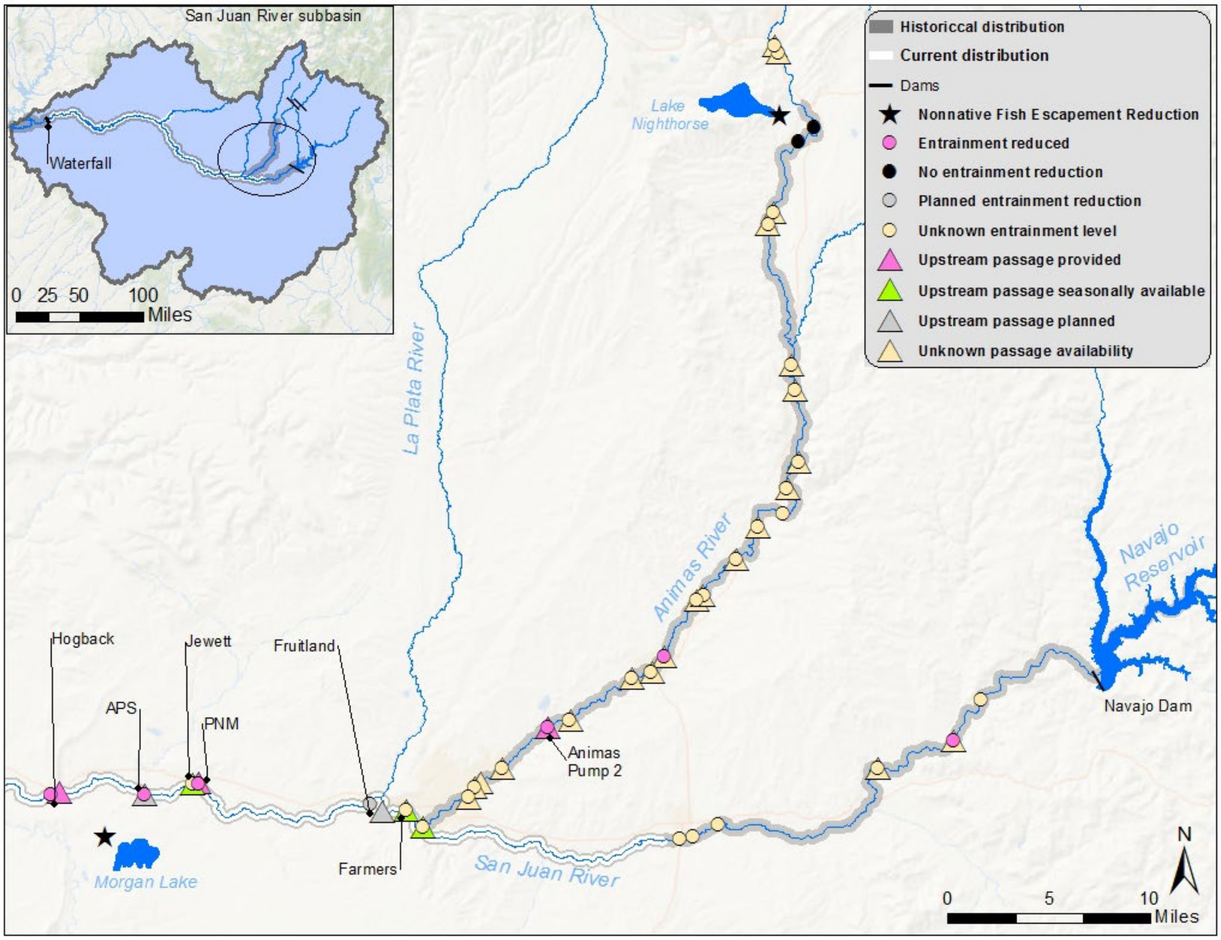


Figure 14. Location of nonnative fish escapement reduction, entrainment, and upstream fish passage and barriers in the San Juan River subbasin. Insert shows section of San Juan River enlarged and location of the waterfall.

Colorado pikeminnow representation is conditional on genetic exchange. Range fragmented by physical barriers reduces genetic diversity and may result in reduced ecological diversity. Dams and reservoirs provide water delivery, generate power, provide recreational opportunities, and thus, the effects on Colorado pikeminnow will likely persist well into the foreseeable future. Smaller low head diversion dams, however, can be retrofitted with fish passages to provide additional habitat to Colorado pikeminnow that use them.

4.1.4 Entrainment of Colorado pikeminnow in water diversion structures

Water for agricultural, municipal, and industrial uses, including electrical generation, will continue to be diverted from rivers and reservoirs throughout the historical range of Colorado pikeminnow (U.S. Bureau of Reclamation 2012a). Water diversion into delivery systems can entrain (trap) all life-stages of Colorado pikeminnow resulting in direct loss of individuals (Renfro *et al.* 2006; McAbee 2017b). Because entrainment can reduce the abundance of individuals at each life-stage, it can decrease a population's resiliency.

The rate of Colorado pikeminnow entrainment is generally positively correlated with the volume of water diverted. As more water enters a facility, more fish would be expected to be entrained (U.S. Bureau of Reclamation 2006a; Speas *et al.* 2016). In the Green River subbasin, the Green River Canal (Figure 13), which is approximately 43 km (27 mi) downstream of a Colorado pikeminnow spawning location (Tyus 1990), was thought to entrain fishes up to 10 times the expected rate based on the volume of water entering (Speas *et al.* 2016; McAbee 2017b). The disproportionate rate of entrainment was because the relatively small canal (2 m^3/s [85 cfs]) is fed by the much larger Tusher Diversion Dam that supplies water (20 m^3/s [700 cfs]) to multiple facilities. The facilities outside the canal were screened to preclude the entrainment of adult fishes, so a fish entering the (20 m^3/s [700 cfs]) diversion is directed towards the much smaller canal or must swim back upstream.

In the San Juan River subbasin, more Colorado pikeminnow were collected in the Hogback irrigation canal (2004, n=140; 2005, n=61) that has a diversion capacity of ~9 m^3/s (~300 cfs), than in the Fruitland irrigation canal (2005, n=19) that has a diversion capacity of ~ 5 m^3/s (~160 cfs; Figure 14; Renfro *et al.* 2006). In two other San Juan River subbasin canals (Jewett and Farmers), whose diversion capacity is ~ 1 m^3/s (~50 cfs), no Colorado pikeminnow were found entrained during 2005 sampling. Overall, fewer fish (n = 166 and 39, Jewett and Farmers, respectively) were entrained in the smaller capacity diversion canals compared to Hogback and Fruitland canals (n = 3,095 and 479, respectively; Renfro *et al.* 2006).

4.1.5 Nonnative fish predation and competition

Colorado pikeminnow evolved in a fish community characterized by low species-richness where it was the apex predator. Since Colorado pikeminnow can grow to large sizes and mainly rely on other fish for forage, adults require sufficient numbers and sizes of suitable prey to survive. Currently, almost 70 species of nonnative fishes, many of which are predators, are present in the Colorado River basin (Martinez *et al.* 2014). These nonnative fishes were introduced in the last 100 years to establish recreational fisheries, as biological control agents, or through unauthorized transfers. Since the late 1990s, few additional species have been introduced (Martinez *et al.* 2014), but some species have expanded their ranges within the basin. Many of the nonnative fishes present in the Colorado River basin have become established and are highly piscivorous (Johnson *et al.* 2008; Martinez *et al.* 2014; Zelasko *et al.* 2016; Bestgen and Hill 2016b).

Since Colorado pikeminnow become largely piscivorous at an early age and into adult size, predaceous species have the potential to compete for prey fishes and to reduce the available forage base across multiple life stages. Studies of age-1 and age-2+ Colorado pikeminnow in the San Juan River showed the spatial distribution of these age classes was positively correlated to the density of native prey species (Franssen and Durst 2014). Tyus and Nikirk (1990) found that the diet composition and abundance of channel catfish in the Green River subbasin suggested the species could reduce food availability for other fishes. They also noted an overlap in diet and habitat between Colorado pikeminnow and channel catfish. Johnson et al. (2008) modeled the consumptive demand of northern pike *Esox lucius*, smallmouth bass, and channel catfish in the Yampa River. While the main purpose of the study was to quantify the predatory threat of these species to native fishes, their estimates demonstrated the potential for these species to consume small-bodied native fishes based on individual diets and the abundance of the nonnative species. McGarvey et al. (2010) modeled predicted fish densities for the Green River and compared those to observed values based on bioenergetics data. Their model did not accurately predict observed densities of Colorado pikeminnow for this system, and they suggested competition from nonnative species could explain the discrepancy. Tyus and Saunders (2000) also identified small-bodied fishes such as red shiner as potential competitors for food and space because of their high abundance in nursery habitats and similar diet to young Colorado pikeminnow (Muth and Snyder 1995). Finally, Colorado pikeminnow have also been found with channel catfish lodged in their esophagus (McAda 1983; Pimental *et al.* 1985; Ryden and Smith 2002). It is unclear to what extent this has had an effect at the population level, but it can cause mortality in affected individuals.

Predation by nonnative fishes is also a primary threat to the resiliency and reestablishment (redundancy) of Colorado pikeminnow (U.S. Fish and Wildlife Service 2002). Colorado pikeminnow may be ill-adapted to living in environments with high predator pressures as they lack defense mechanisms such as heavy scales or spined fin rays. They may also behave naively towards predators, similar to the behavior exhibited by other endemic Colorado River Basin fishes (Ward and Figiel 2013). Although Colorado pikeminnow grow to a large size (1.8 m [6 ft]), there is evidence that nonnative fishes prey on all life-stages and there is no apparent refuge size where predation is reduced (Bestgen *et al.* 2006; Johnson *et al.* 2008; Martinez *et al.* 2014; Elverud and Ryden 2015). The largest northern pike captured in the Yampa River was 1,120 mm (44 in) TL (Zelasko *et al.* 2016), and walleye 800–850 mm (31–33 in) TL have been collected in the upper Colorado River subbasin (Elverud and Ryden 2015). Such large fish have the potential to consume an extended range of Colorado pikeminnow size-classes as evidenced by walleye captured with 289-323 mm (11–13 in) TL Colorado pikeminnow in their stomachs (Elverud and Ryden 2015). Increased numbers of walleye in the Green River subbasin have been implicated in the decline of juvenile and recruit sized Colorado pikeminnow (Bestgen *et al.* 2018), where large numbers of younger fish observed in 2011 were not evident in subsequent years. As mentioned in Section 2.1, Colorado pikeminnow upon hatching are relatively small, and young fish grow slowly over several years to become adults. At currently observed densities in the Green River, smallmouth bass are considered to have the ability to significantly reduce a given Colorado pikeminnow year class (Bestgen and Hill 2016b). Walleye densities in recent years have generally been highest in the lower reaches of the Green and upper Colorado subbasins, and this distribution overlaps with known nursery habitats for Colorado pikeminnow in those rivers, making them more likely to consume younger fish. Channel catfish are the primary large-bodied species in the San Juan River that has the potential to prey upon Colorado pikeminnow. A study of channel catfish consumption of Colorado pikeminnow suggests that channel catfish could be consuming 10-34 age-1 Colorado pikeminnow per RK annually throughout the river (Hedden and Gido 2020). Predation on Colorado pikeminnow by nonnative fishes is not exclusive to large-bodied fishes and can include small-bodied nonnative species. In the laboratory, adult red shiner *Cyprinella lutrensis* reduced survival of Colorado pikeminnow larvae through predation (Bestgen *et al.* 2006). In other experiments red shiner, fathead minnow *Pimephales promelas*, and green sunfish *Lepomis cyanellus* displayed antagonistic and predatory behavior towards age-0 Colorado pikeminnow (Karp and Tyus 1990). These species are present throughout the range of Colorado pikeminnow, particularly in nursery habitats where smaller individuals of Colorado pikeminnow are likely to occur (Appendix I). Different species of introduced fishes likely pose a predatory threat to different life stages of Colorado pikeminnow, such that Colorado pikeminnow are continually exposed to a variety of potential predation pressures from larvae to adults. The compounding effects of mortality at different life stages as a direct result of predation by nonnative fishes decreases Colorado pikeminnow adult abundance and lowers population growth rates (Martinez *et al.* 2014; Bestgen *et al.* 2018).

The impacts of both predation and competition ultimately reduce population resiliency through reduced abundance of larvae, juveniles, and adults. Because predatory nonnative fishes are common throughout the range of Colorado pikeminnow, they may act to preclude the establishment of Colorado pikeminnow populations. The effects of predation on Colorado pikeminnow are reflected in assessments of current conditions for demographic factors. Competition from nonnative fishes reduces available prey resources, and is assessed as a habitat factor in place of prey species abundance.

4.1.6 Water contaminants

Although there are a number of water contaminants in the Colorado River Basin (Spahr *et al.* 2000; Weissinger *et al.* 2018), only the effects of mercury have been quantified for Colorado pikeminnow (Osmundson, B. and Lusk 2019). Mercury likely decreases Colorado pikeminnow population growth rates through reduced reproductive output and suppressed larval fish survival rates (Miller, P. S. 2014). Mercury is deposited throughout the Colorado River basin from local and global sources (EPRI 2015) and has the potential to affect the species throughout its range. Recent modeling of mercury deposition predicted gradually rising mercury concentrations in water and fish tissue (EPRI 2015). Because mercury is expected to persist in water throughout Colorado pikeminnow's range, this stressor likely will continue to have an impact on Colorado pikeminnow populations' resiliency.

The functional relationship between mercury and Colorado pikeminnow reproductive impairment in the San Juan River subbasin was modeled through a population viability analysis (Miller, P. S. 2014). Using current mean concentrations of mercury in adult Colorado pikeminnow (0.37 – 1.01 µg/g wet weight muscle tissue; Osmundson, B. and Lusk 2019) reproductive success was estimated to be reduced by 2% among newly recruited females and further decreased to 5% as females aged (Miller, P. S. 2014). Although reductions in the deposition of mercury were included in modeling, they never exceed a 0.2% reduction in adult Colorado pikeminnow tissue burden within the 85-year simulation period (EPRI 2015). This type of modeling has not been conducted for other populations of Colorado pikeminnow. In the Green River and upper Colorado River subbasins, mercury concentrations from muscle plugs were higher than those from the San Juan River population (Figure 15; Osmundson, B. and Lusk 2019), although fish from those basins were larger than the ones sampled from the San Juan River. We are unaware of any sampling for mercury from the fish stocked into the Verde River in the Gila River subbasin. Given measurements of mercury concentrations in water, whole body concentrations in Colorado pikeminnow can be estimated (Appendix III). For example total dissolved mercury in the lower Colorado River mainstem is <0.010 µg/L (2010–2018; Appendix IV) and might indicate Colorado pikeminnow tissue concentrations of <0.6 µg/g.

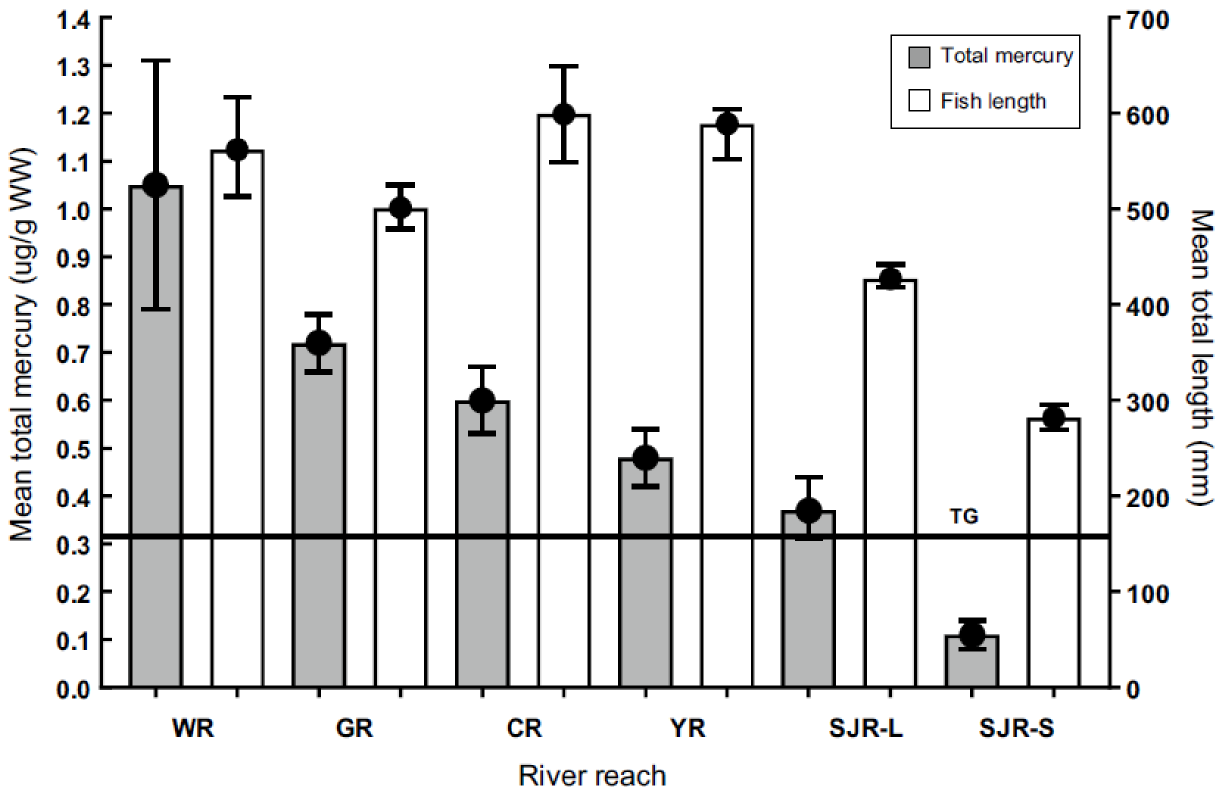


Figure 15. Mercury concentrations (mean and 95% confidence intervals) and fish length of Colorado pikeminnow sampled from upper Colorado River basin rivers (White *WR*, Green *GR*, upper Colorado *CR*, Yampa *YR*, and San Juan *SJR-L* fish >400 mm (>16 in) TL and *SJR-S* fish <400 mm [<16 in] TL). Horizontal line identifies the USEPA's recommended tissue-based mercury toxicity guideline of 0.31 µg/g wet weight (WW). Figure from Osmundson and Lusk (2019).

In addition to mercury, a large suite of contaminants (e.g., petroleum products, radionuclides, selenium, pesticides, pharmaceuticals, microplastics) is found throughout the Colorado River Basin. A number of emerging contaminants are also being identified in water quality sampling and are associated with pharmaceuticals (e.g., immune suppressants, estrogen, testosterone, etc.) and agricultural products, which include atrazine (Spahr *et al.* 2000; Weissinger *et al.* 2018). Little is known pertaining to the concentrations of these contaminants in or their direct effects on Colorado pikeminnow. Hinck et al. (2006) did find a range of contaminants in common carp, channel catfish, and largemouth and smallmouth bass throughout the Colorado River Basin, and documented abnormal biomarkers such as intersex characteristics in smallmouth bass.

Selenium has been sampled from Colorado pikeminnow tissues and ranges from a mean of 0.6 to 1.92 (µg/g wet weight) throughout the upper Colorado River basin (Table 4; Osmundson, B. *et al.* 2000; Osmundson, B. and Lusk 2019). Actions taken through the Colorado River Basin Salinity Control Act (Public Law 106-459 as amended) have resulted in the diversion of 1.07 million tons of salt, which can include selenium, from entering the basin's waterways (U.S. Bureau of Reclamation 2017a). The target for this program is to control 1.8 million tons of salt by 2025 throughout the Colorado River Basin.

Table 4. Average and range of selenium (µg/g wet weight) in Colorado pikeminnow muscle tissues from upper Colorado River basin 2008–2009 (Osmundson, B. and Lusk 2019).

River	Average Se in muscle tissue (min - max)
San Juan River (>400 mm total length)	0.83 (0.74 – 1.0)
Middle Green River	0.98 (0.87 – 1.08)
Upper Colorado River	1.92 (0.93 – 2.16)
White River	0.93 (0.64 – 1.18)
Yampa River	0.62 (0.44 – 0.72)

Contaminants that have been studied in Colorado pikeminnow appear to primarily affect reproductive output. For the current conditions assessment, we did not specifically consider contaminants alone, but do evaluate reproduction and age-0 abundance for the species. If contaminants are currently influencing Colorado pikeminnow, the effects should be reflected in those demographic factors. The future scenarios considered are based on modeling of demographic rates, including the number of offspring per female and survival of different age classes. Given that contaminants are likely to influence these two demographic parameters, the assessment of future condition can be used to consider possible effects from this stressor.

4.1.7 River bank armoring and channel simplification

Age-0 Colorado pikeminnow use low velocity habitats and backwaters along the river channel margins because they provide warmer water temperatures for optimal growth and refuge from river currents. These habitats are more common in complex river channels that contain side channels and sinuosity. Adult and juvenile Colorado pikeminnow also use a variety of river habitats for feeding and refuge from high velocity flows. This channel complexity can be reversed by river bank armoring through various actions or processes such as construction of erosion control structures, dredging of the river channel, or encroachment of nonnative vegetation (Allred and Schmidt 1999; Manners *et al.* 2014; Bassett 2015). Where riverbank erosion control structures exist or the river channel has been dredged, the river may lose its ability to create or provide access to nursery habitat (i.e., backwater, low velocity habitat, or the floodplain) required for larval and age-0 Colorado pikeminnow growth and survival. In the upper Colorado River basin, riverbank armoring has occurred through the encroachment of nonnative vegetation (van Steeter and Pitlick 1998; Bassett 2015). This type of armoring may have less of an absolute effect on the reduction in backwater habitat but likely results in the loss of Colorado pikeminnow nursery habitat because backwaters are constrained from expanding laterally by incised banks stabilized by extensive woody vegetation (van Steeter and Pitlick 1998; Bassett 2015). Given the effects on nursery habitat, riverbank armoring impacts Colorado pikeminnow populations' resiliency by reducing or prohibiting early life-stage survival. Because riverbank armoring may preclude Colorado pikeminnow from inhabiting portions of its historical range this impacts the species' redundancy.

In the Green and upper Colorado river subbasins the establishment and extensive growth of nonnative vegetation has resulted in long-term channel narrowing (van Steeter and Pitlick 1998; Allred and Schmidt 1999). The two most dominant nonnative riparian species are tamarisk *Tamarix spp.* and Russian olive *Eleagnus angustifolia*. In some riparian areas, they can be the third or fourth most frequently occurring woody plant within the riparian corridors (Friedman *et al.* 2005). Although the encroachment of nonnative riparian vegetation has been exacerbated by changes in the historical flow regime (i.e., reduced peak flows and elevated base flows), these nonnative species are also able to establish in relatively unregulated systems like the lower Yampa River (Green River subbasin). In the Yampa River, the channel appears to have narrowed by 6% in its widest reaches with the invasion of tamarisk (Manners *et al.* 2014). In the lower Green River, the interaction between changes in the flow regime and nonnative vegetation led to an 11–22% reduction in the width and meandering of the river (Grams and Schmidt 2002). Although a direct relationship between nonnative vegetation encroachment and backwater abundance was not made for this area of the lower Green River, the number and area of backwaters decreased over that same period (Figure 16; Bestgen and Hill 2016a). In the upper Colorado River subbasin near Grand Junction, Colorado, the channel narrowed by 20 m (66 ft) through the interaction of reduced flows and nonnative vegetation establishment (van Steeter and Pitlick 1998). This resulted in an approximate loss of 25% of the area formed by side channels and backwaters in portions of the upper Colorado and Gunnison rivers.

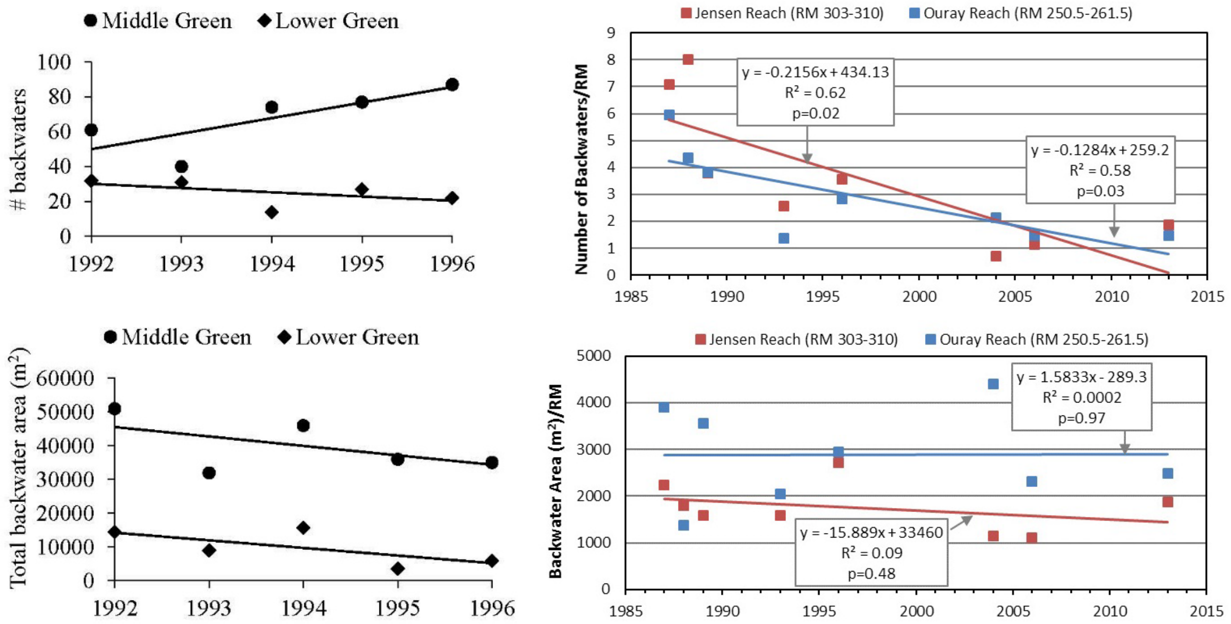


Figure 16. Backwater abundance and density in the Green River subbasin. Left panels: number of backwaters and total area of backwaters in the middle (16 river kilometers [RK, 10 river miles (RM)]) and lower (16 RK [10 RM]) Green River from Bestgen and Hill (2016a). Right panels: density (number and area/ river mile) of backwaters in two sections of the middle Green River from Grippo et al. (2017)

In the San Juan River subbasin, nonnative vegetation has increased by nearly 70% since the 1930s (Figure 17; Bassett 2015). Currently, average bank vegetation cover measured along half the length of the San Juan River is 73.3% (Bassett 2015). The San Juan River has also become more simplified over the time that vegetation cover increased. San Juan River channel area has decreased by more than 77% and the number of islands by approximately 60%. This simplification correlates to long-term decreases in backwater area within the San Juan River (Figure 18; Lamarra, V. A. and Lamarra 2018).

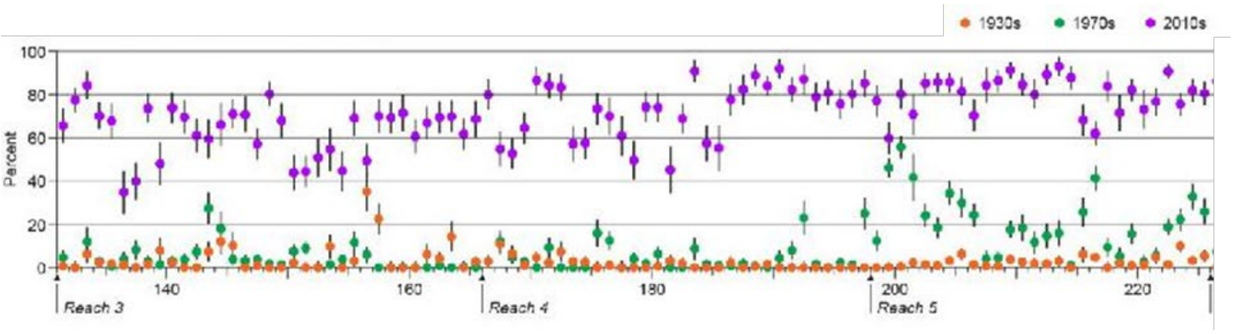


Figure 17. Stream bank vegetation cover and 95% confidence intervals for the San Juan River (RK 131–226 [81–140 RM]) from Bassett (2015).

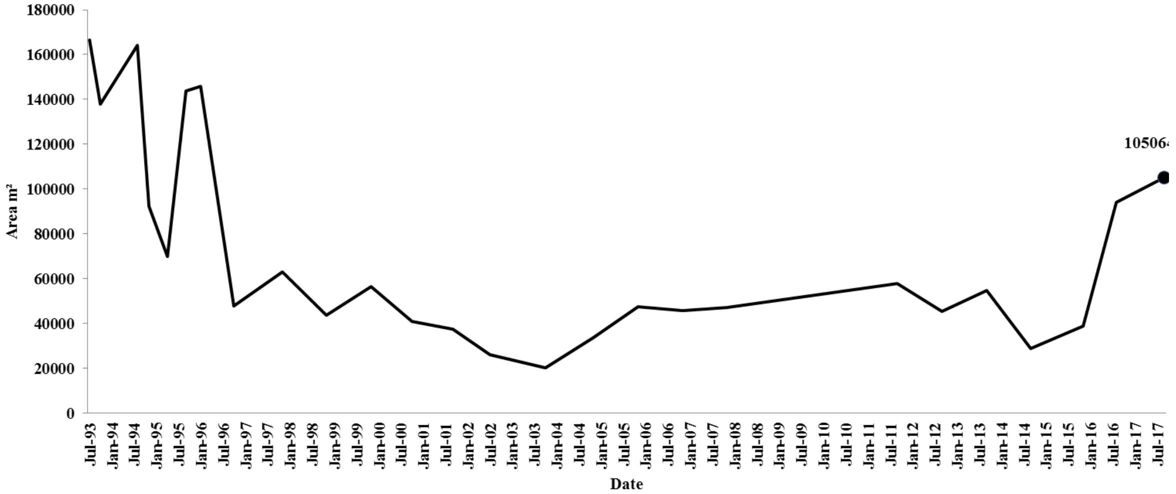


Figure 18. Backwater habitat area in the San Juan River. Data from Lamarra and Lamarra (2018).

In the lower Colorado River basin, the Grand Canyon reach is generally canyon bound. The lower Colorado River (below Lake Mead) mainstem riverbank and the river's meanders have been fully regulated through erosion control structures that include levees, shoreline riprap installation, and channel dredging (Figure 19). Beginning as early as 1952, the lower Colorado River mainstem was armored from Davis Dam to Topock, Arizona, with 50 river kilometers (RK; 31 river miles [RM]) channelized through dredging, placement of 220,254 cubic meters (288,082 cubic yards) of riprap, and construction of 75 kilometers (47 miles) of levees (Lower Colorado River Multi-Species Conservation Program 2004). Also in the lower Colorado River mainstem, from Laguna Dam to the Southerly International Boundary, 7.6 miles of levees were constructed, 28 kilometers (17.4 miles) of river channel dredged, and 201,843 cubic meters (264,000 cubic yards) of riprap placed (Lower Colorado River Multi-Species Conservation Program 2004). In the Gila River basin, the Verde River's riparian vegetation is that of a healthy ecosystem (Paretti *et al.* 2017) and search of aerial images of the Salt River result in a similar assessment. However, where these two rivers confluence, the river is fully diverted into Phoenix metropolitan area canal systems. While some of that water is returned to the Gila River's natural riverbed west of the Phoenix area, the riverbed tends to be dry (aerial imagery and Stewart W. and Weedman D. 2018, pers. comm.).

While river bank armoring and channel narrowing can result in a reduction of habitat, particularly nursery habitat, we did not directly carry this habitat factor forward in the assessment for current conditions. This is partially due to a lack of basin-wide data linking riverbank armoring and vegetation to current habitat availability, as well as the confounding effects of flow regime on both vegetation and habitat formation. The effect of the peak flow regime on habitat conditions has been investigated more directly and will be used for this SSA. It is worth noting that this stressor is particularly relevant to the lower Colorado River mainstem reach since the deliberate channelization of the river has been more extensive in this segment. The other reaches of river have generally experienced channel simplification as a result of flow management and the encroachment of vegetation.

Figure 19. Lower Colorado River mainstem channelization, levee, and river bank armoring. Top photo is south of Davis Dam at Needle, AZ. Lower photo is near the international border with Mexico near Yuma, AZ (image from U.S. Bureau of Reclamation Yuma Division website).

4.1.8 Climate change

Studies using predictive models indicate that changes in precipitation patterns, mean annual air temperature, and antecedent soil moisture will result in changes in flow patterns and magnitude in the Colorado River basin. Certain hydroclimate projections through 2099 (U.S. Bureau of Reclamation 2016b) indicate a slight increase in annual precipitation combined with an increase in mean annual temperature (Figure 20), while others project decreases in precipitation (nearly 6%) and associated snowpack (up to 76%; Christensen *et al.* 2004), and resultant water supplies

(Woodhouse *et al.* 2016). Even with a slight increase in annual precipitation, the risk of drought remains with continued temperature increases in the American Southwest (Christensen *et al.* 2004; Woodhouse *et al.* 2016; Ault *et al.* 2016). For example, an increase in mean annual air temperature of 2.4°C (4.3°F) relative to historical climate in the Colorado River basin could decrease runoff by as much as 17% by 2098 (Nash and Gleick 1991; Christensen *et al.* 2004). Different combinations of changes in precipitation, temperature, and soil moisture can cause flow reductions of similar scales (Woodhouse *et al.* 2016); changes in climatic patterns can also result in earlier snowmelt and spring runoff, leaving summer base flows lower and warmer than they have been historically (Dennis 1991; Gleick and Chalecki 1999). The effects of a warming environment are already evident: between 2000 and 2014, Colorado River annual flows averaged 19.3% below the 1906-1999 period, one third of which was attributed to increased temperature alone (Udall and Overpeck 2017). Future conditions for Colorado pikeminnow could therefore include increased stream temperatures through reduced summer base flows and increased air temperatures under drought conditions (Christensen *et al.* 2004; U.S. Bureau of Reclamation 2012a; U.S. Bureau of Reclamation 2016b). Both the hydroclimate projections (U.S. Bureau of Reclamation 2016b) and analysis by Udall and Overpeck (2017) were based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment, which uses models from the World Climate Research Programme’s most recent (2013) Coupled Model Intercomparison Project (CMIP5; Taylor *et al.* 2012). These models encompass the range of predicted values, and present results within the 10th and 90th percentiles of 97 projections. The central tendency of these models are derived from the 50th percentile value of the projections.

The western United States has experienced increased mean air temperatures of approximately 1.1°C (2°F) since record keeping began in 1895, with most of the warming occurring since 1970. Median projections of future temperatures through the 21st century estimate continued warming of 2.8 to 3.9°C (5-7°F) depending on location (Figure 20; U.S. Bureau of Reclamation 2016a). As reported by the U. S. Fish and Wildlife Service (2018c) and according to the Western Climate Mapping Initiative, during the 20th century mean air temperature increased approximately 1.2°C (2.2°F) in the UCRB and approximately 1.7°C (3°F) in LCRB. River water temperatures have also increased over the past decades. For example, from 1950 to 2015, the annual cumulative daily water temperature (number of degree-days) increased by about 13% in the Colorado River near Cisco, Utah and 11% in the Green River at Green River, Utah (U.S. Fish and Wildlife Service 2018c). This was interpreted as warming of about 1.5 °C (2.7°F) per decade in mean annual water temperatures in the Colorado River and 1.3°C (2.3°F) in the Green River (U.S. Fish and Wildlife Service 2018c).

In addition to altered stream temperatures, climate change could impact snow conditions, runoff timing and magnitude, and annual hydrograph patterns, such as reduced April 1 snow water equivalent (Figure 20, middle left plot), reduced summer runoff, and increased December to March runoff (Figure 20, bottom left plot). Some models predict slight to no increases in annual precipitation, but changes in the timing of precipitation, and a shift from snow to more rain, especially in lower-elevation transition zones (U.S. Bureau of Reclamation 2016b). Other models suggest that warming alone could reduce annual runoff in the absence of increased precipitation (Udall and Overpeck 2017; McCabe *et al.* 2017). Altered hydrographs, especially decreased streamflow or earlier runoff could affect Colorado pikeminnow habitat, individuals, and populations. In the upper basin, decreased April-July runoff could reduce habitat-creating peak flows that clean and maintain spawning bars and decrease base flows that transport larvae and provide nursery habitats (Bestgen and Hill 2016a). Habitat changes could affect reproduction through decreased spawning habitat and reduction in survival and recruitment.

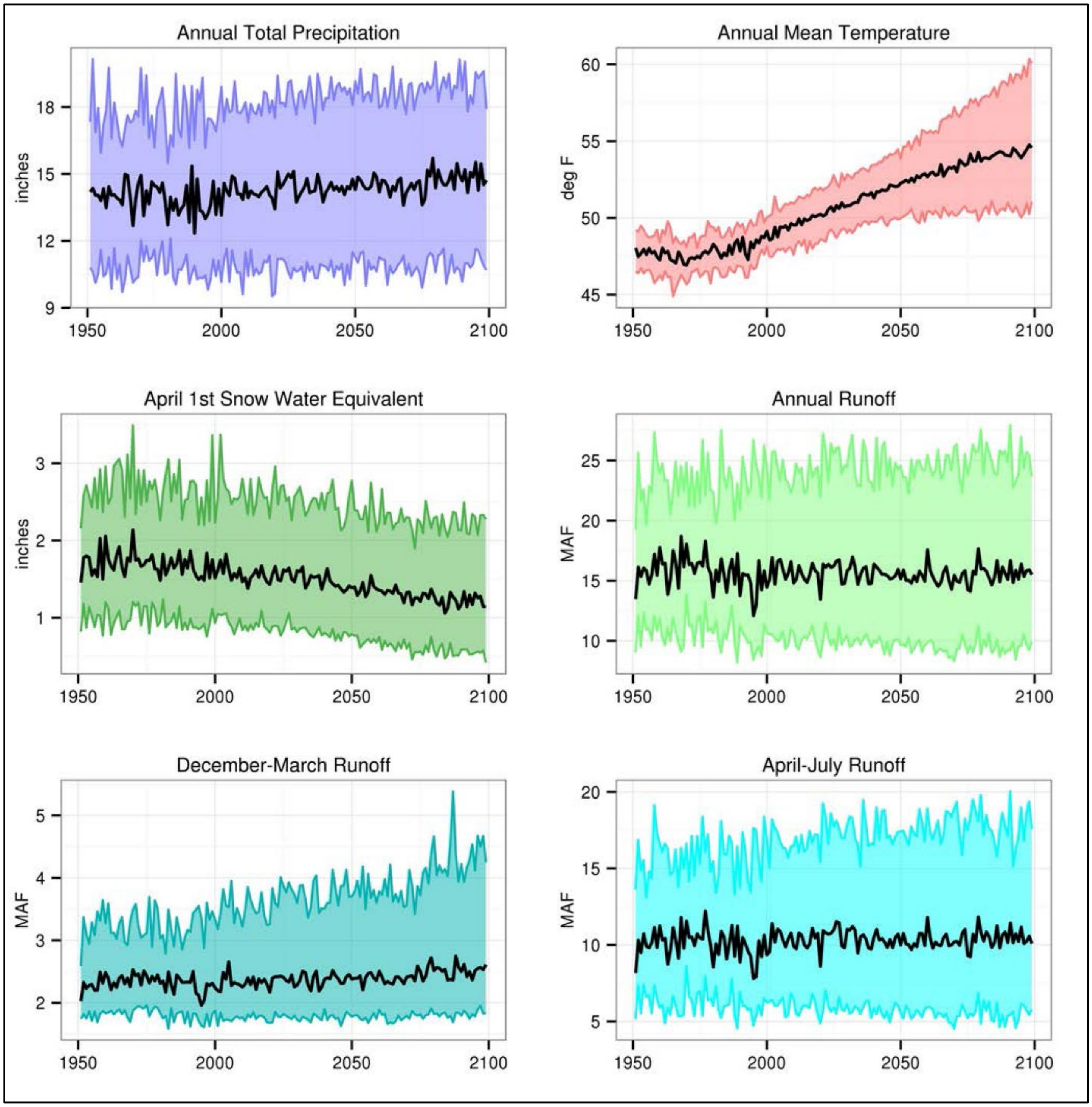


Figure 20. Time series plots for six projected hydroclimate indicators in the Colorado River basin from 1950-2099 (indicators title above each individual plot). The black line shows the annual time-series median value with the 10th and 90th percentiles shaded (figure from U.S. Bureau of Reclamation 2016b).

Warming river temperatures could also expand available habitat in upstream reaches of the upper Colorado River basin influenced by dam releases, such as the Green River below Flaming Gorge, the upper Colorado River upstream of the GVWU diversion, the Gunnison River, and the upper

San Juan River (Osmundson, D. B. 2011). In the lower basin, conditions in the Grand Canyon could become more suitable for Colorado pikeminnow as lower water levels in Lake Powell may increase temperatures and therefore increase habitat availability in the cool water stretches downstream of Glen Canyon Dam. However, increased introduction and expansion of warm-water nonnative fish is also a risk under warming conditions in the Grand Canyon (Kegerries *et al.* 2018; U.S. Fish and Wildlife Service 2018c). Warming water temperatures may also lead to earlier spawning, increased growth rates, and more rapid development of Colorado pikeminnow in some settings. Increased water temperatures could also benefit survival, reproduction, and distribution of nonnative, warm-water species that are known to have negative impacts on Colorado pikeminnow survival and recruitment, such as smallmouth bass in the upper basin. Although changes are expected to occur slowly over decades, the impact may be exacerbated if native fish temperature thresholds are exceeded while nonnative fish are able to successfully reproduce and recruit in areas not currently occupied by nonnatives. The direct negative impacts from climate change primarily result from reduced runoff amounts or earlier peak flows, while indirect negative impacts are associated with increased production of nonnative fishes. Direct positive impacts from climate change includes warming of certain river reaches cooled by reservoir releases and potential increased growth rates. Colorado pikeminnow individuals can likely adapt to increasing water temperatures alone, but if these increased temperatures are accompanied by changes in flow regime, magnitude, and overall water availability, the combined effects are likely to result in an overall negative impact to the species (Osmundson, D. B. 2011).

Because the effects of climate change depend largely on how warming temperatures influence the species' resource needs outlined above, this stressor is reflected in assessing the current and future conditions of habitat factors. For example, climate change models suggest reduced flows might be expected on a more frequent basis, and this SSA examines the effects of peak and base flow magnitudes and frequencies. Climate change also has the potential to affect water temperature, which is evaluated in this process. Warmer water temperatures and reduced flows would also be expected to increase the distribution and abundance of certain nonnative fishes, and this stressor is considered hereafter. Additionally, conservation measures are largely directed at the immediate stressors currently affecting the species, and the Population Viability Analysis (Miller, P. S. 2018) used for assessing future conditions forecasts population responses to changes in underlying demographic rates, based on how these demographic rates react to habitat changes or management actions. Because the UCRB is required to deliver a certain annual volume of water to the LCRB under a variety of legal frameworks collectively referred to as the "Law of the River" (U.S. Bureau of Reclamation 2016a), and because the flow regime is largely determined by releases from water projects throughout the UCRB, it is unclear how reduced runoff might impact flow regimes important to Colorado pikeminnow. The PVA makes predictions, however, of how populations might respond to changes in the frequency of base flows and to changes in carrying capacity due to range expansion.

4.2 Conservation Measures

Colorado pikeminnow conservation activities have occurred since the late 1980s, and five large-scale endangered fish species recovery or conservation programs are currently administered in the Colorado River Basin (Table 5). Two programs, the Upper Colorado River Endangered Fish Recovery Program (UCREFRP) and the San Juan River Basin Recovery Implementation Program (SJRIP), were initiated under cooperative agreements signed by the Secretary of

Interior and the Governors of the impacted states. The goal of these agreements was to recover endangered fishes, including Colorado pikeminnow, while water development proceeds in compliance with applicable State and Federal laws, interstate compacts, and Federal trust responsibilities to Native American tribes. The UCREFRP was established in 1988 as a coordinated effort of governmental agencies, water users, energy distributors, and environmental groups throughout the Green and Colorado river subbasins (Wydoski and Hamill 1991). The San Juan River subbasin was not included in the UCREFRP, but the SJRIP was established as the result of an ESA Section 7 consultation in 1992 (Evans, P. 1993). Recovery plans for Colorado pikeminnow, as well as the other species covered by the programs, guide both programs. Management elements in both programs include instream flow protection; habitat restoration; reduction of nonnative fish impacts; propagation and genetics management; research, monitoring, and data management; information and education; and program management. Cooperative agreements between stakeholders for both programs expire in 2023, and annual funding has been authorized through 2023 (via PL 116-9). The programs and their partners are currently planning what activities may be needed to achieve and maintain recovery after the existing agreements expire, but the scope and character of any future programs is uncertain.

Table 5. Native fish recovery or conservation programs in the Colorado River basin.

Basin	Program Name	Type of Program	Year Est.
Upper	Upper Colorado River Endangered Fish Recovery Program	Recovery Implementation	1988
	San Juan River Basin Recovery Implementation Program	Recovery Implementation	1992
Lower	Glen Canyon Dam Adaptive Management Program	Federal Advisory Committee	1997
	Lower Colorado River Multi-Species Conservation Program	Habitat Conservation Plan	2005
	Gila River Basin Native Fishes Conservation Program	Biological Opinion Conservation Measure	1994
	Salt River Project	Habitat Conservation Plan	2008

Native fish conservation programs in the lower Colorado River basin are also designed to balance demands for water while providing conditions for native fishes to persist (Table 5). The Glen Canyon Dam Adaptive Management Program (GCDAMP) was established through a Secretary of Interior charter and coordinates protection of native fishes within the Grand Canyon reach. The GCDAMP is under the direct supervision of the Secretary of the Interior and funding is currently legislated without sunset. As it pertains to Colorado pikeminnow, Grand Canyon National Park, a GCDAMP participant, identified and prioritized the implementation or initiation of a Colorado pikeminnow reintroduction feasibility study in their most recent Comprehensive Fisheries Management Plan priorities (National Park Service 2013).

Downstream of the Grand Canyon reach, the Lower Colorado River Multi-Species Conservation Program (MSCP) coordinates conservation of native species within the lower Colorado River mainstem from Lake Mead downstream, including the historic 100-year floodplain of the Colorado River, to the international boundary between the United States and Mexico (Lower Colorado River Multi-Species Conservation Program 2004). The MSCP provides ESA compliance for water development projects through a Habitat Conservation Plan (HCP). The goals of the MSCP include the conservation of habitat, work towards the recovery of threatened and endangered species (razorback sucker and bonytail), reduction in likelihood of additional species listings, and accommodation and optimization of current and future water development (Lower Colorado River Multi-Species Conservation Program 2004). Funding for the MSCP will expire in 2055.

The Gila River Basin Native Fish Conservation Program (GRNFCP) was also established as the result of an ESA Section 7 consultation for the operation of the Central Arizona Project (Duncan and Clarkson 2013). The purpose of the GRNFCP is to undertake conservation actions for federal and state-listed or imperiled species by implementing existing and future recovery plans including those for fishes. The Salt River Project's (SRP) Horseshoe-Bartlett HCP is also administered in the Gila River subbasin. This HCP supports conservation of native fishes in the Verde River (Salt River Project 2008). Although neither the GRNFCP nor SRP were established to recover Colorado pikeminnow, both programs fund Arizona Game and Fish Department's Bubbling Ponds Hatchery and Native Fish Research Facility which has produced and stocked Colorado pikeminnow into the Verde River (Duncan and Clarkson 2013; Salt River Project 2017). Both programs also support fish surveys in the system that could aid in monitoring survival of stocked Colorado pikeminnow in the Verde River. Recently, however, Arizona Game and Fish Department decided to cease the stocking of Colorado pikeminnow in the Verde River (J. M. Carter, AZGFD, pers. comm.).

4.2.1 Implementation of flow and temperature recommendations

Flow recommendations

Because the timing and magnitude of river flow is such a critical component for Colorado pikeminnow and other endangered fish, flow targets have been developed for multiple river reaches in the upper Colorado River basin based on relationships between flow and the understanding of endangered fish biological responses. This includes flow targets for the Green, Yampa, Duchesne, Gunnison, San Juan, and the upper Colorado rivers. Achieving (or reducing shortfalls to) these targets is typically accomplished by augmenting or timing instream flows using allocated storage, leased water, and/or modified reservoir operations. Flow recommendations and management across the UCRB are based on providing both peak and base flows necessary to benefit endangered fishes, and Colorado pikeminnow specifically.

Flow targets have been developed and adopted for three reaches of the Green River, demarcated by three river confluences (Flaming Gorge Dam to the Yampa River confluence [Reach1], the Yampa River confluence to the White River confluence [Reach 2], and the White River confluence downstream to the Colorado River confluence [Reach 3]) as described by Muth et al. (2000; Appendix V). These flow recommendations are based on annual hydrologic conditions for the basin (wet, moderately wet, average, moderately dry, and dry), and Flaming Gorge Dam is operated to meet these recommendations under a Record of Decision (ROD; U.S. Bureau of Reclamation 2006b). The recommendations include peak flow targets for Reach 2 (Jensen, UT) of ≥527 m^3/s (≥18,600 cfs) in years with predicted run-off volumes in the wet to average categories (Appendix V; Muth *et al.* 2000), with the exception that this peak be achieved in 50% of average years. The recommendations also include durations for achieving certain peak flows. These flow magnitudes for the recommended duration have been shown to maximize both backwater habitat area and volume (Figure 4; Grippo *et al.* 2017). In addition, these flows provide some in-channel habitat maintenance such as mobilizing bed materials, cleaning gravel bars, and scouring vegetation to maintain channel width and complexity. Spring peak flows of >527 m^3/s (>18,600 cfs) in reach 2 occurred in six years between 2006–2019 (Table 6; LaGory *et al.* 2019), and the recommended duration of two weeks occurred during two of those years. For 2006-2015, the peak flow magnitudes and durations in Reach 2 met the recommendations in all ten years (LaGory *et al.* 2019). Flow recommendations in Reach 3 (measured at Green River, UT) are slightly higher for magnitudes in a given hydrology, but generally follow the same patterns as Reach 2. Because this reach of river relies on additional tributary inputs from the White, Duchesne, and Price rivers, the peak flow targets have been achieved less frequently (Table 7). The Green River Evaluation and Assessment Team report (GREAT; LaGory *et al.* 2019) indicates that peak flow magnitudes of ≥623 m^3/s (≥22,000 cfs) were only achieved in 1 of 4 average years, rather than the 50% of average years recommended, and peak flow duration in average years has not been met. Since the GREAT analysis, recommended peak flow magnitude in both reaches was not achieved in one year (2017) because hydrology in the Green and Yampa rivers was drastically different. Beginning in 2012, experimental changes to management of Green River peak flows have included timing Flaming Gorge releases to maximize the entrainment of razorback sucker larvae into floodplain wetland areas providing favorable nursery habitat. This change in timing may affect the frequency of meeting peak flow targets in the future because Flaming Gorge releases are no longer coordinated to coincide solely with Yampa River peak flows (LaGory *et al.* 2019).

Table 6. Hydrologic classification, recommended peak flows, and observed peak flows and duration in the Green River at Jensen, UT (reach 2), since implementation of the 2006 ROD. From LaGory *et al.* (2019). Bold red text indicates a flow recommendation was not met.

Year	Hydrologic classification	Recommended peak flow magnitude[3] (cfs)	Peak mean daily flow (cfs)	# days ≥22,700 cfs	# days ≥18,600 cfs[4]	# days ≥8,300 cfs
2006	Average	18,600	18,400	0	0	55
2007	Moderately dry	8,300	12,500	0	0	14
2008	Average	18,600	23,500	4	14	59
2009	Average	18,600	18,500	0	0	61
2010	Moderately dry	8,300	19,400	0	2	34
2011	Moderately wet	20,300	31,300	35	58	100
2012	Moderately dry	8,300	10,200	0	0	**5**
2013	Moderately dry	8,300	10,400	0	0	24
2014	Average	18,600	19,500	0	4	44
2015	Moderately dry	8,300	14,900	0	0	40
2016	Moderately dry	8,300	21,100	0	9	60
2017	Moderately wet	20,300	**18,300**	0	0	104
2018	Moderately dry	8,300	12,600	0	0	27
2019	Average	18,600	20,800	0	9	63

---

[3] Peak magnitude recommendation in average years is 18,600 cfs in 50% of those years. Not achieving 18,600 cfs in a particular year does not mean the recommendation was not achieved. Since 2006, the recommendation has been met because mean daily flow in Reach 2 was at or above 18,600 cfs in 2 of 4 average years satisfying the 50% requirement.

[4] Recommended number of days above 18,600 cfs in average years is 14 days in 25% of those years. Not achieving 14 days above 18,600 cfs in a particular year does not mean the recommendation was not achieved. Since 2006, the recommendation has been met because the mean daily flow in Reach 2 was at or above 18,600 cfs for two weeks or more in 1 of 4 average years satisfying the 25% requirement.

Table 7. Hydrologic classification, recommended peak flows, and observed peak flows and duration for the Green River at Green River, UT (reach 3), since implementation of the 2006 ROD. From LaGory *et al.* (2019). Bold red text indicates a flow recommendation was not met.

Year	Hydrologic classification[5]	Recommended peak flow magnitude cfs	Peak mean daily flow cfs	# days ≥24,000 cfs	# days ≥22,000 cfs[6]	# days ≥8,300 cfs
2006	Average	22,000	21,000	0	**0**	63
2007	Moderately dry	8,300	14,100	0	0	20
2008	Average	22,000	26,200	6	**11**	65
2009	Average	22,000	**21,500**	0	**0**	68
2010	Moderately dry	8,300	24,200	1	6	41
2011	Moderately wet	24,000	43,700	59	61	116
2012	Moderately dry	8,300	10,900	0	0	**5**
2013	Moderately dry	8,300	11,500	0	0	28
2014	Average	22,000	**20,600**	0	**0**	49
2015	Moderately dry	8,300	15,900	0	0	45
2016	Moderately dry	8,300	24,200	3	10	62
2017	Moderately wet	24,000	**21,800**	0	**0**	115
2018	Moderately dry	8,300	12,700	0	0	29

Modifications to the recommended summer base flows in the Green River have been implemented on an experimental basis since 2008. Since 2015, based on the analysis of Bestgen and Hill (2016a), managers have attempted to meet revised flow recommendations using flexibility allowed under the 2006 ROD (Appendix VII). These experimental changes, which are intended to favor greater survival of age-0 Colorado pikeminnow, include somewhat higher base flows in normal and drier hydrologic years than recommended by Muth et al. (2000). Looking at the most recent 10-year period (2009-2018), recommended August-September base flows based on Bestgen and Hill (2016a) have been achieved in 7 of 10 years (Table 8), although it is worth noting that flows were still relatively high and above the recommendations when Colorado pikeminnow larvae were still drifting in 2016 and 2017. Backwater habitats are believed to be limited at flows >85 m^3/s (3,000 cfs) since the sandbars that form backwater margins are inundated.

---

[5] Classification for 2006–2015 based on May 1 forecast for April-July inflow into Flaming Gorge and updated exceedance values.

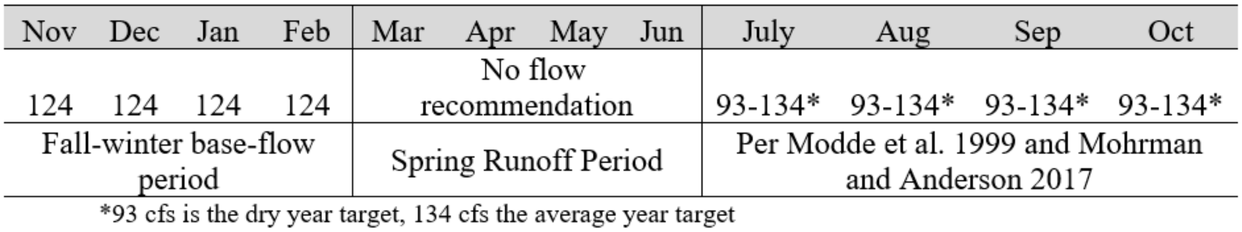
[6] Recommended number of days ≥623 m^3/s (≥22,000 cfs) in average years is 14 days in 25% of average years. Not achieving 14 days ≥623 m^3/s (≥22,000 cfs) in a particular year does not mean the recommendation was not achieved that year, however this duration has not been met in any of the average years since implementing the ROD.

Table 8. Mean August-September flows (cfs) for the middle and lower Green River, 2009-2018. Bold red text indicates revised flow recommendations from Bestgen and Hill (2016a) were not met.

Year	middle Green River	lower Green River
2009	2479	2785
2010	2165	2543
2011	**3686**	**5686**
2012	**1403**	**1342**
2013	**1506**	**1625**
2014	2978	3463
2015	2118	2328
2016	2151	2660
2017	2762	2998
2018	2261	2037

Summer base flow targets have also been identified for the Yampa River (Table 8; Modde *et al.* 1999; Anderson, R. and Stewart 2003; Roehm 2004; Mohrman and Anderson 2017), and procedures have been established to release water from Elkhead Reservoir to help meet these recommendations (Mohrman and Anderson 2017). These targets were designed to maintain productivity within the river and to allow for fish passage over shallow riffles, both of which should contribute to adult fish survival and habitat availability (Modde *et al.* 1999). Flows fell below the recommended minimum of 3 m^3/s (93 cfs) in 3 of 10 years between 2007–2016 over a total of 75 days (Mohrman and Anderson 2017), versus a history of falling below this threshold in about 38 percent of years, on average for nine days (1916-1995 period). Development of flow recommendations are underway for the White River (Anderson, D. M. *et al.* 2019) as are efforts to increase environmental flows in the Price River (Keller *et al.* 2018). The White River supports a large but declining adult Colorado pikeminnow population in the Green River subbasin (Bestgen *et al.* 2018), and flow recommendations here also seek to maintain the native fish community that serves as a forage base and fish passage during base flows. Flow recommendations have also been developed for the Duchesne River (Modde and Keleher 2003), with peak flow targets identified to maintain channel complexity and base flow targets to allow fish passage and to maintain primary productivity. In the 2005–2018 period, the average annual peak flow recommendations were met for the Duchesne River. Base flows fell below the target recommendation of 2 m^3/s (50 cfs) anywhere from 0 to 108 days during the same time because water availability is limited to meet targets in drier hydrologic years. The year 2004 was the first when managers attempted to meet flow targets, and the years 2009–2018 averaged 38 days where target flows were not achieved (range 0–108 days).

Table 9. Base flow (cfs) targets for Yampa River at Maybell gage location, Green River subbasin (Roehm 2004).



Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct
124	124	124	124	No flow recommendation				93-134*	93-134*	93-134*	93-134*
Fall-winter base-flow period				Spring Runoff Period				Per Modde et al. 1999 and Mohrman and Anderson 2017			

*93 cfs is the dry year target, 134 cfs the average year target

In the upper Colorado River subbasin, Osmundson et al. (1995) developed flow recommendations for a portion of the Colorado River called the "15-Mile Reach." These 15 miles of the Colorado River just upstream of its confluence with the Gunnison River are considered important Colorado pikeminnow habitat, and are influenced by water depletions from large diversions above this reach before Gunnison River flows contribute to the river's discharge. Peak flows are particularly important within this reach of river because they can contribute to the maintenance of spawning habitats. Recommendations were developed for peak and base flows, both expressed in terms of desired frequency of exceedance. Real-time flow targets for this river reach are based on the basin's current hydrologic condition (determined on the basis of projected natural runoff). The frequency with which recommended peak flows have been achieved since 1988 is summarized in Figure 21 (U.S. Fish and Wildlife Service 1999; Upper Colorado River Endangered Fish Recovery Program in prep.). This reach's base flow recommendations are expressed as mean monthly targets; during the irrigation season, flow in this reach of the river is typically supplemented with releases from storage in one or multiple reservoirs upstream made available for this use. Likewise, natural spring peak flows may be augmented by water voluntarily bypassed or released from upstream reservoirs by participants in the Coordinated Reservoir Operations (CROS) program.

Flows in the lower mainstem of the upper basin Colorado River are often disproportionately influenced by Gunnison River inflows, because of water depletions from the Colorado River upstream of the Gunnison confluence. This is particularly true for most of the spawning habitat and all of the currently occupied nursery reach of the Colorado River, which are located downstream of this confluence.

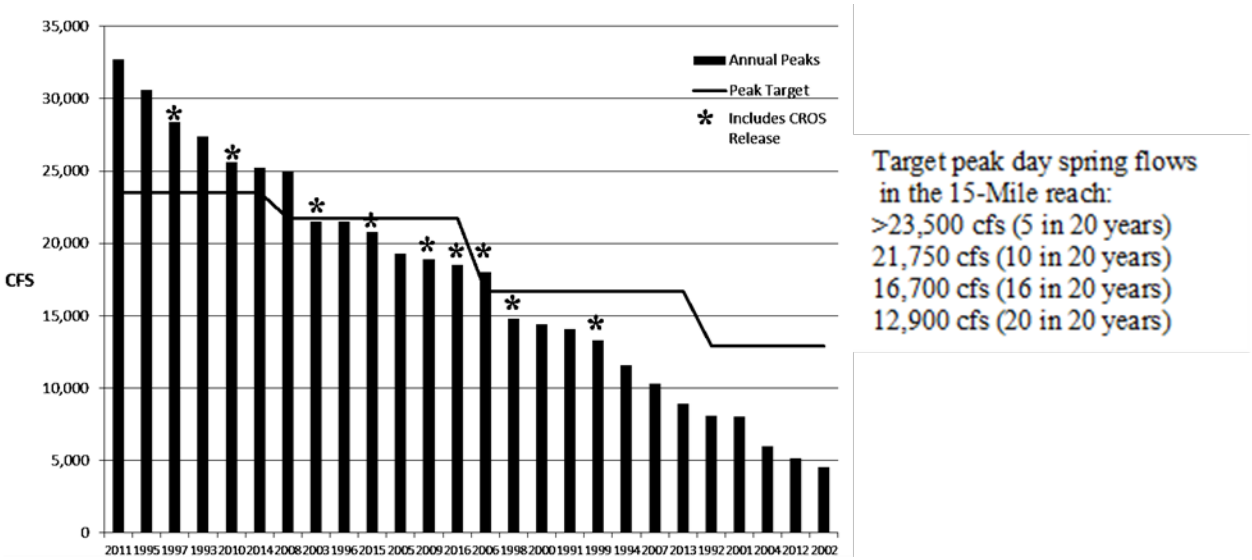


Figure 21. Annual peak flows (cfs) in the upper Colorado River 15-Mile Reach, 1991-2016, ranked highest to lowest. Asterisk indicates years in which flows were augmented from Coordinated Reservoir Operations (CROS) releases. Peak target line illustrates the recommended frequency of peak flows exceeding particular recommended magnitudes. Figure from Upper Colorado River Endangered Fish Recovery Program (in prep.).

On the Gunnison River, the 2012 ROD for operation of the Bureau of Reclamation's Aspinall Unit - composed of Blue Mesa, Morrow Point, and Crystal dams - included recommendations for both peak and base flows (Table 10; U.S. Bureau of Reclamation 2012b). The augmented flows of the Colorado River below the Gunnison River confluence would approximate channel maintenance flows recommended by Pitlick et al. (1999) and described in McAda (2003; Table 11). Summer base flows for the upper Colorado River follow recommendations of McAda (2003) for the reach below the Gunnison River confluence. The PVA team performed an analysis similar to that done for the Green River by Bestgen and Hill (2016a), where upper Colorado River base flows were assessed in terms of age-0 Colorado pikeminnow production (Valdez *et al.* 2017; McAbee 2017a). The Colorado River data displayed a similar trend as the Green River, where moderate mean August-September flows produced larger year classes of Colorado pikeminnow, and the high and low flow extremes showed lower production. These revised flows based on age-0 production are listed in Table 12. Because of the Gunnison River flow contribution, base flow targets below the Gunnison River confluence have largely been met (Figure 22; Miller, P. S. 2018).

Table 10. Spring peak flow and duration targets for a range of forecasted inflows. Aspinall Unit ROD (U.S. Bureau of Reclamation 2012b).

Blue Mesa Forecasted April-July Inflow (acre-feet)	Desired Peak at Whitewater, CO (cfs)	Duration of Half-Bank Days (8,070 cfs)	Duration at Peak Flow Days (up to 14,350 cfs)
<381,000	900	0	0
381,000 to 516,000	2,600 to 8,070	0	0
516,001 to 709,000	8,070	10	0
709,001 to 831,000	8,070 to 14,350	20	2
831,001 to 1,123,000	14,350	40	10
>1,123,000	14,350	60	15

Table 11. Peak flow recommendations for the Colorado River below the Gunnison River confluence (McAda 2003).

Hydrologic category	Magnitude (cfs)	Duration (days)
Dry (90-100% exceedance)	5,000-12,100	1
Moderately dry (70-90% exceedance)	9,970-27,300	1
	≥18,500	0-10
Average dry (50-70% exceedance)	≥18,500	20-30
	1-d peak of 18,500-26,600	
Average wet (30-50% exceedance)	≥18,500	30-40
	≥35,000	6-10
	1-d peak of ≥35,000	
Moderately wet (10-30% exceedance)	≥18,500	50-65
	≥35,000	15-18
	1-d peak of 35,000-37,000	
Wet (10% exceedance)	≥18,500	80-100
	≥35,000	30-35
	1-d peak of 39,300-69,800	

Table 12. Base flow recommendations (cfs) for the Colorado River below the Gunnison River confluence.

Hydrologic category	McAda 2003	Revised Miller 2018
Dry (90-100% exceedance)	≥1,800	3,000-3,600
Moderately dry (70-90% exceedance)	2,500-4,000	3,600-4,700
Average dry (50-70% exceedance)	2,500-4,000	3,600-4,700
Average wet (30-50% exceedance)	3,000-4,800	3,900-5,500
Moderately wet (10-30% exceedance)	3,000-4,800	3,900-5,500
Wet (10% exceedance)	3,000-6,000	3,900-6,400

Table 13. Peak flows and durations for the Colorado River at the Colorado-Utah state line, 2009-2018. Numbers in bold denote either flow magnitude or duration targets recommended by McAda (2003) were not achieved.

Year	Hydrologic Category[7]	Peak flow (cfs)	Days ≥18,500 cfs	Days ≥35,000 cfs
2009	moderately wet	**29,000**	**35**	**0**
2010	average dry	30,300	**14**	0
2011	wet	47,700	**70**	**16**
2012	dry	5,960	0	0
2013	moderately dry	13,100	0	0
2014	moderately wet	38,000	**31**	**7**
2015	average dry	31,400	26	0
2016	average wet	**24,500**	**20**	**0**
2017	average wet	**26,600**	**19**	**0**
2018	dry	8,570	0	0

---

[7] Hydrologic category determined by combining April-July forecast run-off volumes for the Colorado River and Plateau Creek near Cameo and the Gunnison River near Grand Junction. The combined volume was then compared to forecast run-off volume exceedances described in Table 4.2 from McAda (2003).

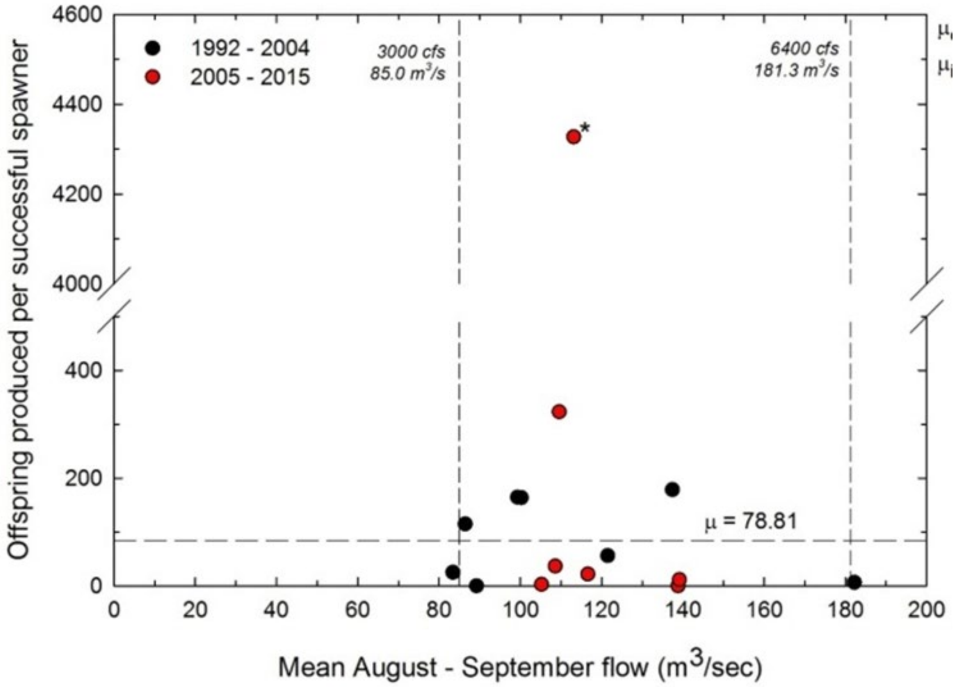


Figure 22. Mean summer base flows for the upper Colorado River (below the Gunnison River confluence) and relationship to offspring produced per successful spawning female Colorado pikeminnow. Vertical lines are recommended flow targets of 85 – 181 m^3/s (3000–6400 cfs) based on McAda (2003) and revised by the PVA team (Valdez *et al.* 2017). The horizontal line is the mean production of offspring over the full time period. The data point denoted by an asterisk (*) is the 2015 "spawning spike" described in Miller (2018). Figure from Miller (2018).

Attempts to achieve San Juan River flow targets are conducted through operations of Navajo Dam (Holden 1999; U.S. Fish and Wildlife Service 2018b). Flow targets are expressed in terms of flow magnitude, duration, and frequency. The desired and minimum frequencies for achieving peak flow targets are shown in Table 14. For the period 2009-2018, peak flows of >227 m^3/s (>8,000 cfs; to be met at least 1 in 6 years for 10 days) or >283 m^3/s (>10,000 cfs; to be met at least 1 in 10 years for 5 days) have not occurred in the San Juan River (Figure 23). A base flow target of 14 – 28 m^3/s (500–1,000 cfs) was identified to maximize backwater habitat while still allowing capacity to accommodate additional storm flows (Holden 1999). Recent analysis suggest that flows in the higher end of the target range (>21 m^3/s [>750 cfs]) may increase backwater habitat (Lamarra, V. A. *et al.* 2018). Median August through September flows have been within the recommended range in nine of the last ten years, but flows >21 m^3/s (>750 cfs) have been achieved less frequently (Figure 24). Median flows are presented because the San Juan River is prone to large discharge due to monsoonal events and typical flow management would be masked by using a mean daily flow.

Table 14. Desired and minimum peak flow target magnitudes, durations, and frequencies for the San Juan River (from U.S. Fish and Wildlife Service 2018b).

Flow target (cfs)	Duration (days)	Desired frequency (% years)	Maximum number of consecutive years between meeting target (years)
10,000	5	20%	10
8,000	10	33%	6
5,000	21	50%	4
2,500	10	80%	2

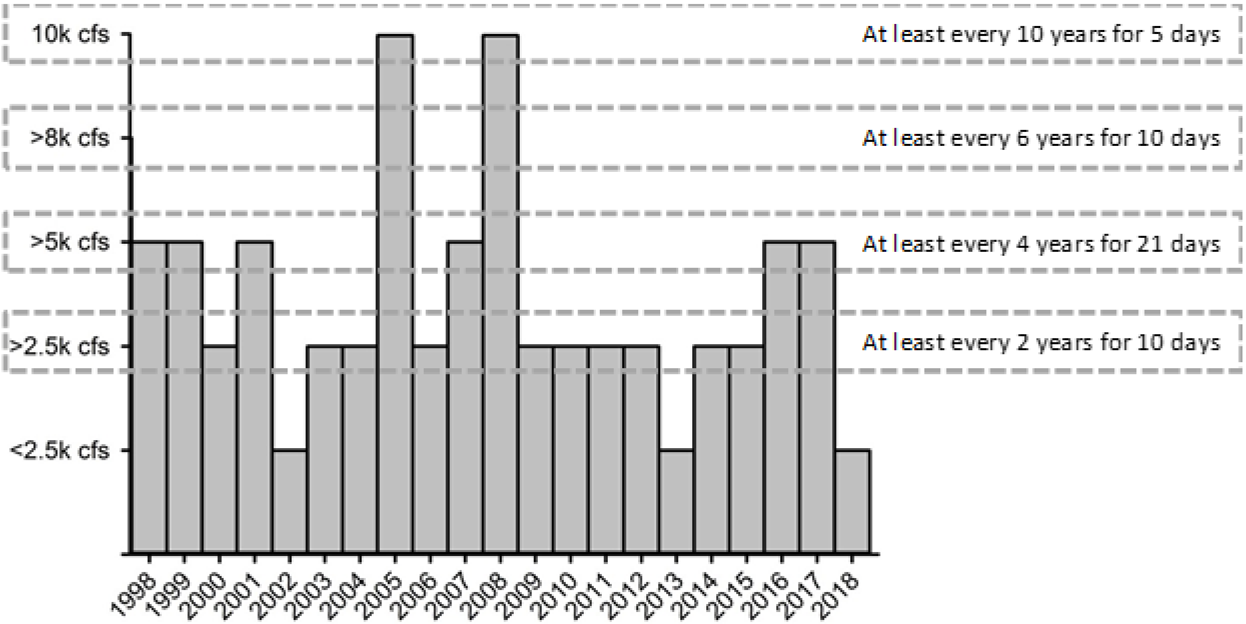


Figure 23. San Juan River spring peak recommendations and spring flow conditions (July to March). Figure modified from N. Franssen.

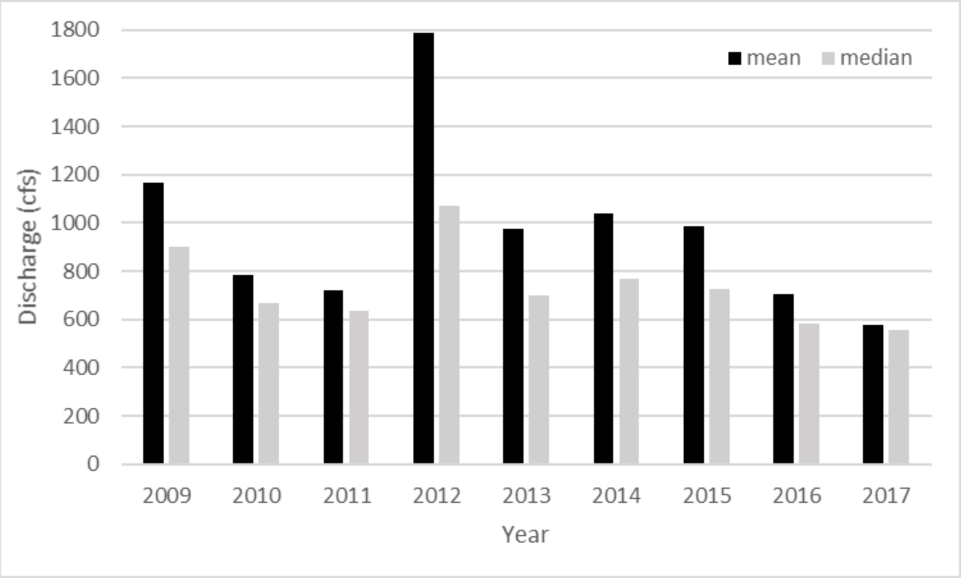


Figure 24. Mean and median August through September flows in the San Juan River at Four Corners. Flow recommendations target a base flow of 14 – 28 m^3/s (500–1,000 cfs).

In the lower Colorado River basin, the flow regime in the Grand Canyon reach is regulated by Glen Canyon Dam, which has some operational guidelines to support federally endangered humpback chub and other native fishes (U.S. Department of the Interior 2016). While peak and summer flows are not included in the protocols for operation of Glen Canyon Dam, daily flow fluctuations are held to no more than 227 m^3/s (8,000 cfs). Such fluctuations can produce a daily stage fluctuation of approximately 0.5 m (2 ft) at Lees Ferry during the base flow period, depending on flow (USGS gage 09380000). High experimental flows up to 1,274 m^3/s (45,000 cfs) are authorized for the creation of backwater habitat (Melis 2011) or disruption of nonnative fish species (Coggins *et al.* 2011). Other flow experiments have been implemented to restore the depauperate aquatic invertebrate community (Kennedy *et al.* 2016). We do not know of flow regulations or dam operations to support endangered fishes in the lower Colorado River mainstem, and environmental flows are not allocated for either the Verde or Salt rivers in the Gila River subbasin (Weedman, D. 2018, pers. comm.).

Temperature Recommendations

The operation of large dams can be altered to influence downstream water temperature regimes. For example, selective withdrawal structures can be used to make water releases from specified reservoir depths to adjust release temperatures. Because Colorado pikeminnow are a warmwater fish and reservoir releases typically depress water temperature, existing temperature recommendations for large dams often include operational recommendations that increase stream temperatures during critical times of the pikeminnow life history.

Tributaries in the Green River subbasin generally provide thermally suitable habitat between April–September (Figure 25). During the summer spawning and growing season, both the Yampa (Green River subbasin) and the Animas rivers (Figure 26; San Juan River subbasin) are now warmer than the mainstem rivers they flow into due to hypolimnetic releases from Flaming Gorge and Navajo dams, respectively (Holden 1999; Muth *et al.* 2000). These tributaries now function to ameliorate the temperature effects of hypolimnetic releases. Although these warmer tributaries mediate the influence of hypolimnetic release, spawning by Colorado pikeminnow in these tributaries could lead to larval mortality due to cold shock as they drift from warmer water into colder mainstem rivers (Muth *et al.* 2000). Management of water temperature below reservoirs can occur through the rate and timing of reservoir releases, and installation and use of devices that control the depth from which reservoir water is released. To reduce the risk of temperature shock to larvae drifting into the Green River a temperature control device (TCD) at Flaming Gorge Dam, is used with the goal of maintaining release temperatures which favor a temperature difference of no more than 5°C (9°F) between the Green and Yampa rivers at their confluence during the period of larval drift (Muth *et al.* 2000).

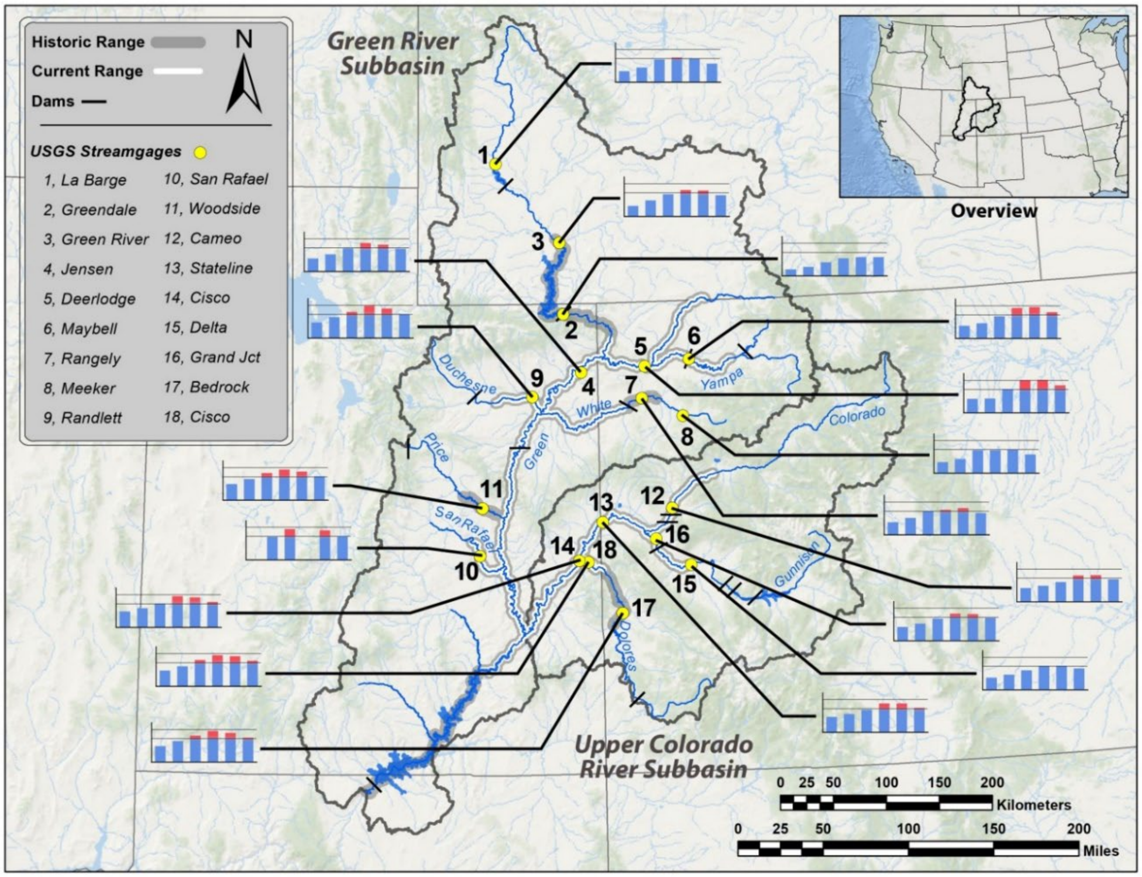


Figure 25. Mean monthly (April to September) water temperatures in Green and Colorado river subbasins (2010–2016). The lower horizontal line denotes 16°C (61°F) and upper line 25°C (77°F).

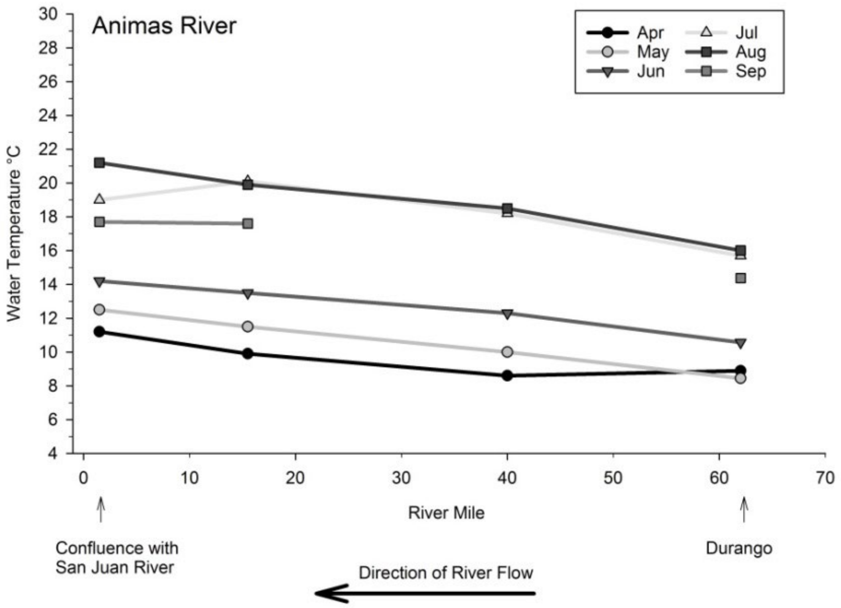


Figure 26. Animas River, tributary to the San Juan River, USGS gage water temperatures: mean monthly April to September (2010–2016).

The temperature control device at Flaming Gorge Dam is the only one in place within Colorado pikeminnow's historical range. Flaming Gorge Dam was retrofitted with a selective withdrawal structure in 1978 to improve water temperatures for the trout fishery just below the dam, although benefits to native communities further downstream were also anticipated (Peters 1978). Since 1993, releases from this structure were modified to support endangered fish recovery and have averaged >12.5°C (>54.5°F) from July to September, 0.4 RK (0.25 RM) downstream from the dam (USGS gage 09234500; 1993–2017). Releases from the dam are manipulated to increase water temperature during mid-June, usually well in advance of Colorado pikemnnow spawning activity. Since the 2006 Record of Decision (U.S. Bureau of Reclamation 2006b), these operations have resulted in increased frequency of river temperatures favorable for Colorado pikeminnow spawning (18°C [64°F]) in Lodore Canyon and have greatly reduced potential of thermal shock for larvae drifting out of the Yampa River into the Green River.

In the upper Colorado River subbasin, modeling of a temperature control device at the Aspinall Units (Gunnison River; Figure 13) estimated the average water temperatures from May to October could be increased to 9.5–19.5°C (49 - 67°F), to better support reestablishment of Colorado pikeminnow in the lower Gunnison River (Boyer and Cutler 2004; Osmundson, D. B. 2011). Similar modeling indicated warming of the San Juan River could occur with the installation of a temperature control device on Navajo Dam (Cutler 2006) and has been modeled for Glen Canyon Dam, which releases water into the Grand Canyon reach (Valdez *et al.* 2013). Temperature modeling for the Grand Canyon reach concluded that without modifications to Glen Canyon Dam to release warmer water, the entire reach is not likely to support the full life cycle of Colorado pikeminnow (Valdez *et al.* 2013). This same report concluded that installation of a temperature control device could provide water temperatures suitable for humpback chub spawning and growth in the lower Grand Canyon. Recent observations in that reach have shown increases in water temperatures as a result of lower Lake Powell reservoir elevations, and subsequently, humpback chub numbers have been increasing below Diamond Creek (~386 RK [~240 RM] from Glen Canyon Dam), with spawning suspected in the main channel (Van Haverbeke *et al.* 2017; Rogowski *et al.* 2018). These observations suggest that the current thermal regime may be more similar to that modeled for a TCD controlling temperature on two of Glen Canyon Dam's eight hydropower units. If this assumption is valid, the temperature modeling from Valdez et al. (2013) indicated the most downstream reach of Grand Canyon might currently provide suitable temperatures for all life stages of Colorado pikeminnow. Data from the Grand Canyon Monitoring and Research Center (GCMRC; Figure 27) show that water temperatures have exceeded 18°C (64°F) at Spencer Creek (USGS gage 09404220) in western Grand Canyon 12.6% of the time between 2009 and 2018. Rogowski et al. (2018) reported that water temperature in the same reach averaged 17.0°C (63°F) from May through September in 2016.

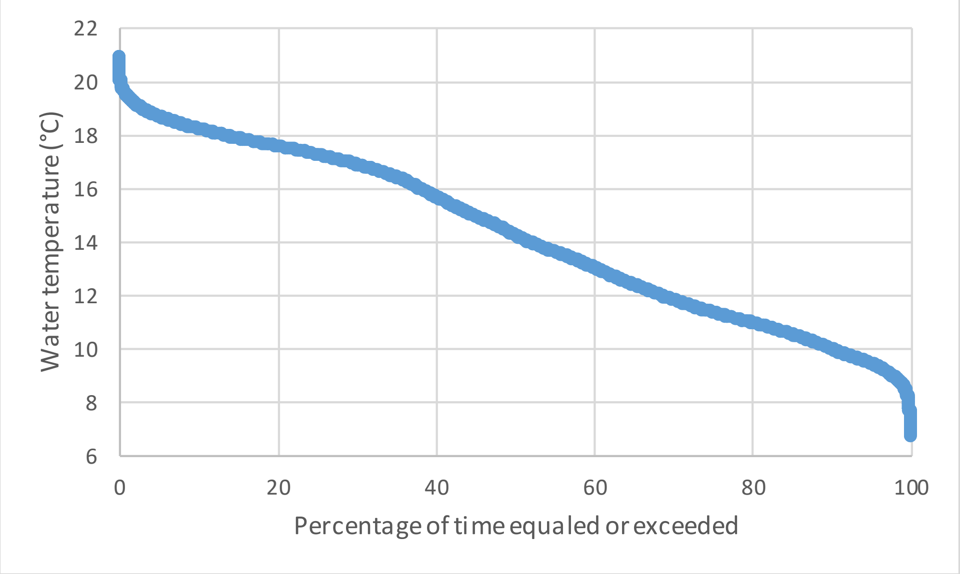


Figure 27. Duration curve of water temperatures for the Colorado River above Spencer Creek, Grand Canyon (RMI 246; USGS gage 09404220), 2009-2018.

There are few water temperature data sets available for the lower Colorado River mainstem as the USGS gages currently do not record water temperature, however, some information can be obtained from various reports. The MSCP Habitat Conservation Plan (Lower Colorado River Multi-Species Conservation Program 2004) describes the reach between Hoover Dam and Davis Dam as a "cold tailwater." The same document describes the reach immediately below Davis Dam as "controlled by the cold water discharge." From Parker Dam to Imperial Dam is characterized as warm. The 12 miles of the lower Colorado River mainstem between Davis and Parker dams was reported as "cool" in one fish survey report (Nevada Department of Wildlife 2015). Coldwater species like rainbow trout were collected during the survey but so were many warmwater nonnative species (see Section 4.1.5). The MSCP constructed backwaters in the lower Colorado River mainstem and these were described as being able to reach "high temperatures" (Lower Colorado River Multi-Species Conservation Program 2018). It is important to note, however, that these backwaters are large off channel habitats that resemble oxbow sloughs, rather than the smaller backwaters described above for nursery habitats. Between

2006 and 2007, water quality monitoring in some of these backwaters was highly variable, ranging from ~6–32°C (43 - 90°F) during the summer and between 15–30°C (59 - 86°F) during much of that time (Figure 28; Barkstedt *et al.* 2008).

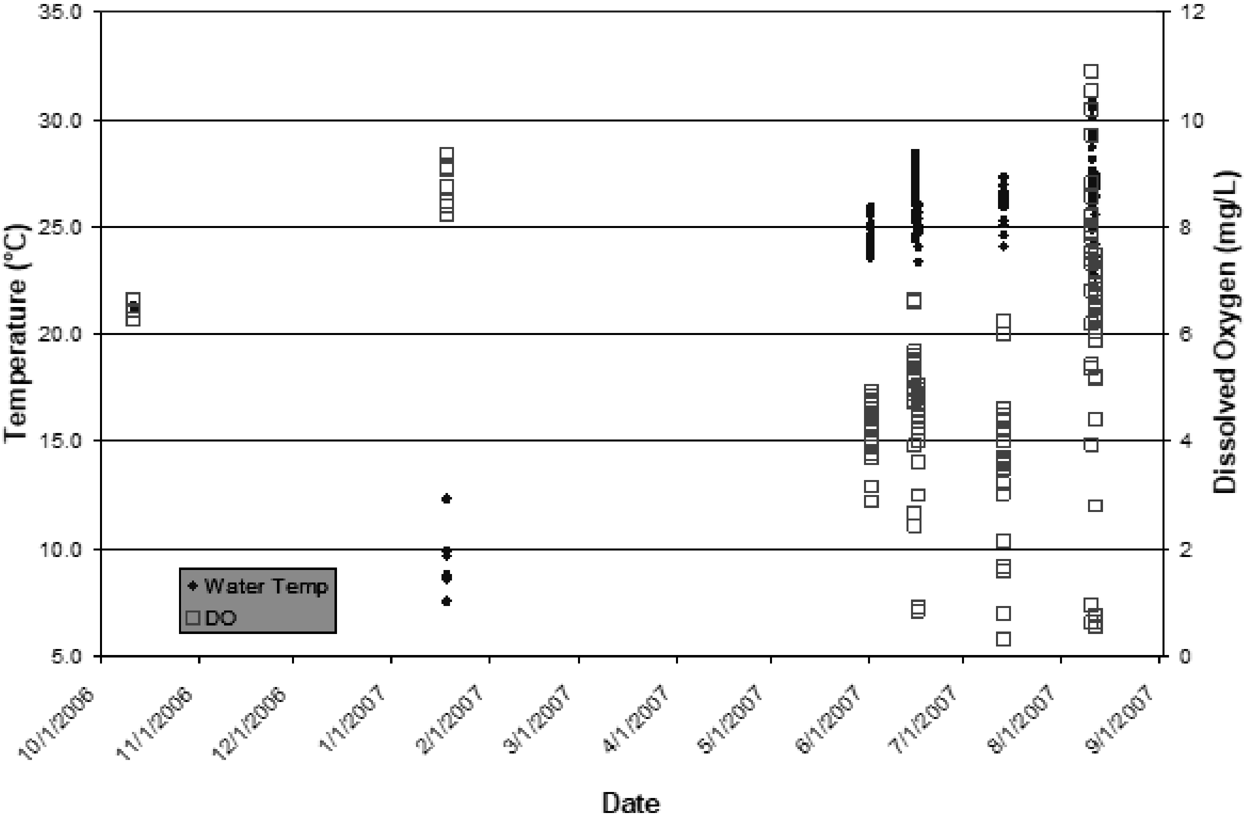


Figure 28. Lower Colorado River water temperatures (and dissolved oxygen) in a backwater (Barkstedt *et al.* 2008).

We also could not identify any USGS gages in the Gila River subbasin that collect water temperature data. However, the Verde River Institute has begun collecting water temperatures in variable types of habitats along the Verde River (verderiverinsititute.org). About 66 RK (41 RM) downstream of the Verde River headwaters, water temperature between March and October 2017 ranged from 11.5–26.3°C (53-79°F) and was consistently above 20°C (68°F) by June (Figure 29). In the Salt River above its system of reservoirs, water temperatures during fish surveys were recorded as 20.6°C (69°F) and 22.8 °C (73°F) in May (2004) at the top and bottom, respectively, of 64 RK (40 RM) sampled (Weedman 2004a). Three miles below the lowest reservoir in the Salt River system (Saguaro Lake) surface water temperature was 21–24°C (70 - 75°F) between August and October 2009 (Figure 29; Tarrant *et al.* 2009).

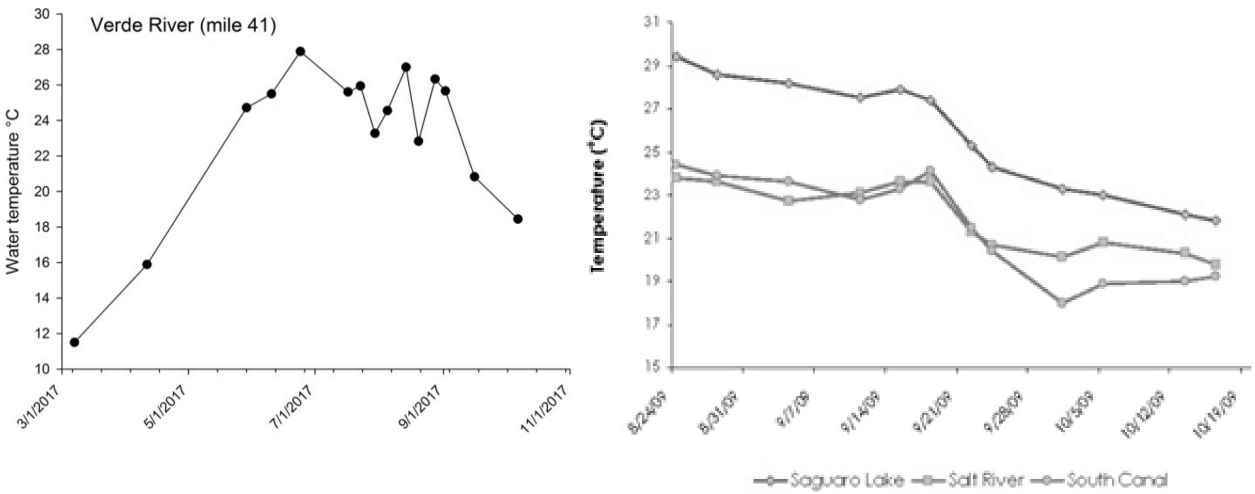


Figure 29. Water temperatures in the Verde (left) and Salt rivers (right). Verde River data from verderiverinsititute.org and Salt River data from Tarrant et al. (2009) collected ~5 kilometers (~3 miles) downstream of Stewart Mountain Dam's Saguaro Lake.

4.2.2 Fish passage and availability of connected habitats

Fish passages have been installed throughout the UCRB in order to facilitate the movement of endangered fishes, including Colorado pikeminnow. These passages are intended to allow the movement of fishes between reaches separated by the barrier, and often restore access to reaches that were historically occupied. The limited placement of large dams in the Green River subbasin has allowed Colorado pikeminnow to continue accessing ~901 RK (~560 RM) of critical habitat (Figure 13; Bestgen and Hill 2016a). However, two large dams (Flaming Gorge and Taylor Draw) prevent access to some historical habitat. The presence of Flaming Gorge Dam on the Green River precludes access to ~163 RK (~101 RM), and Taylor Draw Dam on the White River prevents Colorado pikeminnow from accessing about 72 RK (~45 RM) of designated critical habitat (Figure 13; 59 FR 13374; March 21, 1994). Two low head diversions are present in the Green River subbasin within critical habitat: one in the Yampa River (Maybell), and the Tusher Wash diversion dam which serves the Green River Canal and a small hydropower plant on the Green River (Figure 13). Colorado pikeminnow are thought to be able to pass upstream of the Maybell diversion at most river flows. The original 100 year old Tusher Wash diversion was considered a potential barrier to upstream fish movement during seasonal low flows (Modde *et al.* 1999; Natural Resources Conservation Service 2014). In 2016, the diversion was rebuilt with a design that would make it a more complete fish barrier, so a fish ladder was installed in the new construction (Upper Colorado River Endangered Fish Recovery Program 2016). While this should provide upstream fish passage, large river debris loads appear to be able to reduce the passage's efficacy (Jones, M.T. 2018 pers. comm.). Physical barriers do not exist between the Green and upper Colorado rivers which allows movement between these subbasins, although observed annual rates are low and estimated at 6.5 fish/yr in each direction (Osmundson, D. B. and White 2017a).

In the upper Colorado River subbasin, physical barriers to fish movement are present in the upper reaches but most diversions have been modified to provide upstream fish passage resulting in seasonal access to a total of ~398 RK (247 RM) for Colorado pikeminnow (Figure 13;

Osmundson, D. B. 2011; Osmundson, D. B. and White 2014). In the upper Colorado River above its confluence with the Gunnison River, three fish passages are present. The most downstream fish passage is at the GVIC diversion. This passage, a simple slot in the diversion dam, allows fish movement most of the year when flows are sufficient. At lower flows when the diversion intake is compromised, an inflatable bladder (Obermeyer gate) is used to block flow to the fish passage in order to raise the water elevation at the diversion. A second fish passage was constructed at the now inactive Price-Stubb diversion dam in 2008 and was designed to be nonselective, meaning the river is open to passage of all fish species fish year-round. This passage can become blocked by debris loads after high flows or can become unpassable during low flows in summer. Passage at this fish ladder is monitored by the use of passive integrated transponder (PIT) antennas. About six river miles upstream of Price-Stubb diversion dam is the GVWU (Government Highline) diversion, which was retrofitted in 2004 with a selective passage. This passage is actively operated from approximately mid-April to mid-October, through the use of a fish trap at the most upstream end of the fish passage. Thus, native fishes are able to move upstream when the passage is in operation, but nonnative fishes are not. Colorado pikeminnow use of the passage is monitored by captures at the fish trap.

Use of these fish passages by Colorado pikeminnow has been somewhat limited. From 2010–2017, fifty-four individual Colorado pikeminnow were detected by the Price-Stubb PIT antennas with some individuals encountered more than once (Ryden 2017). In 2017, 21 Colorado pikeminnow detections occurred. Of these, 17 were identified as fish that had moved in an upstream direction and some of these detections may have been of the same individual. At the GVWU Government Highline diversion fish passage, which has been in operation 11 years (since downstream passage was installed at Price-Stubb in 2008), five Colorado pikeminnow have been captured and moved upstream (Ryden 2017). The first Colorado pikeminnow capture was in 2014 (n = 1) with individual captures again in 2015 (n = 1), and 2016 (n = 1), and two individuals captured in 2017 (n = 2).

On the Gunnison River, just upstream of its confluence with the Colorado River, a fish passage was installed at the Redlands diversion in 1994. This passage is selective, operating from approximately April to October, and provides fish capture data. Over the 22 years the passage has been in operation (1996–2017), 187 Colorado pikeminnow were captured and moved upstream of the diversion dam (Table 17). Annual captures and upstream passage of Colorado pikeminnow has ranged from 0–33 individuals.

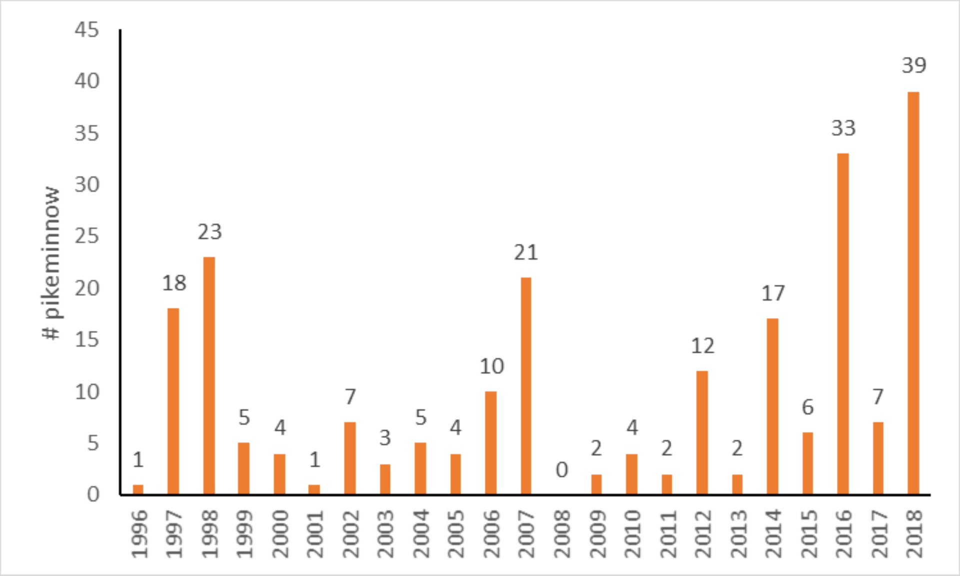


Figure 30. Number of Colorado pikeminnow passed over Redlands diversion dam through the fish passage, 1996-2018 (Francis 2018).

For San Juan River basin Colorado pikeminnow, Lake Powell appears to restrict movement between this and the Green and upper Colorado river subbasins. Colorado pikeminnow have not been detected making such trans-basin movements (Osmundson, D. B. and White 2017b; Colorado Natural Heritage Program 2019). Besides Lake Powell, two other major physical barriers to Colorado pikeminnow are present in the San Juan River subbasin (Figure 14). Navajo Dam is the most upstream barrier, precluding Colorado pikeminnow use of at least 12 RK (7.5 RM) of its most upstream historical range. About 370 RK (230 RM) downstream of Navajo Dam, a waterfall (Piute Waterfall) formed which is impassable to fishes swimming upstream. Piute Waterfall formed in the late 1980s when Lake Powell's elevation declined, leaving behind a sediment delta deposited when the lake elevation was higher (Figure 31; Ryden and Ahlm 1996; Cathcart *et al.* 2018). Piute Waterfall has migrated around the delta as Lake Powell water elevation has fluctuated, but has been in its present location since 2000 and is currently >6 m (>19.7 ft) tall (Cathcart *et al.* 2018). As of 2018, there was approximately 24 kilometers (15 miles) of riverine habitat between the waterfall and the reservoir.

The waterfall presents some challenges and potential benefits to Colorado pikeminnow in the San Juan River subbasin. Recent fish surveys directly below the waterfall, and within ~ 16 RK (~ 10 RM) of downstream riverine habitat, resulted in the capture of 45 sub-adult/adult (ages 3–12 years) and 263 age-1 Colorado pikeminnow (Pennock *et al.* 2018). Some of these fish had been implanted with PIT tags when first captured in the San Juan River upstream of the waterfall (Pennock et al. unpublished data). We do not currently know how long entrained fish can survive in the more lentic habitat of Lake Powell, and the presence of abundant nonnative, predaceous fishes in the lake may increase Colorado pikeminnow mortality in this habitat. Colorado pikeminnow entrained over the waterfall may be lost from the San Juan River subbasin population. However, the waterfall also prevents the upstream movement of Lake Powell's nonnative predaceous fishes, protecting Colorado pikeminnow in the San Juan River above the waterfall.

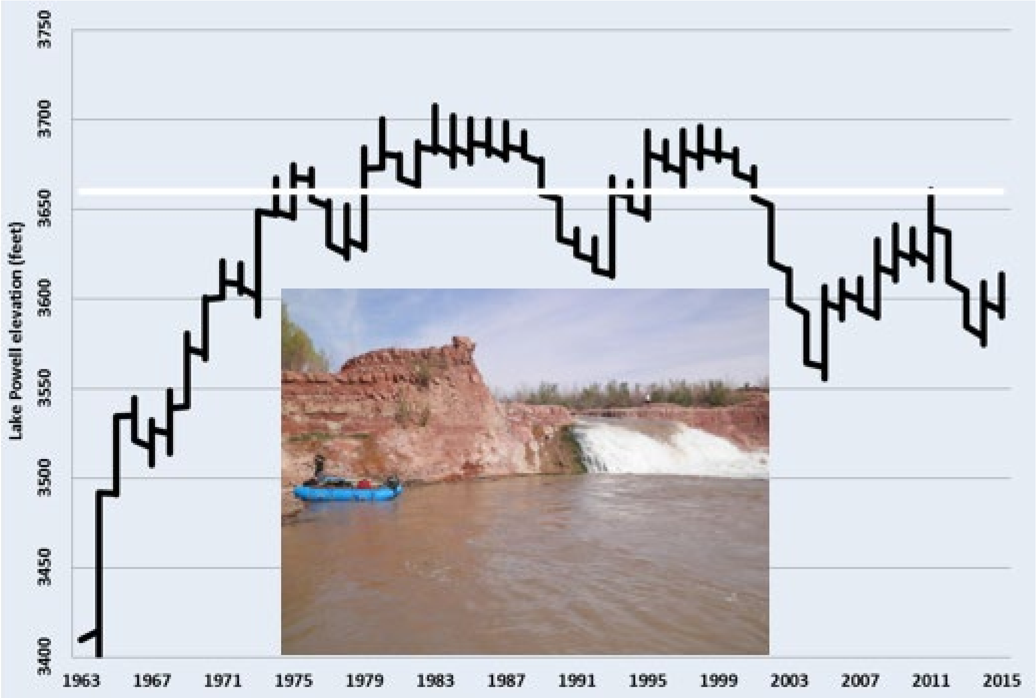


Figure 31. Relationship of Lake Powell's elevation to the presence of a waterfall on the San Juan River at the river's inflow to Lake Powell. At elevations below 3660' (white horizontal line) the waterfall forms (McKinstry *et al.* 2016); photo - March 2015.

Thirty-three low head diversions are present in the upstream portions of Colorado pikeminnow's current range in the San Juan River subbasin (Figure 14; Lyons *et al.* 2016) and of these three are equipped with fish passages. The passages at Hogback and Animas Pump 2 are non-selective. The Public Service Company of New Mexico diversion (PNM) fish passage is operated from March to October, and was managed selectively prior to 2018. More recently, this passage has been open (non-selective) in the spring (March-May) and operated selectively the rest of the season. Assessment of upstream fish passage at Fruitland, Jewett, and Farmer's Mutual irrigation diversions indicated they were likely passable, while the diversion at Arizona Public Service (APS) was thought to be an impediment during low river flows (Stamp *et al.* 2005). Although the remaining 23 diversion structures have not been assessed for upstream fish passage, at a minimum Colorado pikeminnow potentially have seasonal access to ~ 418 RK (~ 260 RM) of habitat in the San Juan River subbasin. This includes approximately 26 RK (16 RM) of McElmo Creek.

PIT tag antennas have been installed in the Hogback irrigation canal sluiceway and diversion facility since 2015. Data from these systems in March 2018 indicated that passage rates of Colorado pikeminnow at the Hogback canal, when the variable frequency drives were not in operation, was 28% (n = 8; Figure 32). Of those eight fish, 75% (n=6) passed upstream of the APS weir as they were detected at the PNM PIT antenna system. None of the 15 fish detected at APS were detected as having moved upstream to PNM. The fish passage at PNM was not in operation in March and so none of the fish detected there were moved upstream. However, when the passage has been in operation, 1,152 Colorado pikeminnow were captured and passed upstream of the PNM weir with annual captures ranging from 1–625 (Table 15; Colorado Natural Heritage Program 2019).

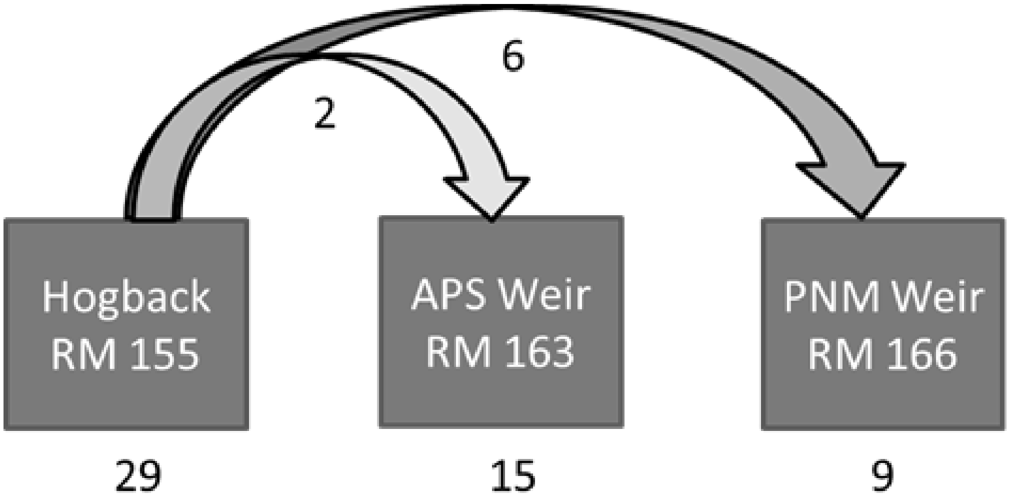


Figure 32. Detection of Colorado pikeminnow by PIT tag antennas in the San Juan River (March 2018). The number below each square indicates fish detected below the diversion and the number associated with the arrow are those detected upstream (Franssen May 22, 2018).

Table 15. Number of Colorado pikeminnow captured and passed upstream at the San Juan River's Public Service of New Mexico fish passage (Colorado Natural Heritage Program 2019).

Year	Number	Year	Number	Year	Number
2017	174	2011	625	2005	8
2016	137	2010	85	2004	4
2015	4	2009	NA	2003	7
2014	11	2008	5		
2013	73	2007	NA		
2012	18	2006	1		

It is likely that Colorado pikeminnow that passed upstream at both the Hogback and APS diversions in the San Juan River used the sluiceways at these facilities. A camera installed on 19 February 2018 at the Hogback irrigation canal system showed the nonselective fish passage was dry until 9 April when diversion into the irrigation canal began (Figure 33). Water does not flow over the APS weir during certain river flows and in March 2018 the average discharge at the USGS gage (09365000) upstream of the APS weir the river was 15 m^3/s (517 cfs). At this flow, the APS weir was not inundated but water was flowing through the sluiceway (Figure 34). Thus, the eight and six Colorado pikeminnow that passed upstream of Hogback and APS, respectively, likely used the systems' sluiceways.

In the near future, the Fruitland irrigation diversion facility will be rehabilitated and a nonselective fish passage similar to that at the Hogback irrigation diversion will be installed (Figure 33). Plans are also underway to retrofit the APS system to make it more permeable to upstream fish passage. Constructing these passages to improve operational efficiency would increase Colorado pikeminnow upstream passage and use of the full extent of connected river.

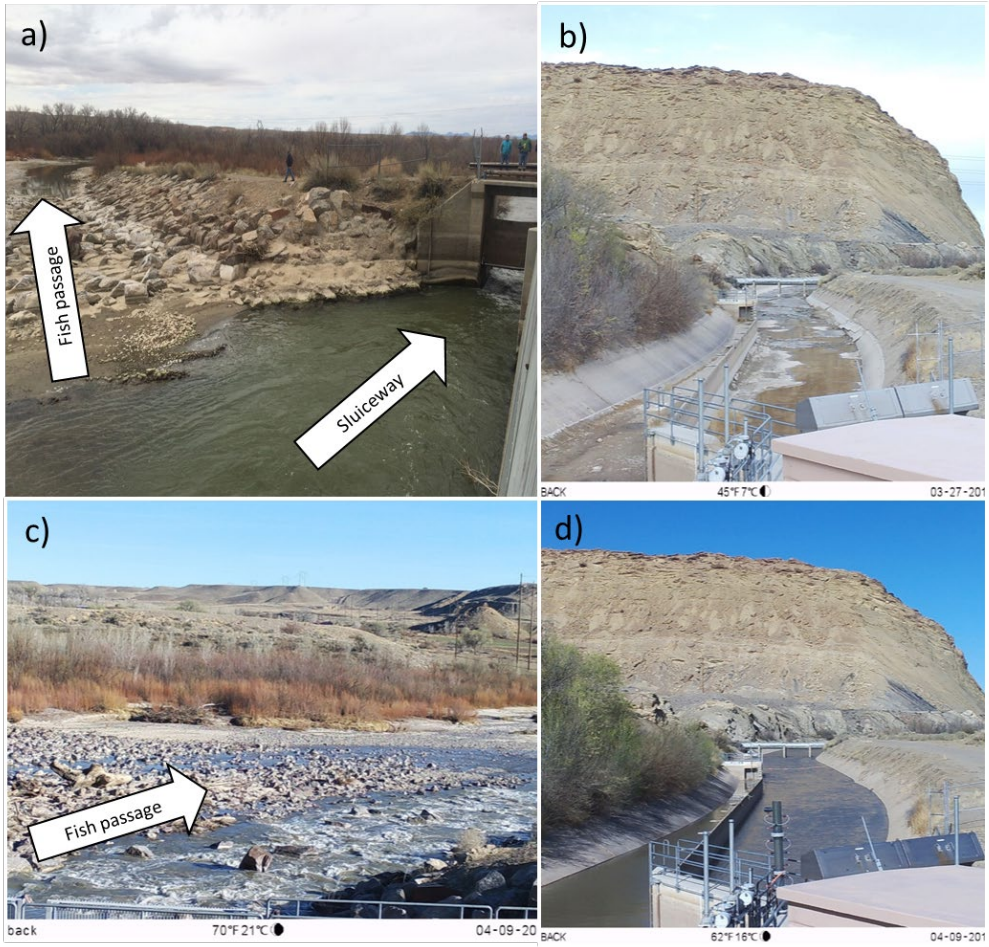


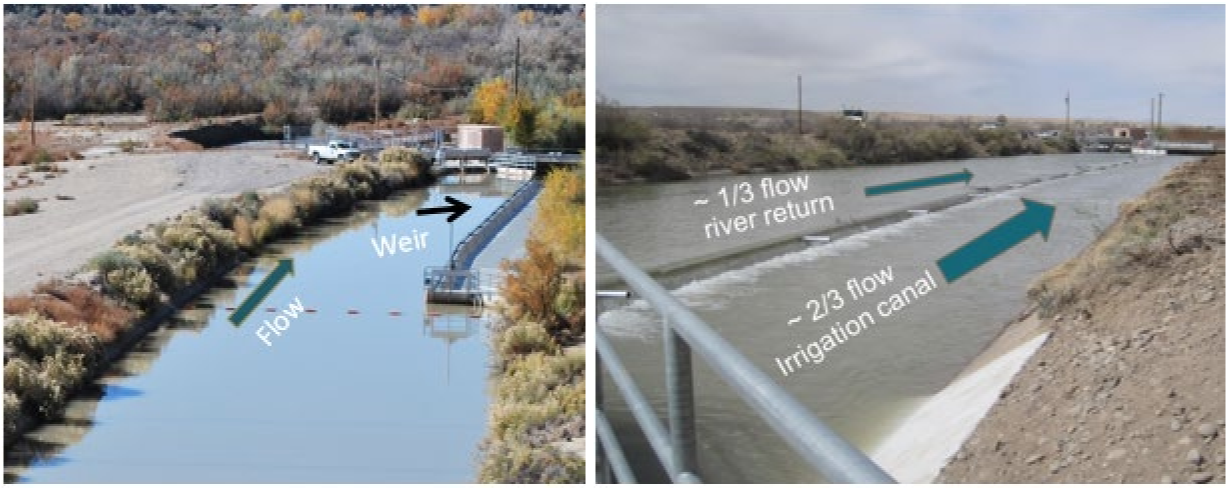
Figure 33. Hogback Irrigation canal diversion system and fish passage: a) 27 March 2018 river diverted through sluiceway, b) 27 March diversion canal, c) 9 April fish passage wet, and d) 9 April first day of river diversion into canal.

Figure 34. Arizona Public Service weir (left) and sluiceway (right) on the San Juan River, March 2018. Photos courtesy M. McKinstry.

All three upper Colorado River basin Colorado pikeminnow populations are isolated from the lower Colorado River basin by Glen Canyon Dam. While Colorado pikeminnow is no longer present in the Grand Canyon reach, the Colorado River flows from the dam, unobstructed, for approximately 502 RK (312 RM) before it reaches Lake Mead (Rogowski *et al.* 2018). There is speculation, however, that the Pearce Ferry rapid near the inflow to Lake Mead may serve to prevent fish movement between the lake and western Grand Canyon. From Lake Mead downstream to the international border with Mexico the longest unimpeded section of riverine habitat in the Colorado River is only ~ 63 RK (~ 39 RM). This reach is between the Palo Verde diversion and the lakes created by Imperial Dam. In the Gila River subbasin, the longest stretch of connected river is likely the Verde River where there are 101 RK (63 RM) of continuous riverine habitat. This river reach extends from White Bridge, which is a barrier to upstream fish passage (Chmiel, M. 2018 pers. comm.), downstream to the upper end of Horseshoe Reservoir (measurements were made using the Verde River Institute Google Earth file downloaded from their website July 2018). The Salt River is connected for at least 84 RK (52 RM) upstream from Roosevelt Lake and may continue to be connected upstream where it is within tribal jurisdiction (Stewart W. 2018, pers. comm.). Other portions of the Gila River drainage may contain longer reaches without barriers, but these do not have perennial flow (Stewart W. 2018, pers. comm.).

4.2.3 Preventing entrainment into diversions

Entrainment of fishes into water delivery systems can be reduced by the installation of entrainment reduction devices (e.g., screens). Screens are often constructed of mesh or horizontal slats. They allow enough water to pass to serve the diversions' purpose while physically excluding fish (U.S. Bureau of Reclamation 2006a). Most screens can reduce entrainment of larger sized fishes but are unlikely to prevent entrainment of larvae or smaller size classes (U.S. Bureau of Reclamation 2006a). To further reduce fish entrainment and as a way to overcome operation and maintenance issues associated with fish screens, the U.S. Bureau of Reclamation has recently developed and begun installing weir walls at diversions (Good *et al.* 2007). The weir consists of a concrete wall, installed at an oblique angle. The goal is to pass a few inches of water over the top of the wall, a layer of water in which it is presumed most life-stages of fishes do not occupy (Figure 35).



In 2013, a weir wall was constructed in the San Juan River subbasin at the Hogback irrigation canal (Figure 14 and

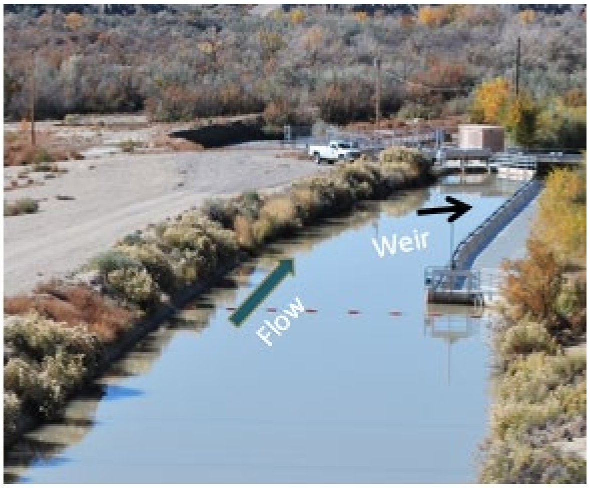


Figure 35). A full evaluation of the efficacy of the weir wall has not occurred due to the interference of the diversion's variable frequency drive pump with the PIT antennas installed for evaluation of fish entrainment (McKinstry M. 2018, pers. comm.). However, Brandenburg et al. (2017) conducted a preliminary evaluation by stocking larval razorback sucker, hatchery raised sub-adult Colorado pikeminnow (n = 383; mean 230 mm TL), and wild flannelmouth sucker *Catostomus latipinnis* and bluehead sucker *Catostomus discobolus* directly into the canal upstream of the weir wall. Results were variable as larvae were entrained in proportion to the volume of water diverted into the canal. Of the Colorado pikeminnow detected (n = 122; 32%), 57 were entrained (46.7%), however, suckers were precluded from entrainment. A full evaluation of this system's efficacy will be important, as the intake for a new water diversion in the San Juan River subbasin, the Navajo Gallup Pipeline project, is likely to be installed at the Hogback Canal in the near future (Durst S. 2018, pers. comm.). The Navajo Gallup Pipeline project will increase the amount of water diverted into the Hogback Canal and extend the use of the canal from eight months during irrigation season to year-round (U.S. Fish and Wildlife Service 2009).

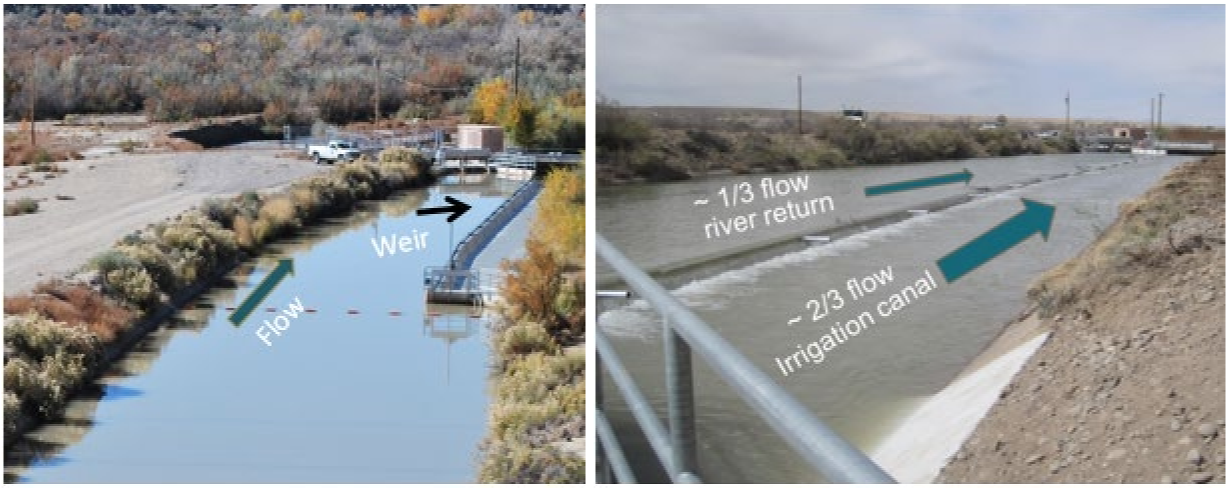


Figure 35. Weir wall installed in 2013 to reduce fish entrainment into the Hogback irrigation canal of the San Juan River (images from Brandenburg *et al.* 2017).

In the Green River subbasin, entrainment of fishes into two water delivery systems has been assessed with PIT antennas. These studies occurred at the Maybell and Tusher Wash (Green River canal) diversions (Figure 13). In the Yampa River, entrainment of Colorado pikeminnow into the Maybell diversion was not detected in 2011. In 2012, entrainment into this canal was estimated at 0.3–1.3% of the number of Colorado pikeminnow estimated for the Yampa River in the most recent year (140 adults in 2008; Speas *et al.* 2014). Downstream in the Green River, entrainment of fishes into the Green River Canal system via the Tusher Wash diversion was assessed during the 2013–2016 irrigation seasons. In that study period, 1,604 tagged fishes were detected in the canal system with 149 (9%) identified as Colorado pikeminnow (Speas *et al.* 2016). In addition to these detections, salvage operations in the Green River Canal during 2014–2017 resulted in the capture of 10 untagged Colorado pikeminnow, including two adults and eight fish <200 mm (<8 in; Ahrens and Jones 2017). A recent analysis of the mortality rate applied to adult Colorado pikeminnow in Green River subbasin through entrainment into the Green River Canal as estimated to be between 0.5–4.1% annually (McAbee 2017b). To reduce entrainment of endangered fish in the Green River Canal, a weir wall (equipped with an overflow fish screen on its crest) was constructed at the facility intake in spring 2019.

In the upper Colorado River subbasin, three water diversion facilities are equipped with screens to reduce fish entrainment (Figure 13). One screen was installed on the GVIC intake in 2002 (Crowley and Ryden 2017). Upstream of this diversion is the GVWU intake where a fish screen became fully operational in 2010 (Crowley and Ryden 2017). In the Gunnison River, just upstream from its confluence with the Colorado River, a fish screen began operation in 2005 at the Redlands Diversion Dam intake (Uilenberg 2005).

At times these fish screens can become clogged and are lifted or bypassed, which can increase the risk of entrainment. For the period 2010-2017, the GVIC fish screen was in operation between 32–84% of the time, GVWU was operational 32–100%, and Redlands was functioning 72–97% (Table 16). The length of time screens were operational was not available for every year, but fishes maybe become entrained during periods of time when fish screens are bypassed (Crowley and Ryden 2017). Therefore, fish salvage operations occur in both the GVIC and GVWU irrigation canals. Between 2004–2016, annual salvage of native fishes totaled 713–5,744 and 31–54,254 from the GVIC and GVWU, respectively (Table 16; Crowley and Ryden 2017). No Colorado pikeminnow have been found entrained in these canals since the screens were installed, however, abundance upstream of these two diversions may be low as few individuals were detected moving upstream of these diversions (see section 4.2.2).

Both fish screens and the weir wall at the Hogback irrigation canal likely reduce entrainment of fishes into water delivery systems in the San Juan River subbasin. Of the approximately 32 diversions, two (Arizona Public Service [APS] and PNM) have fish screens installed specifically to reduce fish entrainment (Figure 14; Lyons *et al.* 2016). These are permanent screens and act to reduce fish entrainment year-round. Three other irrigation diversions are fitted with debris screens that can potentially reduce fish entrainment when they are in operation. Similar to the Green River Canal system (Tusher Wash diversion), plans are underway to install a weir wall at the inlet to the Fruitland Canal system in the San Juan River (U.S. Fish and Wildlife Service 2018a).

Table 16. Operations of fish screens at water delivery diversions in the upper Colorado River subbasin and fish salvaged from those delivery system canals after the irrigation season (2004–2017). A (-) indicates data is not available. Canal salvage does not occur for Redlands.

Year	GVIC fish screen % operating[1]	Native fishes salvaged[2]	CO pikeminnow salvaged[2]	GVWU fish screen % operating[3]	Native fishes salvaged[2]	CO pikeminnow salvaged[2]	Redlands fish screen % operating[4]
2017	71	1,964	0	100	38,722	-	87
2016	78	3,442	0	95	54,254	0	97
2015	84	1,005	0	95	49,101	0	-
2014	64	845	0	95	31	0	-
2013	59	2,327	0	84	7,410	0	84
2012	32	5,744	0	32	12,075	0	72
2011	59	713	0	-	18,052	0	74
2010	68	1,061	0	-	25,977	0	84
2009	-	1,240	0	Not screened	38,722	0	-
2008	-	1,102	0	Not screened	1,598	0	-
2007	-	166	0	Not screened	7,140	0	-
2006	-	3,698	0	Not screened	-	-	-
2005	-	1,707	0	Not screened	4,759	1	-
2004	-	2,419	0	Not screened	6,343	24	Not screened

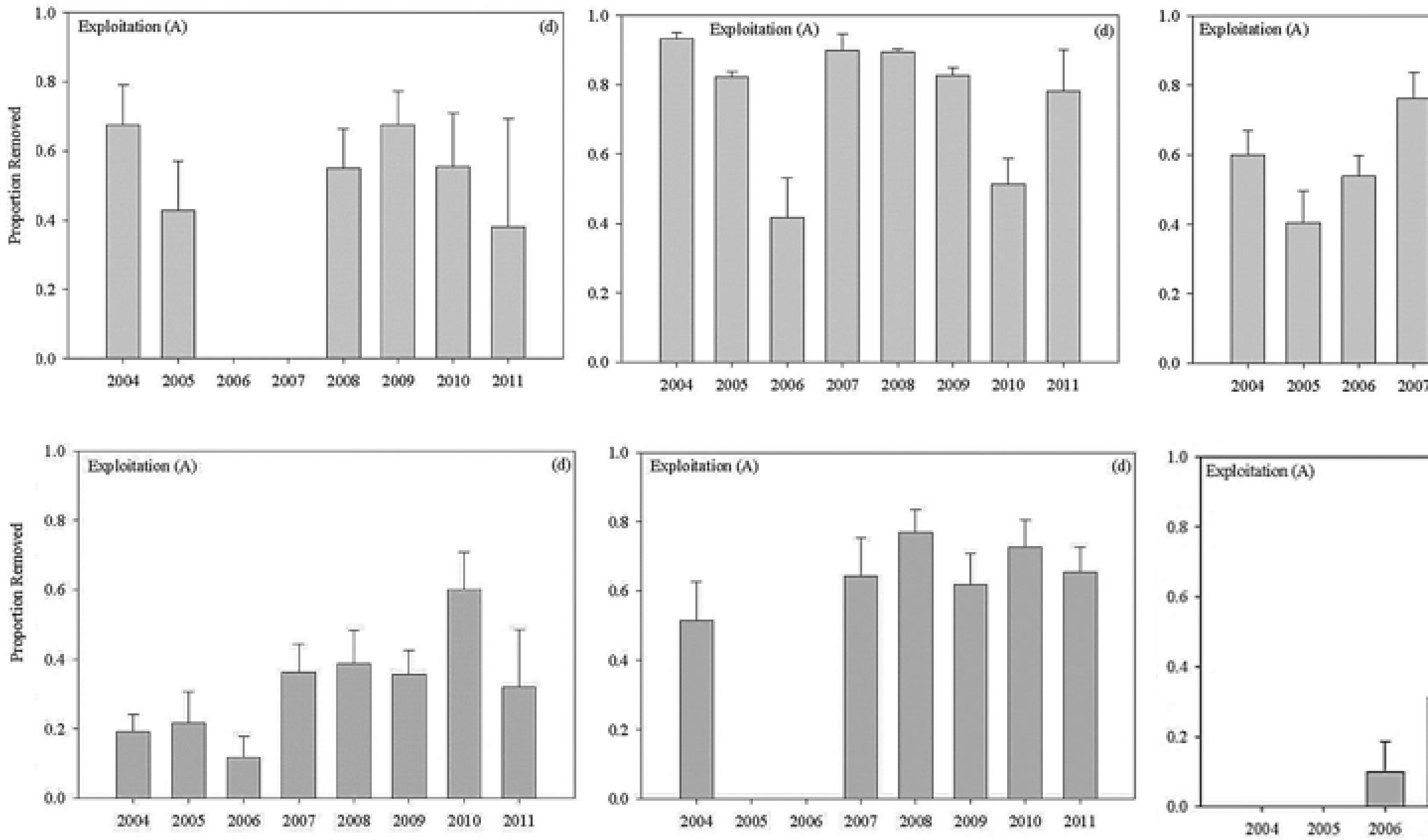
[1] Grand Valley Irrigation Company (GVIC; Guenther 2017), [2] fish salvage (Crowley and Ryden 2018), [3] Grand Valley Water Users (GVWU; Conrad 2017), [4] Redlands (Jones, K. E. 2017).

In the lower Colorado River basin, we do not know of any installed entrainment reduction devices at water delivery system intakes. Although there are no water diversion systems in the Grand Canyon reach, the lower Colorado River mainstem has over 40 delivery systems that pump water directly from the river (U.S. Bureau of Reclamation 2018). In 2004, when the MSCP HCP was developed, installation of fish screens at 21 diversions within the planning area (Lake Mead to the international border) was rejected (Lower Colorado River Multi-Species Conservation Program 2004). Thus, it is unlikely these, or the additional pump systems, are screened to reduce fish entrainment (Lantow J. 2018, pers. comm.). We do not currently have a count on the number or location of water delivery systems in the Salt and Verde rivers, from the rest of the Gila River and its tributaries, or the extent to which these systems have been retrofitted to reduce fish entrainment.

4.2.4 Nonnative fish control

Since nonnative fishes can significantly increase mortality of native species, control of nonnative species is a foundational management element for most native fish conservation programs within the current and historical range of Colorado pikeminnow. One approach to control has been large-scale physical removal through a combination of electrofishing and netting. In the Green and upper Colorado river subbasins, this has resulted in the annual removal or "exploitation" of

10–95% of the smallmouth bass population (Figure 36; Breton *et al.* 2014). For northern pike, removal in the Yampa River (Green River subbasin) has resulted in an annual reduction in the population (Figure 37; Zelasko *et al.* 2015). Throughout both subbasins, annual removal of walleye *Sander vitreus* has ranged from tens of fish to over 700 (Figure 38; Michaud *et al.* 2018). In the San Juan River subbasin, ~10–30% of the channel catfish population has been removed annually (Figure 39; Pennock *et al.* 2018). Although nonnative fishes are not removed as part of the MSCP from the lower Colorado River mainstem or as part of conservation actions in the Verde and Salt rivers, salmonids are intensively removed from the Grand Canyon reach in order to benefit humpback chub. During a 4-years (2003–2006) almost 20,000 rainbow trout *Oncorhynchus mykiss* and brown trout *Salmo trutta* were removed from approximately 24 RK (15 RM) in the upper portion of the Grand Canyon reach (Coggins *et al.* 2011).



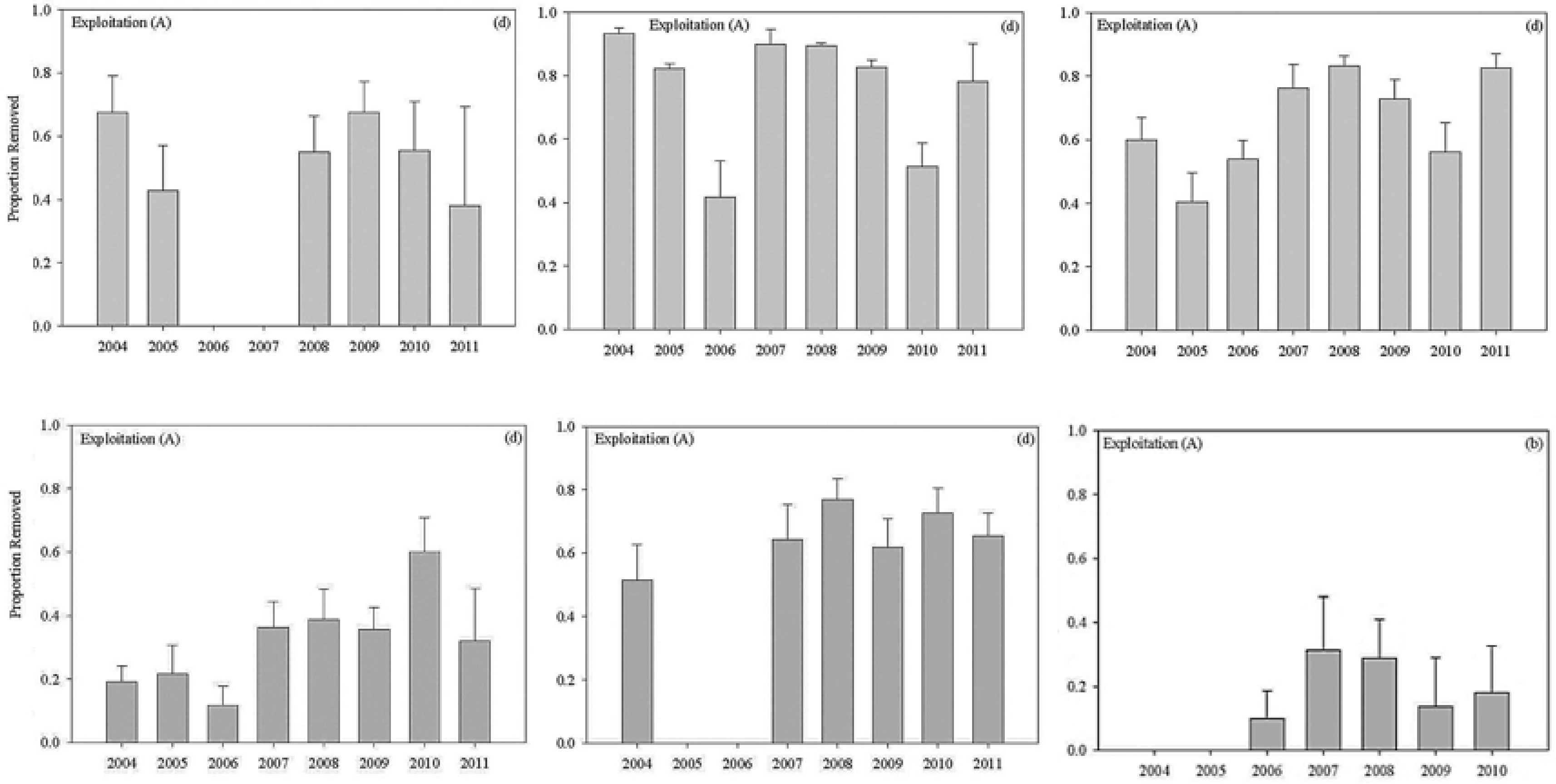


Figure 36. Removal (exploitation) rates of adult (A) smallmouth bass in the Green River and Upper Colorado river subbasins: upper panels are from the Yampa River Yampa Canyon (left), Lily Park (middle), and Little Yampa Canyon (right) and lower panels are from the Green River Echo-Split (left), Middle Green River (middle), and Upper Colorado River and Gunnison River (right). Adapted from Breton et al. (2014).

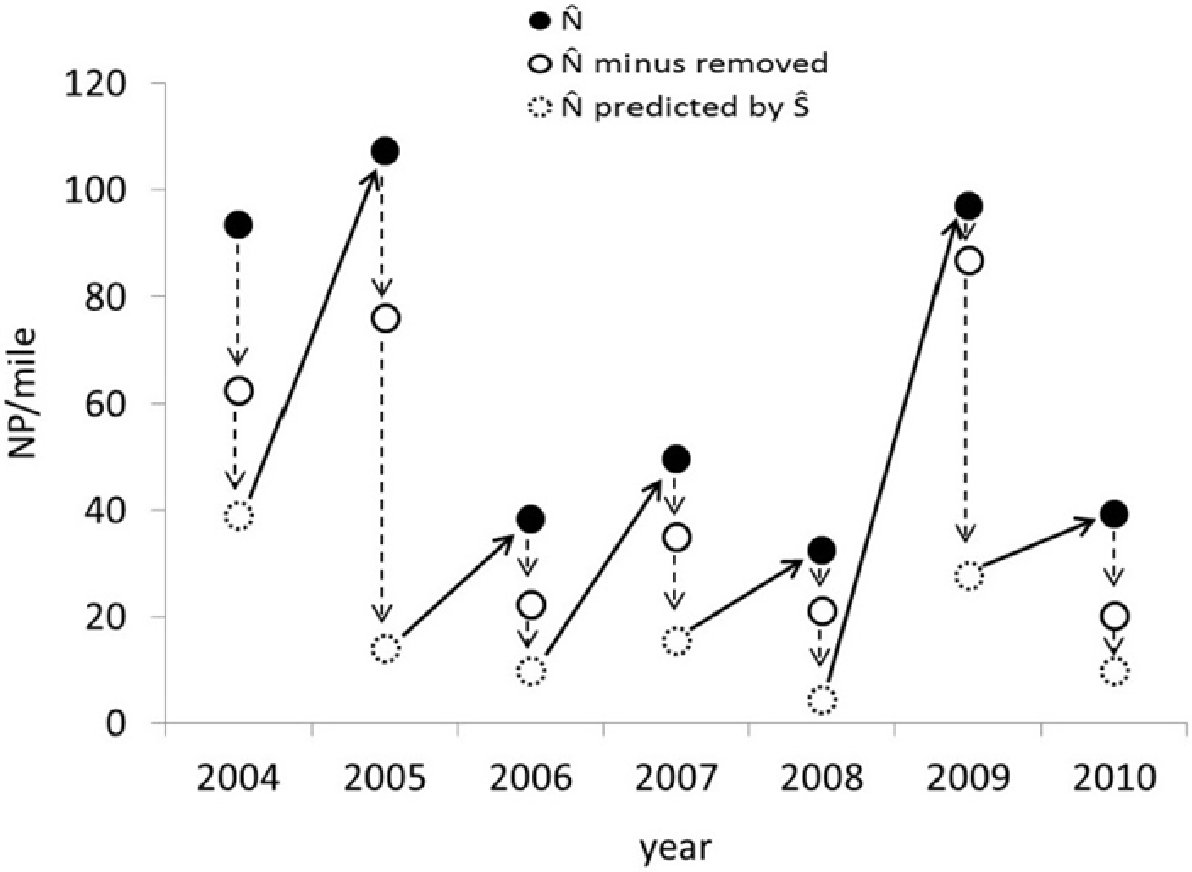


Figure 37. Estimated northern pike (NP) abundance in response to removal from the Yampa River, Green River subbasin. Black circles are estimated abundance prior to removal. Open circles indicate the estimated abundance minus northern pike removed. Dashed open circles represent the predicted abundance of northern pike after removal based on survival rates. Dashed line from filled to open circle is due to removal and to dashed circle is effect of natural mortality. Solid arrows from year to year indicate increase in density due to recruitment and immigration (Zelasko *et al.* 2015).

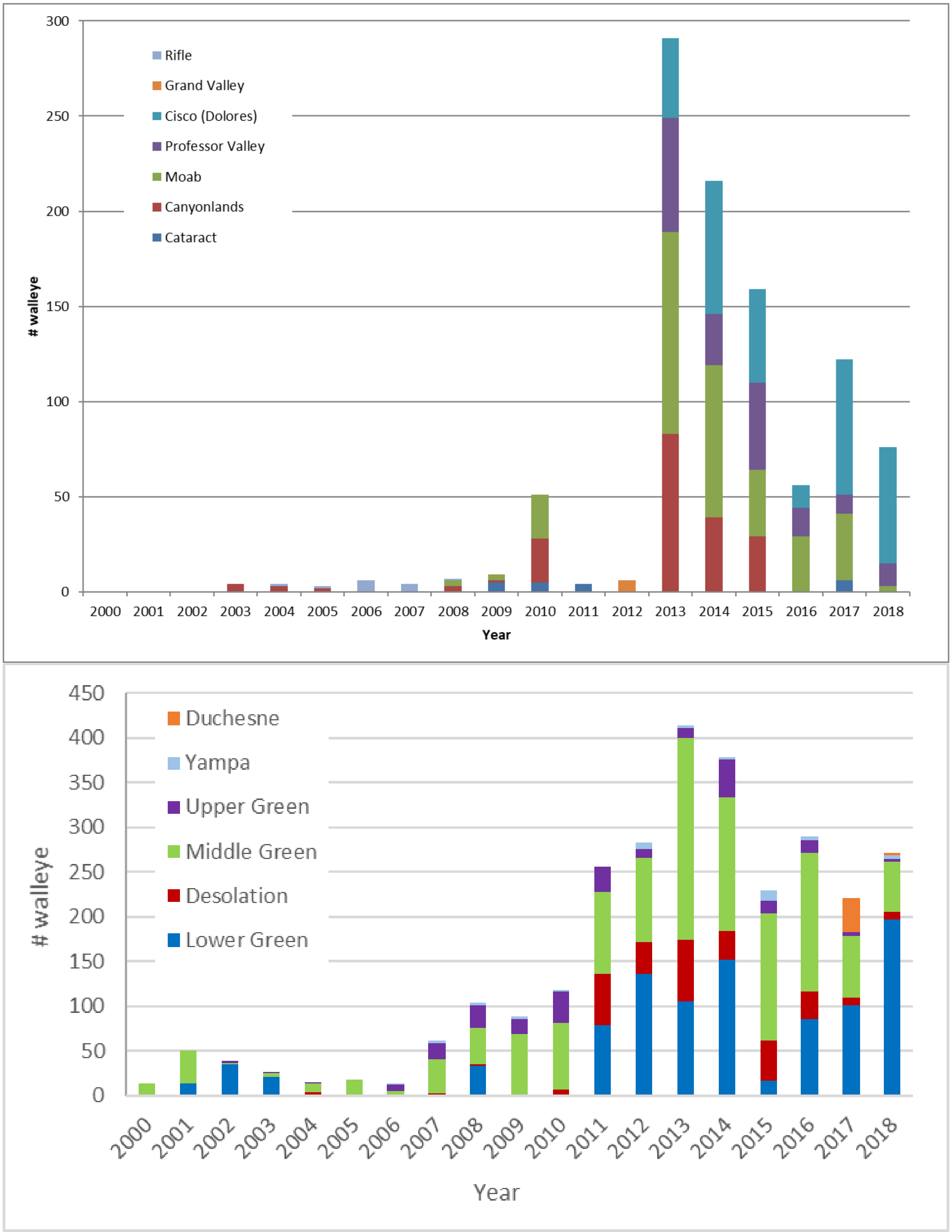


Figure 38. Number of walleye removed with varying effort from the upper Colorado River (top) and Green River (lower) subbasins. Figures from T. Francis, USFWS and Michaud et al. (2018).

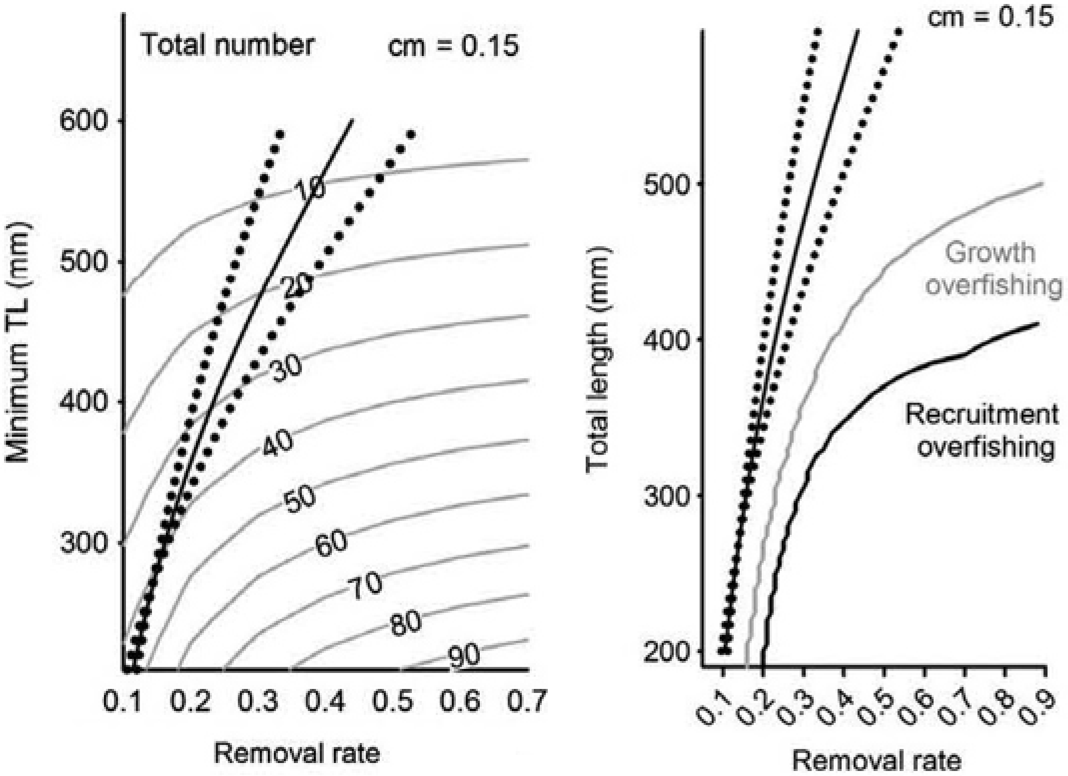


Figure 39. Predicted responses of channel catfish populations to removal efforts in the San Juan River. Left panel: isoclines represent the predicted reduction in percent of population for each removal rate and the intercept of actual removal rates (black lines with 95% CI represented by dotted lines). Right panel: removal rates which would predict growth overfishing (i.e., crash the population) and recruitment overfishing (i.e. crash in population's ability to increase through adequate reproduction) and actual removal rates (black lines with 95% CI represented by dotted lines) as a function of total length (mm). Adapted from Pennock et al. (2018).

Empirical evidence and modeling has shown that large-scale nonnative fish removal can result in population level reductions in abundance and biomass of the targeted nonnative species. However, eradication of problematic nonnative fish species is difficult and control of their populations will likely be a long-term management action (Martinez *et al.* 2014). The effects of nonnative fish removal are often short lived as removal rates may not be sufficient to result in either a population or reproductive crash, where reproduction is insufficient to offset removal and natural mortality (Figure 37 and Figure 39; Breton *et al.* 2014; Zelasko *et al.* 2015; Pennock *et al.* 2018). Without such a crash, immigration of nonnative fishes among river reaches results in a short-term reduction in population sizes even when large portions of a population are removed. Direct relationships between various nonnative piscivore predation rates and Colorado pikeminnow population dynamics are currently unknown (Miller, P. S. 2018). However, modeling the effect of removal efforts on the target nonnative species can serve to set removal targets and refine management (Figure 39; Breton *et al.* 2015; Pennock *et al.* 2018). Until the direct relationships between nonnative species removal and apparent Colorado pikeminnow survival is quantified, considerable uncertainty remains in regards to the amount of effort required to increase Colorado pikeminnow survival to rates that result in population recovery (Bestgen *et al.* 2007; Miller, P. S. 2018).

One way by which nonnative fishes continue to persist throughout Colorado pikeminnow's range is established populations escaping from reservoirs (Appendix II). Johnson et al. (2014) found evidence for reservoir escapement of walleye and northern pike in the Green and upper Colorado river subbasins. Smallmouth bass escapement from Elkhead Reservoir in the Yampa River basin was also documented (Hawkins *et al.* 2009), and a later study estimated this represented a significant contribution to the riverine population (Breton *et al.* 2013). To reduce the number of nonnative fishes escaping into rivers, escapement reduction devices, such as screens and nets, have been installed, or have been proposed, on some reservoir outlets and spillways. In the Green River subbasin, screens and nets have been installed at Starvation and Elkhead reservoirs (Figure 13). In the upper Colorado River subbasin, they have been installed at Highline Lake and Rifle Gap and Juniata reservoirs. These devices are effective at limiting fish escapement during water releases, but are still at risk for failure in extreme situations and therefore do not represent fail safe solutions. Testing of some devices such as the energy dissipating sleeve valve installed at Lake Nighthorse in the San Juan River subbasin (Figure 14) suggests almost 99% of nonnative fishes, including larvae, were killed during passage through the sleeve (Bark *et al.* 2013). The potential for nonnative fishes to escape from Morgan Lake (San Juan River subbasin) has also been recently reduced due to the installation of a screen at this settling pond's overflow outlet (Day, H. February 21, 2018).

Other methods to control and contain nonnative fishes include use of selective fish passages and manipulation of flows. Selective fish passages are managed so that fish are caught in a trap within the passage facility, and a worker must choose which species or individuals will be released on the other side of the passage. Individual fish can be removed from such a facility, and these passages can preclude nonnative fishes downstream of a passage from moving upstream. Such passages are present in the upper Colorado River (Figure 13; Grand Valley Water User [GVWU]), and in the Gunnison River (Redlands Water and Power) and San Juan River subbasins (Figure 14; Public Service of New Mexico [PNM]). Another method to control nonnative fishes is to disadvantage them through release of carefully timed high flows. This technique was used in the Grand Canyon reach in an attempt to reduce early survival and growth rates of age-0 rainbow trout; however, results were equivocal (Korman *et al.* 2011). In the Green River subbasin, modeling of high reservoir releases to disrupt smallmouth bass nests in combination with spring mechanical removal suggested pairing these techniques could significantly reduce smallmouth bass populations (Breton *et al.* 2015; Bestgen and Hill 2016b; Bestgen 2018).

Although extensive effort has occurred to control nonnative fish predators, the release in the predatory pressure and commensurate increase in survival by either endangered fishes such as Colorado pikeminnow or common native species is poorly understood (Figure 40 and Figure 41; Bestgen *et al.* 2017; Duran *et al.* 2018). In the Yampa River although the frequency of native fishes within a sampled reach tended to be greater in treatment (i.e., removal) reaches than control (i.e., no removal) reaches, this was not consistent year to year (Figure 40; Bestgen *et al.* 2017). The overall percent of native fishes did not significantly increase over the period that age-0 smallmouth bass removal was annually occurring. The native fish assemblage has yet to exceed 15% and in most years was ~5% of the fishes captured. Similarly, removal of channel catfish in the San Juan River did not result in increased Colorado pikeminnow populations in removal reaches as compared to control reaches (Figure 41; Duran *et al.* 2018).

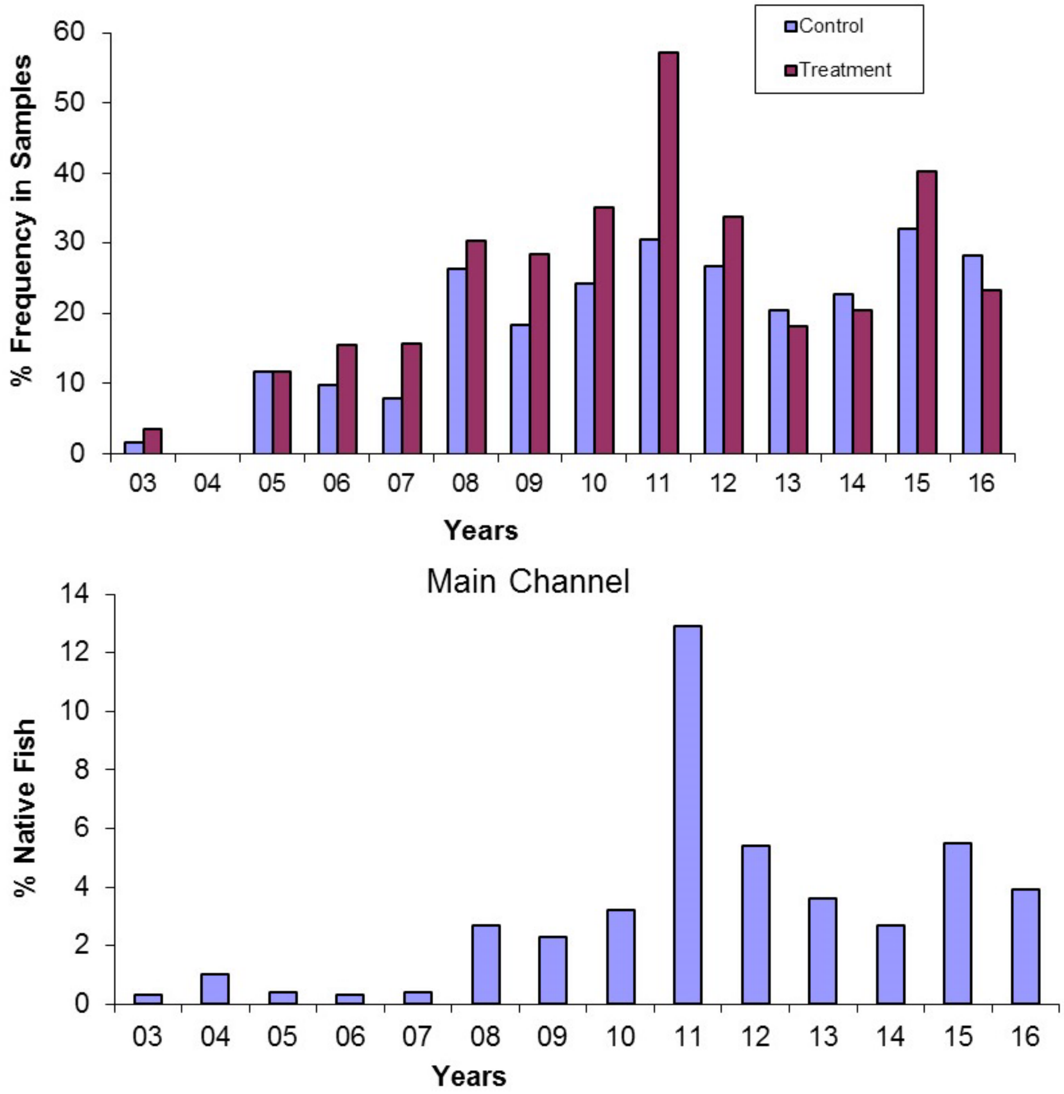


Figure 40. Frequency of native fishes in Yampa River surveys during smallmouth bass removal (Bestgen et al. 2017). Top panel is the frequency of native fishes between treatment (i.e., removal) reaches and control reaches (i.e., no removal). Bottom panel is the native fish composition (%) of all fishes captured.

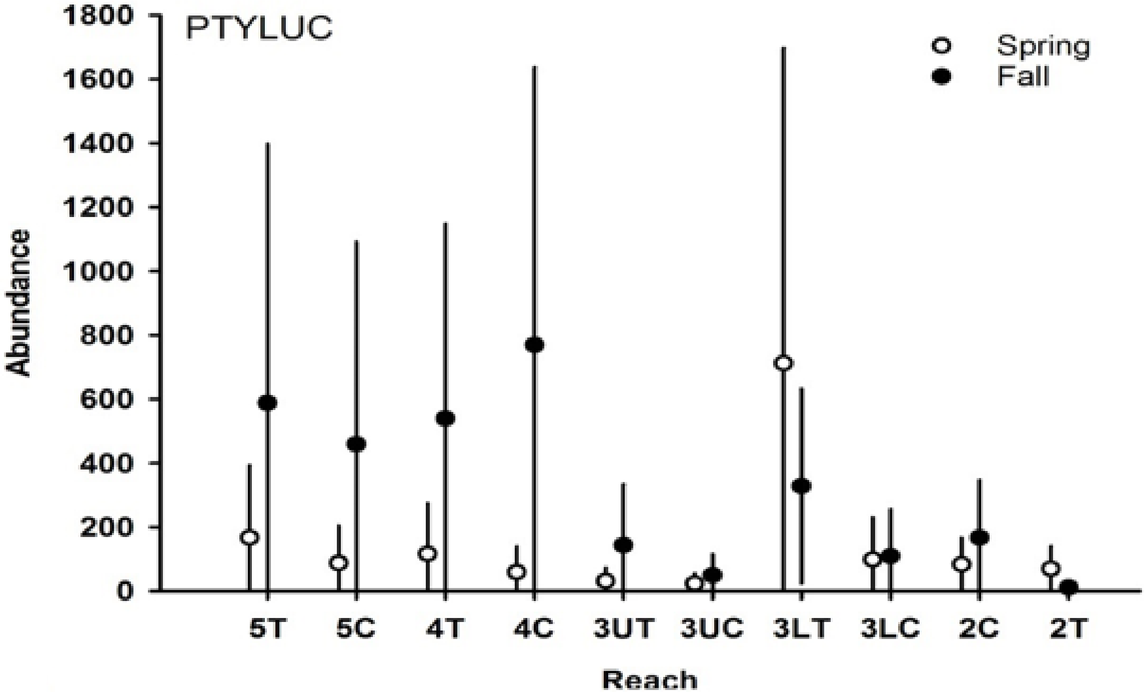


Figure 41. Response of Colorado pikeminnow (PTYLUC) abundance (estimated population with 95% CI) to intensive removal of channel catfish in the San Juan River (2016–2017) in five treatment reaches (T = removal) versus control (C = no removal) between spring and fall of each year (Duran *et al.* 2018).

4.2.6 Population augmentation

In portions of Colorado pikeminnow's range, rivers have been stocked with hatchery-reared individuals. This conservation management action has been used either to repatriate the species to locations where it was extirpated or nearly extirpated or to augment established populations. Stocking Colorado pikeminnow can serve to increase the number of fish in a population, making populations more resilient, and can increase the species' redundancy by broadening its distribution on the landscape. When hatchery populations are managed for the highest possible genetic diversity, this conservation management action can increase the species' resiliency and representation.

Release of propagated Colorado pikeminnow into the Green and upper Colorado river subbasins has been limited because natural populations are considered self-sustaining (Tyus 1991). The most recent stocking in the Green River subbasin occurred 1988-1990 with 96,597 juvenile fish (41-172 mm [2–7 in]) stocked into Kenney Reservoir on the White River (Trammell *et al.* 1993). These stockings were an attempt to establish a Colorado pikeminnow sport fishery as a mitigation measure for the construction of Taylor Draw Dam. In the upper Colorado River subbasin, stocking occurred between 2003 and 2004 in an attempt to repopulate reaches above impassable diversions (Table 17). Successful population augmentation may have been minimal as few of these fish (4%) were recaptured within the first year and their long-term survival rate was estimated at 0.3% (Osmundson, D. B. and White 2014).

Table 17. Colorado pikeminnow stocking records for the upper Colorado River subbasin from Osmundson and White (2014).

Year	River	Number stocked	Mean length (mm)
2003	Colorado RMI 167.7	12	120
2003	Colorado, near DeBeque	1,001	222
2003	Gunnison, near Delta	1,048	242
2004	Colorado, near Rifle	1,164	184
2004	Colorado, near Rifle	651	204
2004	Gunnison, near Delta	1,200	217
Total		5,084	

From 1991 to 1995, surveys of the San Juan River yielded the capture of seventeen wild adult fish, and the population was thought to consist of fewer than 40 adults by 1995 (Holden 1999). A population augmentation program was then developed, and since 2002 over 5 million age-0 and age-1+ fish have been stocked into the San Juan River (Figure 42; Furr 2018). Since 2010, only age-0 fish have been stocked at rate of ~400,000 per year (Furr 2018).

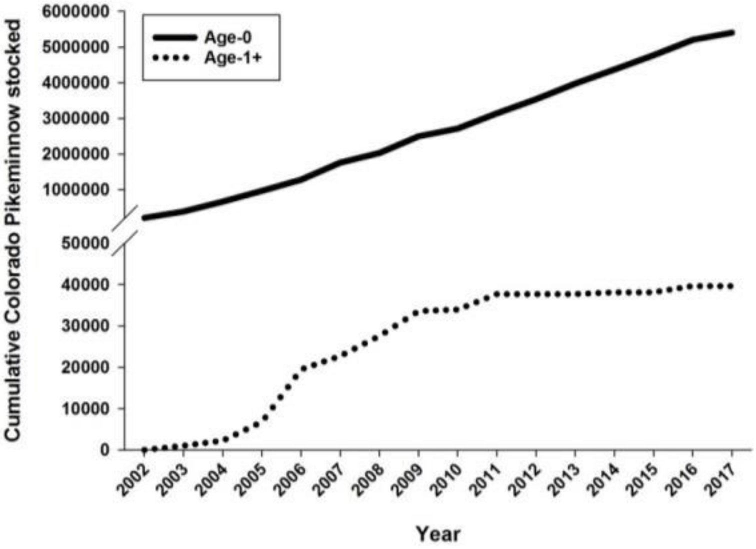


Figure 42. Cumulative number of Colorado pikeminnow stocked between 2002–2017 into the San Juan River (Furr 2018; figure developed by S. Durst).

The apparent survival rate for stocked Colorado pikeminnow in the San Juan River subbasin is relatively low. Fish that retain in the system for more than a year have an apparent annual survival rate of 19%, which gradually increases to 54.0% at age 4 (Table 18; Clark, S. R. *et al.* 2018). Analysis of stable isotopes from these stocked fish indicated they transition to piscivory at a later age than expected (Franssen *et al.* 2019). Isotopic signatures indicated that these stocked age-1 and age-2 Colorado pikeminnow from the San Juan River also had a lower rate of piscivory (Franssen *et al.* 2019) than wild fish from the Green River subbasin (Vanicek and

Kramer 1969). This difference in diet may be one cause for the lower apparent survival of these stocked fish as compared to the wild populations (Clark, S. R. *et al.* 2018; Franssen *et al.* 2019). Despite low survival to adult sizes, Clark et al. (2018)estimated survival for adult Colorado pikeminnow in the San Juan River subbasin to be comparable to those estimated in the Green and upper Colorado river subbasins. Also, the current population of Colorado pikeminnow in the San Juan River is believed to be the result of the stocking program (Schleicher 2018), indicating that this activity has prevented the extirpation of the species and maintained sufficient numbers of adults to maintain spawning and the production of larvae.

Table 18. Mean apparent survival (95% CI in parentheses) for age-1–4 Colorado pikeminnow stocked into the San Juan River subbasin between 2003 and 2015 (Clark, S. R. *et al.* 2018). Mean size at age from Durst and Franssen (2014).

Age	Apparent survival	Mean size (mm TL)
1	0.19 (0.10-0.37)	177
2	0.25 (0.15-0.39)	235
3	0.22 (0.12-0.36)	310
4	0.53 (0.33-0.72)	380
4+	0.60 (0.39-0.79)	

4.3 Summary

All of the stressors discussed in this chapter are those that have and will continue to affect the future viability of Colorado pikeminnow. Two are primary drivers: alterations of flow regimes that maintain and provide suitable habitat and a high predatory burden caused by nonnative fishes (Bestgen *et al.* 2018; Miller, P. S. 2018). Flow regimes that support Colorado pikeminnow into the future could be affected by changes in natural runoff magnitude and timing as a result of warming climate and increased human water demands. Problematic nonnative fish predators have established populations throughout the current and historical range of Colorado pikeminnow. In addition to these widespread and common stressors, other stressors include range reductions due to barriers, decreased water temperatures from hypolimnetic dam releases, entrainment into water delivery systems, contaminants, channel simplification, and climate change impacts to flow and nonnative species distributions.

Recovery and conservation programs have been established within the current range for Colorado pikeminnow, and in some parts of its historic range. The Upper Colorado River Endangered Fish Recovery Program and San Juan River Basin Recovery Implementation Program have coordinated conservation activities throughout the current range of Colorado pikeminnow to address many of the stressors listed above. These two programs have instituted flow recommendations in reaches of critical habitat, constructed fish passages and entrainment reduction solutions at barriers and diversions, and conducted nonnative fish control measures. Activities directed at native fish conservation in other reaches within historic range could provide benefits if Colorado pikeminnow were reintroduced, but the benefits of such activities is unclear in the absence of the species.

CHAPTER 5 – CURRENT CONDITIONS FOR COLORADO PIKEMINNOW VIABILITY

We identified a suite of demographic and habitat parameters to compare resiliency (i.e., health) among Colorado pikeminnow analysis units (Table 20 and Table 28). Criteria used to assess demographic and habitat factors used to describe current conditions were based on the best available science from studies of Colorado pikeminnow in the upper Colorado River basin over the last three decades and were developed with input from a panel of species experts. The metrics explained in the next section of the chapter were then applied across all populations to assess the resiliency of each population analysis unit (Table 25; Table 29; Figure 63). The demographic factors use ten-to-fifteen-year timescales to assess current conditions. The ten-year timeframe is based on the time to maturity for female Colorado pikeminnow (Osmundson 2006) and is intended to predict population responses into the near future. For example, we might expect age-0 densities to be reflected in the adult breeding population in about 10 years. The generation time for Colorado pikeminnow females is fifteen years based on the age at sexual maturity (10 years) and the survival rate for adults (0.8; see Valdez 2018). This longer timescale can be used to assess a population's response in the recent past and reflects the average time for a population to increase by a factor equal to its net reproductive rate. Since many of the monitoring studies that evaluate Colorado pikeminnow demographic parameters do not occur every year, this SSA used a minimum of six data points for demographic factors that evaluate processes over a ten-year scale and eight data points for the 15-year time scale. Through this exercise, we assessed the extant populations (Green, upper Colorado, and San Juan rivers) as being in a low condition, and three analysis units (Grand Canyon, lower Colorado, and Gila) were considered extirpated. In the assessment, used the scoring values presented in Table 19, which were derived based on input from a panel of species experts from throughout the species' current range. The panel recommended weighting adult abundance and trajectory since those factors represent the reproductive potential for populations and are better understood demographic measures with longer term data. Reproduction and recruitment were also considered important, but the team expressed more uncertainty around values that might indicate these processes support resilient populations. Finally, the panel developed ranges of scores to reflect the overall demographic condition for populations and recommended that a population not be given a condition more than one category above its lowest score in any demographic factor (Table 25). For example, a population considered extirpated for a single factor could not be given an overall condition of moderate or higher.

Ultimately, Colorado pikeminnow demography is an interdependent relationship among the abundance and survival of reproducing adults, the magnitude of offspring production, and recruitment into the adult life-stage (Miller, P. S. 2014; Bestgen and Hill 2016a; Miller, P. S. 2018). Mechanisms causing variation in offspring production and recruitment through each proceeding life-stage are particularly difficult to assess (Bestgen and Hill 2016a). This is because Colorado pikeminnow has a multi-phase life cycle with larvae typically drifting long distances from spawning sites, juveniles through adults exhibiting wide-ranging movements, and survival and abundance of each life-stage being limited by different factors. Colorado pikeminnow, like most aquatic organisms with dispersing life-stages, has highly variable recruitment because even though the species is highly fecund, small variations in biotic or abiotic processes can generate large differences in survival (Fogarty *et al.* 1991; Bestgen *et al.* 2006; Bestgen and Hill 2016a). Thus, factors that regulate distribution, abundance, size-structure, and survival of early and sub-adult life-stages are integrated into processes that structure adult recruitment and abundance and cannot be fully independent of one another especially since some populations are augmented with hatchery-produced fish.

Table 19. Condition scores for demographic factors used to assess Colorado pikeminnow resiliency.

Condition Category	Wild Reproduction	Wild recruitment to sexual maturity	Adult Abundance	Long-term Population trajectory
High	3	3	6	4
Moderate	2	2	3	2
Low	1	1	1	1
Functionally Extirpated	0	0	0	0

Table 20. Demographic factors and their underlying categories of condition used to compare health (resiliency) among Colorado pikeminnow analytical units.

Condition Category	Wild Reproduction[8] (Density of wild age-0 juveniles)	Wild recruitment to sexual maturity[9]	Adult Abundance[10]	Long-term Population trajectory[11]
High	Green River subbasin: ≥ 10 age-0 per 100m^2 habitat	Recruitment to sexual maturity equals or exceeds adult mortality over the last 15 years	Green River subbasin: ≥ 3100 adults	The trend for wild adult abundances is stable or increasing over the last 15 years.
	Upper Colorado River subbasin: ≥ 6.6 age-0 per 100m^2 habitat		Upper Colorado River subbasin: ≥ 760 adults	
	San Juan subbasin[12]: ≥ 2.2 age-0 per 100m^2 habitat		San Juan subbasin: ≥ 400 adults	
Moderate	Green River subbasin: 5 < 10 age-0 per 100m^2 habitat	Recruitment to sexual maturity equals or exceeds adult mortality over the last 10 years	Green River subbasin: 2600 < 3100 adults	The trend for adult abundance (wild and/or stocked) is stable or increasing over the last 15 years.
	Upper Colorado River subbasin: 3.3 < 6.6 age-0 per 100m^2 habitat		Upper Colorado River subbasin: 500 < 760 adults	
	San Juan subbasin: 1.4 < 2.2 age-0 per 100m^2 habitat		San Juan subbasin: 250 < 400 adults	
Low	Green River subbasin: < 5 age-0 per 100m^2 habitat	Adult mortality exceeds recruitment to sexual maturity over the last 10 years	Green River subbasin: < 2600 adults	The trend for adult abundances is decreasing over the last 15 years.
	Upper Colorado River subbasin: < 3.3 age-0 per 100m^2 habitat		Upper Colorado River subbasin: < 500 adults	
	San Juan subbasin: < 1.4 age-0 per 100m^2 habitat		San Juan subbasin: < 250 adults	
Functionally Extirpated	No age-0 fish detected	No recruits detected	Too few adults to estimate	Too few adults to generate appropriate trend data

---

[8] Mean density of wild age-0 juveniles collected in autumn for the last 10 years (female age at sexual maturity).

[9] Proportion of fish 400 ≤ 449 mm total length measured against adult abundance and compared to average annual adult mortality over the same time period.

[10] Minimum adult abundance for the last 10 years, based on adequate number of estimates (i.e. six) calculated in each subbasin. Adults are defined as fish ≥ 450 mm total length, either wild produced or stocked at sizes ≤ 350 mm.

[11] Adult abundance trend over 15 years (female generation time), based on adequate number of estimates (i.e. eight) and methods appropriate for the data.

[12] Densities of age-0 juveniles supporting corresponding adult abundances in the San Juan subbasin are model derived estimates, not derived from capture data.

5.1 Current condition of demographic factors used to assess resiliency

5.1.1 Wild reproduction

Assessing the abundance of age-0 fish characterizes a Colorado pikeminnow population's resiliency in multiple ways. Age-0 fish abundance can be used to assess adult female fecundity which is an important determinant of long-term population health (Bestgen and Hill 2016a; Miller, P. S. 2018). This metric also reflects reproductive success and recruitment to the early juvenile stage. The abundance of this age class also provides insight into the frequency of optimal river flows (Bestgen and Hill 2016a) and is positively related to the next year's abundance of age-1 fish. Bestgen and Hill (2016a) recommended an annual production of age-0 Colorado pikeminnow for the lower (≥15/100 m^2) and middle (≥5/100 m^2) Green River, which represent above average densities for the long term data set. The rationale is that higher densities are required to offset declines in both age-0 recruitment and adult abundances. The mean of these values is 10/100 m^2. The long term mean for age-0 catch rates in the upper Colorado River subbasin has been 6.6 fish/100 m^2 (McAbee 2017a). A recent analysis for the San Juan River subbasin estimated that catch rates of 2.2 fish/100 m^2 might be expected for an adult population to reach 400 adults (calculated based on methodology in Zeigler *et al.* 2019). We assessed the health of each Colorado pikeminnow analysis unit based on the mean age-0 catch rate over a ten year period, using thresholds listed in Table 20. Lack of detection of age-0 fish over ten years was considered a condition of extirpation. A ten year period was used since that is the age at which female Colorado pikeminnow reach sexual maturity, which should give an indication of young fish that might enter the population in the near term.

5.1.2 Wild recruitment to sexual maturity

For adult Colorado pikeminnow populations to be resilient, recruitment of fish into the adult life-stage must meet or exceed adult mortality on average. In the Green River subbasin, annual adult mortality (difference between 1 and apparent survival) was estimated from 1991 to 2013 and has ranged from 0.18 to 0.26 (Table 22; Bestgen *et al.* 2018). Mortality also varies by length for Colorado pikeminnow in the Green River subbasin and can be <0.18 but also >0.50 for some adult size classes.

For this SSA, we assessed the proportion of recruits (fish 400-449 mm [16-18 in] TL) relative to the adult population, and whether this proportion is sufficient to offset adult mortality over the last 10-15 years. Once calculated, we partitioned this metric into whether recruit abundances, in relation to the adult abundances, were higher, equal to, or less than mean annual adult mortality over the time period and then assessed current population health (Table 20). Lack of detection of any recruit-sized fish was considered a condition of extirpation.

5.1.3 Adult abundance

The abundance of adult Colorado pikeminnow is indicative of the long-term health of a population because adults are long-lived and have a multi-decadal reproductive period. In addition, recovery of the species and listing status are partially based on adult abundances over a certain time. A panel of species experts from each subbasin identified adult abundances that would indicate the resiliency for each population where Colorado pikeminnow still occur. These abundances were derived from long-term data for the Green and upper Colorado river subbasins, and from estimates of carrying capacity from bioenergetics modeling for the San Juan River subbasin. Adult abundances used for the high condition category in the Green and upper Colorado river subbasins also represent observed population sizes when other demographic rates, such as reproduction and recruitment, were sufficient to maintain the populations. These abundances occurred in the years before 2000 when these populations were stable or increasing (Bestgen *et al.* 2007, 2018; Osmundson and White 2017). The moderate condition value in the Green River subbasin was based on an estimate of the minimum viable population, a number below which the population might not be considered viable.

To assess this demographic factor and determine population resilience, we describe each population based on the mean adult density of fish ≥450 mm (≥16 in) total length. We averaged the last ten years of data and included abundance of both wild and stocked fish. Given off-years, when estimates are not conducted, using at least six of the most recent data points typically spans this ten year period. The categories were based on thresholds identified in Table 20.

5.1.4 Long-term population trajectory

The long-term population trajectory is an important factor in assessing a population’s condition because the population growth rate (lambda) describes whether a population is increasing, stable, or decreasing. Lambda estimates allow for a summary of the trajectory a population exhibits. The recent PVA for Colorado pikeminnow (Miller, P. S. 2018) used historical abundance data for the Green and upper Colorado river subbasins to fit population estimate regression curves to the population point estimates. Abundance data for both subbasins produced two possible models that describe recent trends for these populations, described as the single-phase and dual-phase dynamics. The single-phase dynamic is characterized by a single trajectory over the entire period of estimates, whereas the dual-phase dynamic represents separate population growths rates in two different periods.

To describe population stability for each extant population of Colorado pikeminnow, we summarized the trajectory of adults for each population over the last 15 years (Table 20). A population considered in high condition was one where wild adult abundances are stable or increasing over the last 15 years. A population in moderate condition was one where the trend for adult abundance, including wild and stocked fish, is stable or increasing over the last 15 years. A low condition population was one where adult abundances are decreasing over the last 15 years. An extirpated population was one where there are too few adults to generate a trend.

5.2 Upper Colorado River Basin Populations

5.2.1 Wild reproduction

Data collected since the 1990s indicate some level of reproduction has occurred annually in both wild populations in the upper Colorado and Green river subbasins (Anderson, R. 1998; Bestgen and Hill 2016a; Breen and Michaud 2018). In the Green River subbasin, larval Colorado pikeminnow production from one of two primary spawning sites has been monitored annually since 1990 (Bestgen and Hill 2016a). Larvae are collected at the confluence of the Yampa and

Green river to assess the timing and magnitude of reproduction at the Yampa River spawning site. This monitoring has concluded that Colorado pikeminnow reproduced in each year of sampling, with the timing of spawning positively correlated to spring peak flow magnitude and water temperature. The data also show that larval abundances are influenced by flows, such that higher flows lead to more larvae being produced and transported into the nursery reach, and fewer larvae were produced and transported in low flow years. Limited monitoring of larval production occurred from 1991 to 1996 in the lower Green River for the spawning site in that reach (Bestgen *et al.* 1998). Those data, as well as annual monitoring for age-0 Colorado pikeminnow in autumn (see below, Bestgen and Hill 2016a), indicate reproduction at the lower Green River spawning site has occurred each year since 1979.

Sampling for larval Colorado pikeminnow occurs in the lower Gunnison River and downstream of its confluence in the 18-Mile Reach of the Colorado River to the Utah/Colorado state line (Elverud 2018). This study has not collected larval Colorado pikeminnow from 2014-2017. Reproduction can also be inferred from age-0 monitoring conducted in the fall (see below). Age-0 Colorado pikeminnow have been caught in all but two years since 1986, indicating that reproduction has occurred in a majority of years, and every year since 2009 (Table 21; Breen and Michaud 2018).

In the Green and upper Colorado river subbasins, annual monitoring for age-0 Colorado pikeminnow has been conducted each autumn since 1986. Reaches of the middle Green, lower Green, and lower Colorado rivers are sampled using standardized protocols to evaluate recruitment of young fish from the larval to juvenile (age-0) stage (U.S. Fish and Wildlife Service 1987). For the Green River subbasin, the density of age-0 Colorado pikeminnow has typically been higher in the downstream reach than in the middle Green River, but both reaches have experienced declining densities in recent years (Figure 43; Table 21; Bestgen and Hill 2016a; Breen and Michaud 2018). It is also believed that recruitment in the lower Green River nursery reach can provide individuals that recruit into the adult population throughout the rest of the Green River subbasin, potentially compensating for reduced age-0 densities in the middle Green River nursery reach.

In the upper Colorado River subbasin, age-0 densities have been variable over the long term, and a “spawning spike” was observed in 2015, when large numbers of age-0 Colorado pikeminnow were encountered (Figure 44; Table 21; Miller, P. S. 2018; Breen and Michaud 2018). Catch rates were consistently higher between 1986 and 2000, followed by generally lower densities of fish in the 2000s. Since 2009, higher catch rates of age-0 Colorado pikeminnow in the lower Colorado River have been inconsistent. The 2015 fish density is not shown in Figure 44 because of the unprecedented catch rate in that year, which was an order of magnitude higher than any other year observed in the project. Table 21 shows the seven year mean for age-0 catch rates including the 2015 spawning spike, as well as the mean with this data excluded. Both values were considered in assessing this factor for the upper Colorado River subbasin in order to capture the uncertainty in this single datum and based on input from investigators in this reach. Data from both the Green and upper Colorado river subbasins suggest spawning occurs regularly in each system, and some level of recruitment has been observed in most years. There is some concern, however, that recent declines in age-0 densities in the Green River may signal that recruitment is not sufficient to offset observed declines in adults (Bestgen and Hill 2016a; Bestgen *et al.* 2018).

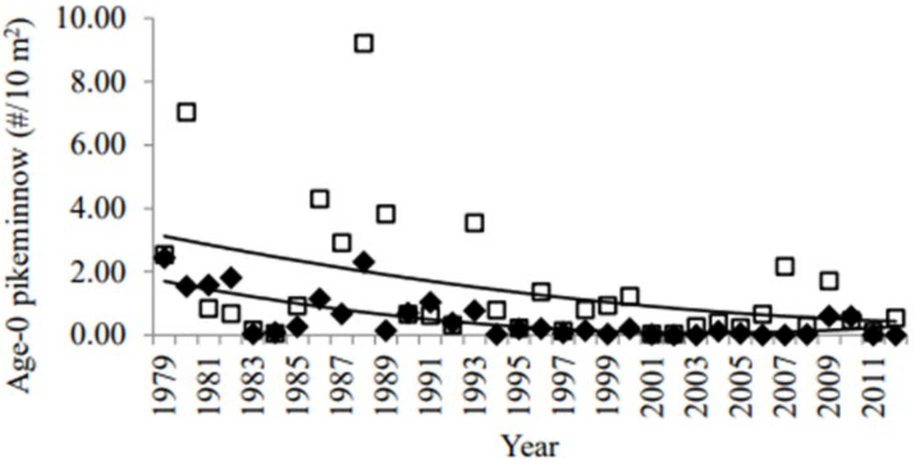


Figure 43. Mean annual density of age-0 Colorado pikeminnow captured during standardized sampling in the middle (black diamonds) and lower (open squares) Green River, 1979-2012 (Bestgen and Hill 2016a). Density is number of pikeminnow captured in area swept by a seine.

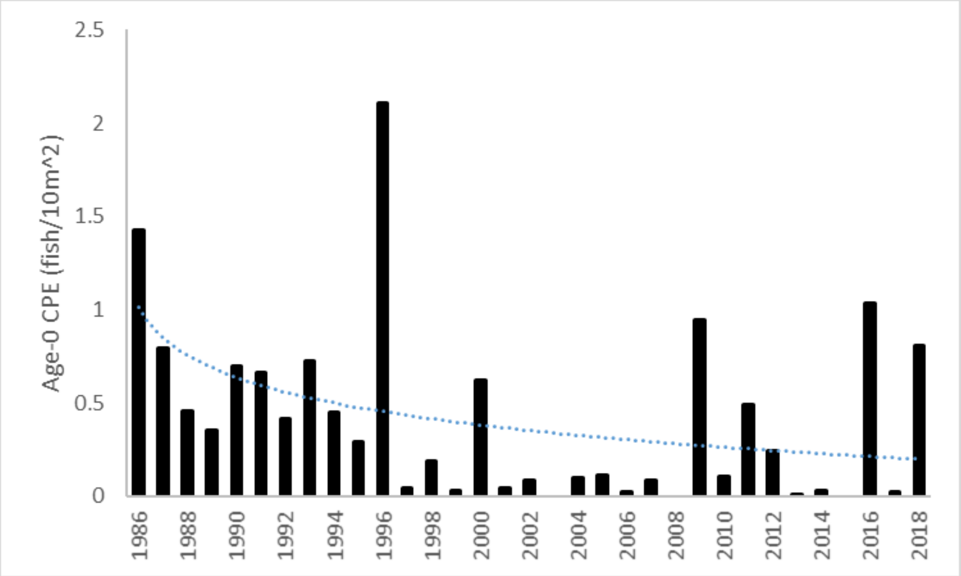


Figure 44. Catch per effort (CPE; fish per 10 m^2) of age-0 Colorado pikeminnow seined in the lower Colorado River during Interagency Standardized Monitoring Protocol, 1986-2018 (Breen and Michaud 2018). Data from 2015 has been omitted from this graph because catch rates were an order of magnitude higher than any from the entire data set.

Table 21. Post-larval age-0 Colorado pikeminnow catch per unit effort (#/100 m^2) in the Green River and upper Colorado River subbasins (Breen and Michaud 2018) and San Juan River subbasin (Zeigler and Ruhl 2017; Zeigler *et al.* 2018) for the last ten years of available data. * denotes the mean catch rate for the upper Colorado River subbasin when 2015 is excluded.

Years	Green River subbasin (middle/lower)	Upper Colorado River subbasin	San Juan River subbasin[13]
2009	4.33 / 16.6	9.46	0.00
2010	NA / 4.57	1.03	0.00
2011	0.00 / 0.95	4.94	0.00
2012	0.03 / 6.21	2.41	0.00
2013	1.37 / 1.30	0.05	0.00
2014	1.44 / 0.30	0.31	0.00
2015	4.60 / 22.7	106.39	0.00
2016	0.14 / 26.8	10.32	1.37
2017	0.03 / 1.52	0.20	0.134
2018	0.11 / 3.42	8.05	0.00
mean	5.07 (combined)	14.3 (4.1*)	0.15

Recent data from the San Juan River subbasin (2011-2017) also indicate reproduction has occurred in 6 of 7 years (Figure 46; Farrington *et al.* 2018). Genetic investigations of San Juan River Colorado pikeminnow larval fish have led to a better understanding of the proportion of the population that successfully spawns each year as well as drift dynamics and habitat use (Diver and Mussman 2019). Using larval fish collected between 2011 and 2018, estimates of the mean number of adult Colorado pikeminnow that successfully spawned (N_b) were calculated to be 3–50. From this it was estimated that between 3.0–40.3% of adults in the population successfully participated in spawning in those years.

The first documentation of Colorado pikeminnow larvae recruiting into age-0 fish in the San Juan River occurred in 2016 with the capture of 23 wild fish (Zeigler and Ruhl 2017). Wild age-0 fish (n=5) were also captured in 2017 (Zeigler *et al.* 2018). Because age-0 hatchery fish are stocked into the San Juan River each autumn, we are unable to determine whether wild produced fish have survived their first winter and survived to age-1. Other studies suggest, however, that age-0 Colorado pikeminnow that have reached 39-44 mm (1.5-1.7 in) TL prior to winter have a greater likelihood of survival than smaller fish (Haines *et al.* 1998). Based on the length of age-0 Colorado pikeminnow captured in the San Juan River in 2016 (Figure 45), environmental conditions appear to support a level of growth that would allow fish to reach this size by winter (Zeigler and Ruhl 2017).

---

[13] San Juan River data were calculated to make them comparable to Green and Colorado rivers ISMP data. Namely, only backwater and zero-velocity habitat catch rates were used, rather than catch rates for all habitat types.

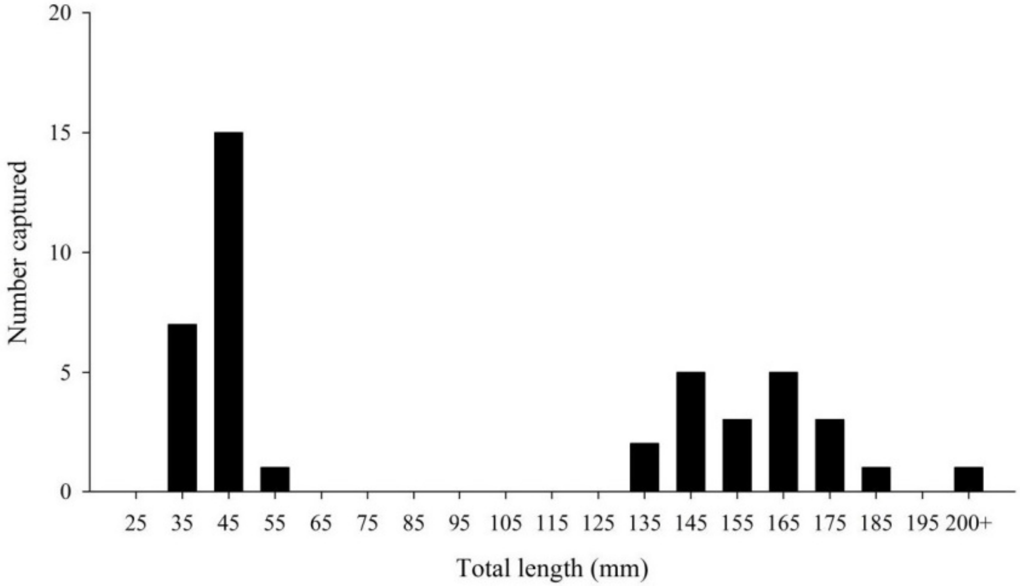


Figure 45. Size frequency distribution of age-0 and age-1+ Colorado pikeminnow captured in the San Juan River, 2016. Figure from Zeigler and Ruhl (2017). Most age-1+ Colorado pikeminnow are presumed to be of stocked origin while the age-0 fish captured are wild progeny based on sampling and stocking dates.

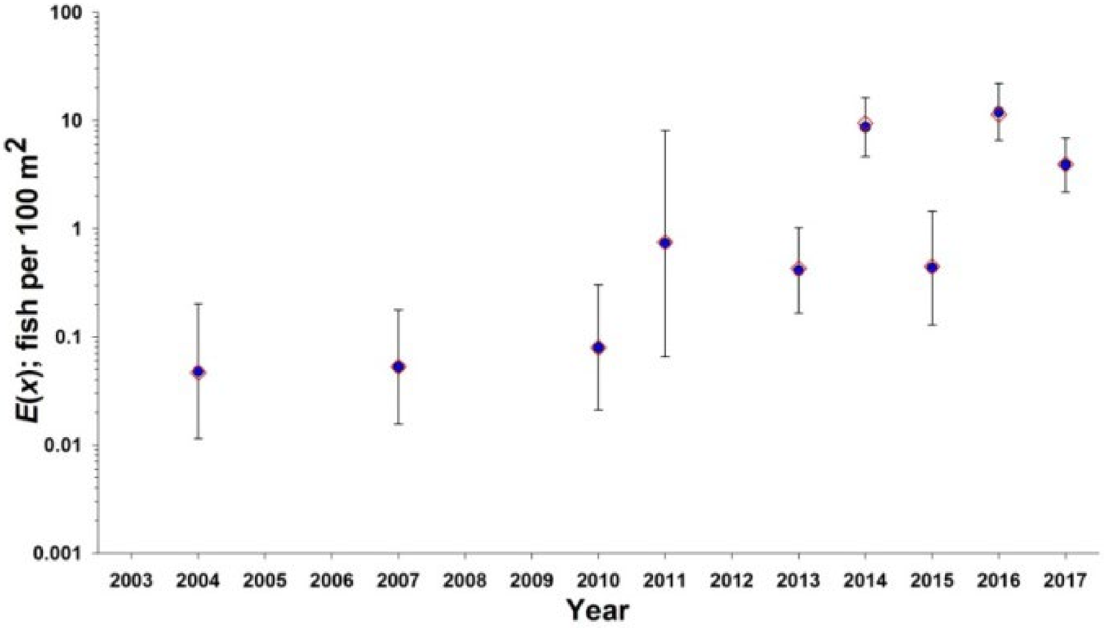


Figure 46. Larval Colorado pikeminnow density (catch per unit effort in red diamonds and estimated delta GLM with 95% CI in blue circles) in the San Juan River subbasin, San Juan River. Figure from Farrington et al. (2018).

5.2.2 Wild recruitment to sexual maturity

The reduction in the abundance of adult Colorado pikeminnow in the Green River subbasin may be due to a number of factors that have resulted in reduced survival rates (Table 22) but is also dependent on the number of fish that recruit into the adult population each year. In order to maintain or increase adult abundance in a given river reach, the number of recruits in the population must equal or exceed the number of adults lost to mortality. One way to assess this is by comparing the proportion of recruits in the population to the survival rate of adults. Bestgen *et al.* (2018) succinctly described the trend in Colorado pikeminnow in the Green River subbasin that were of recruitment size from 1991 to 2013:

> Population structure of recruit and adult Colorado pikeminnow in [standardized monitoring sites] changed dramatically between the four periods, 1991–1999, 2000–2003, 2006–2008, and 2011–2013 (Figure 18). Number of Colorado pikeminnow recruits (*n* = 186 total) during 1991–1999 averaged 24.7% (7.9 to 58.5% per sample) of the number of adults in samples (*n* = 826). During 1991–1999, there were four years (three from 1992–1994) when proportion of recruits was high (>20%), three years when proportion of recruits was moderate (>10 to 20%), and two years when it was low (0 to 10%). In 2000–2003, number of Colorado pikeminnow recruits per year (*n* = 14 over all years) was low, at only 3.4% (0 to 6.6%, mean of annual percentages) of the number of adults captured (*n* = 418), and was zero in three of those (2001–2003). In the period 2006–2008, and consistent with abundance estimates, the percentage of Colorado pikeminnow recruits in ISMP samples increased to an average of 22.1% (9.2 to 33.3%) of the number of adults captured (*n* = 166), with % recruits increasing each year through the period. However, in the recent period, and using a slightly different but comparable method to estimate % recruits, the proportion of Green River recruits in samples was high in 2011 (28%) but only 4% in 2012 and 12% in 2013.

Table 22. Adult Colorado pikeminnow apparent survival probability estimates from capture-recapture data from the Green River subbasin (table from Bestgen *et al.* 2018).

Parameter	Period	Apparent survival	95% CI	Annual adult mortality rate
Survival	1991–1999	0.82	0.71 to 0.89	0.18
	2000–2003	0.65	0.59 to 0.71	0.35
	2006–2008	0.80	0.60 to 0.91	0.20
Yampa River	2000–2013	0.72	0.66 to 0.76	0.28
White River	2000–2013	0.75	0.71 to 0.77	0.25
Middle Green	2000–2013	0.68	0.65 to 0.72	0.32
Deso-Gray	2000–2013	0.70	0.66 to 0.74	0.30
Lower Green	2000–2013	0.78	0.74 to 0.81	0.22
Mean (2000-2013)				0.27

Furthermore, Bestgen *et al.* (2018) found that recruit abundance was relatively high in 2011, but declined to an extent that observed recruit abundances were not sufficient to replace estimated mortalities of adults (Figure 47). Relatively high numbers of recruits and juveniles observed in 2011 were not evident in 2012 and 2013 sampling. The abundance of recruits is also dependent on the number of juveniles (<400 mm [<16 in] TL) observed in previous years. Since 2000, the abundance of these fish has also declined in most reaches of the Green River subbasin. As described at the beginning of this chapter, demographic factors are largely interrelated and overall abundance of juvenile through adult life stages in the Green River subbasin could be driven by the decline in age-0 fish over time (Figure 43).

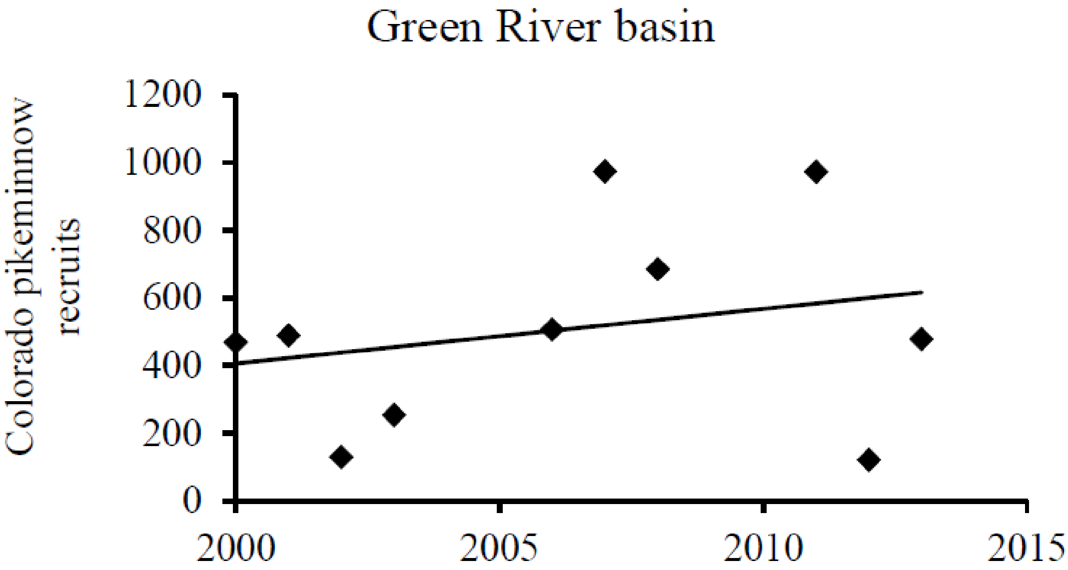


Figure 47. Recruit-sized Colorado pikeminnow (400-449 mm TL) estimates (2000–2003, 2006–2008, 2011–2013) in the Green River subbasin. Figure from Bestgen *et al.* (2018).

In the upper Colorado River subbasin, the abundance of recruit-sized Colorado pikeminnow have been estimated periodically since 1992 (Osmundson, D. B. and White 2014; Elverud and Ryden 2018), and are summarized in Table 23. Osmundson and White (2017a) also estimated survival of fish ≥500 mm (20 in) in the upper reach to be 86% (95% CI: 77-91%) between 2004-2013. Survival of fish (≥500 mm [20 in]) in the lower reach in that same period was 78% (95% CI: 72-83%), but the difference was not statistically significant. For the period 1992-2005, they estimated survival in the upper reach at 90%, while it was 80% in the lower reach for the same size fish. In the earlier period, survival estimates were significantly different between reaches, but there was no difference in survival estimates between the two periods.

Recruit abundances for the San Juan River subbasin (unpublished data) were generated from pass-specific detection probabilities from standardized adult monitoring in a 166 km (103 mi) reach (Schleicher 2018). As mentioned previously, these fish are believed to be the result of augmentation efforts and not wild-recruited individuals.

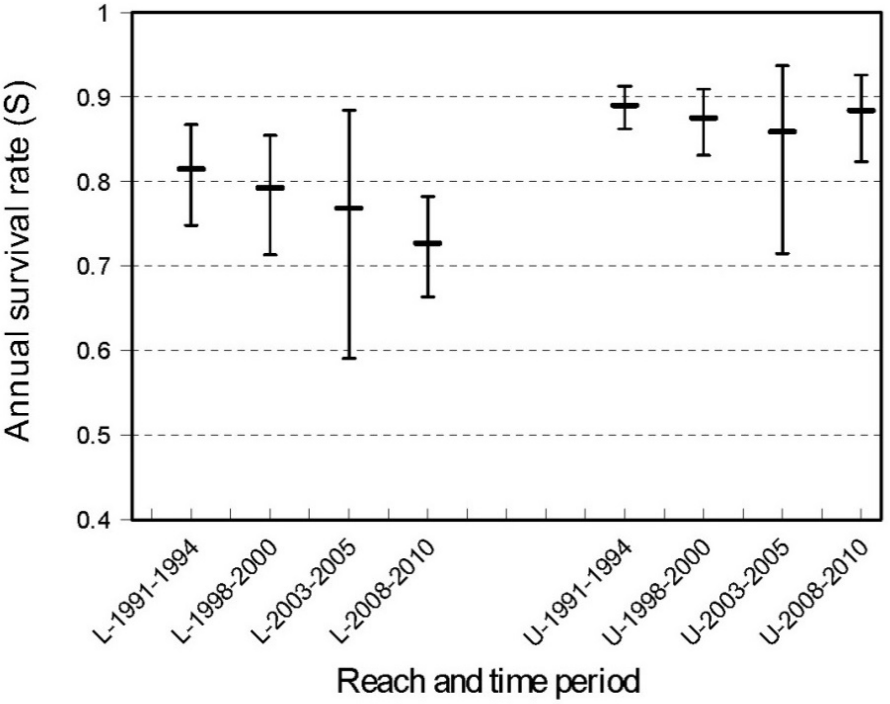


Figure 48. Annual apparent survival rates (95% CI) of adult Colorado pikeminnow (≥ 500 mm [20 in] TL) in the upper Colorado River subbasin. Reaches identified as upper (U) and lower (L). Figure from Osmundson and White (2014).

Table 23. Percent of Colorado pikeminnow population that represent the cohort prior to assumed sexual maturity (400–449 mm [16-18 in] TL) in the Green, upper Colorado, and San Juan river subbasins, for the last fifteen years that data were available. Data from Osmundson, D. B. and White (2014); San Juan River Basin Recovery Implementation Program (2017); Bestgen *et al.* (2018); Schleicher (2018); Elverud and Ryden (2018).

Year	Green River subbasin (509 RMI)			Upper Colorado River subbasin (182 RMI)			San Juan River subbasin (103 RMI)		
	Adult N	Recruit N	%	Adult N	Recruit N	%	Adult N	Recruit N	%
2002	3,676	130	4						
2003	3,131	284	9	661	250	38			
2004				688	239	35			
2005				889	25	3			
2006	2,542	426	17						
2007	2,339	828	35						
2008	3,000	652	22	710	19	3			
2009				511	8	2			
2010				493	7	1			
2011	2,083	973	47				81	122	151
2012	1,787	122	7				19	6	32
2013	2,128	479	23	332*	198	60			
2014				482*	85	18	67	30	45

2015				429*	89	21	100	33	33
2016							133	22	17
Mean %			20.5			18			56
Mean % mortality			Adult mortality (2000-2013) 27%			Adult mortality (2004-2013) 14-22%			Age 4+ mortality (2003-2016) 40%

5.2.3 Adult abundance

At times, abundance estimates for adult Colorado pikeminnow in the Green River subbasin have exceeded the threshold to be considered in a high condition (3,100 adults; Table 20). However, recent estimates have dropped below this target, and modeling results from the PVA indicate this population has been declining over at least the last 15-20 years (Section 5.2.2; Miller, P. S. 2018). Over that time, abundance estimates document a decline in adults for all sampled reaches of the Green River subbasin, except the lower Green River (Figure 49; Bestgen *et al.* 2018).

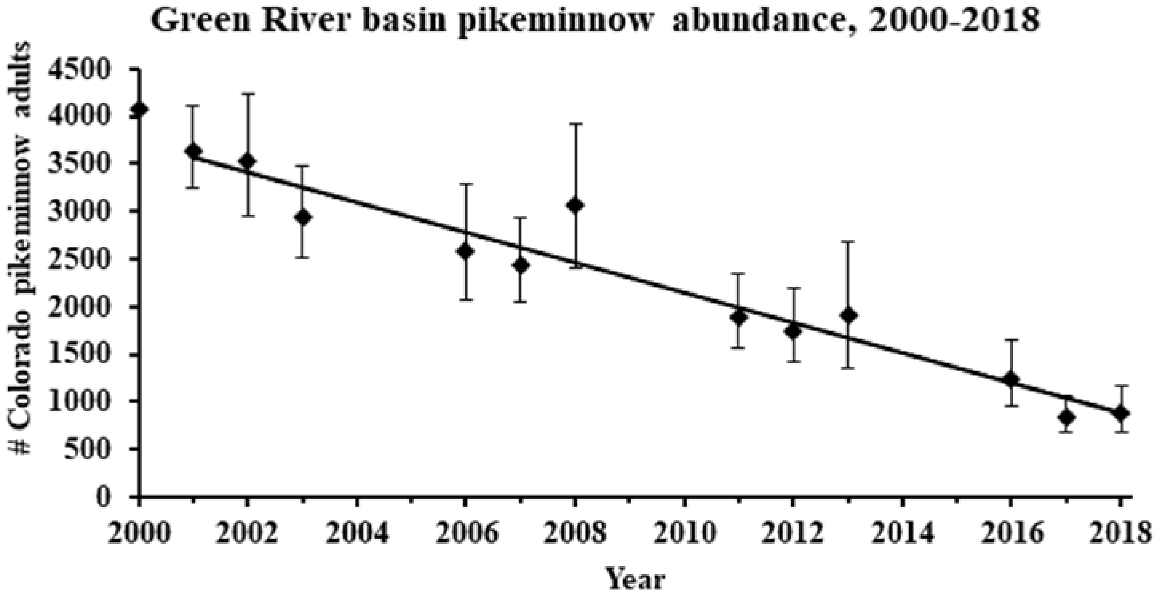


Figure 49. Adult Colorado pikeminnow estimates (2000–2003, 2006–2008, 2011–2013, 2016-2018) and linear regression in the Green River subbasin. Figure from Bestgen *et al.* (2018) and unpublished preliminary data (2016-2018).

In the upper Colorado River subbasin, the highest estimates of adult abundance have exceeded the threshold for the high condition (760 adults; Table 20; Osmundson, D. B. and White 2014), but estimates since 2009 have been lower (Figure 50). The more recent declines in adult populations are believed to be the result of weak year classes and poor recruitment (Osmundson,

D. B. and White 2014; Osmundson, D. B. and White 2017b). Captures of juvenile fish were also lacking in 2014 and 2015 (Elverud *et al.* 2014; Elverud and Ryden 2015). This may account for a reduction in fish recruiting to adult size even though reproduction has occurred annually and age-0 fish abundance has been relatively high in some recent years (Table 21; Breen and Michaud 2018).

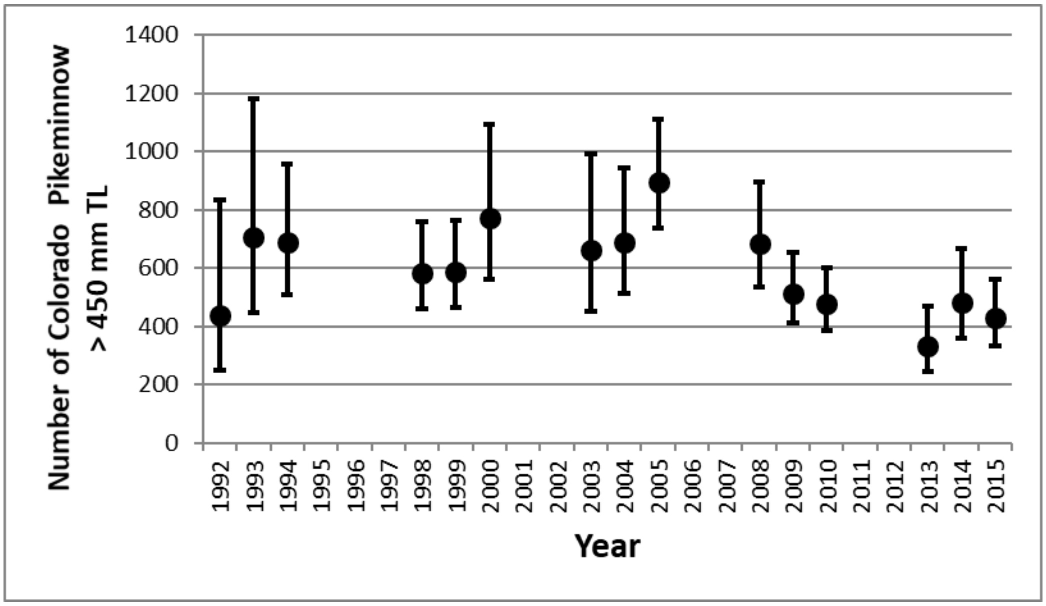


Figure 50. Abundance of adult Colorado pikeminnow in the upper Colorado River subbasin, 1992-2015. Figure from Elverud and Ryden (2018).

Colorado pikeminnow was considered functionally extirpated from the San Juan River as recently as the 1990s (Ryden 2000). Since then, extensive stocking of age-0 and juvenile Colorado pikeminnow has resulted in an adult population (Figure 51). The 95 % confidence intervals around adult population estimates are relatively large. However, enough adults are in the system that since 2004 wild-produced larvae have been detected (Figure 46; Farrington *et al.* 2018). While confidence intervals overlap between consecutive years, the number of larval fish collected has generally increased over time.

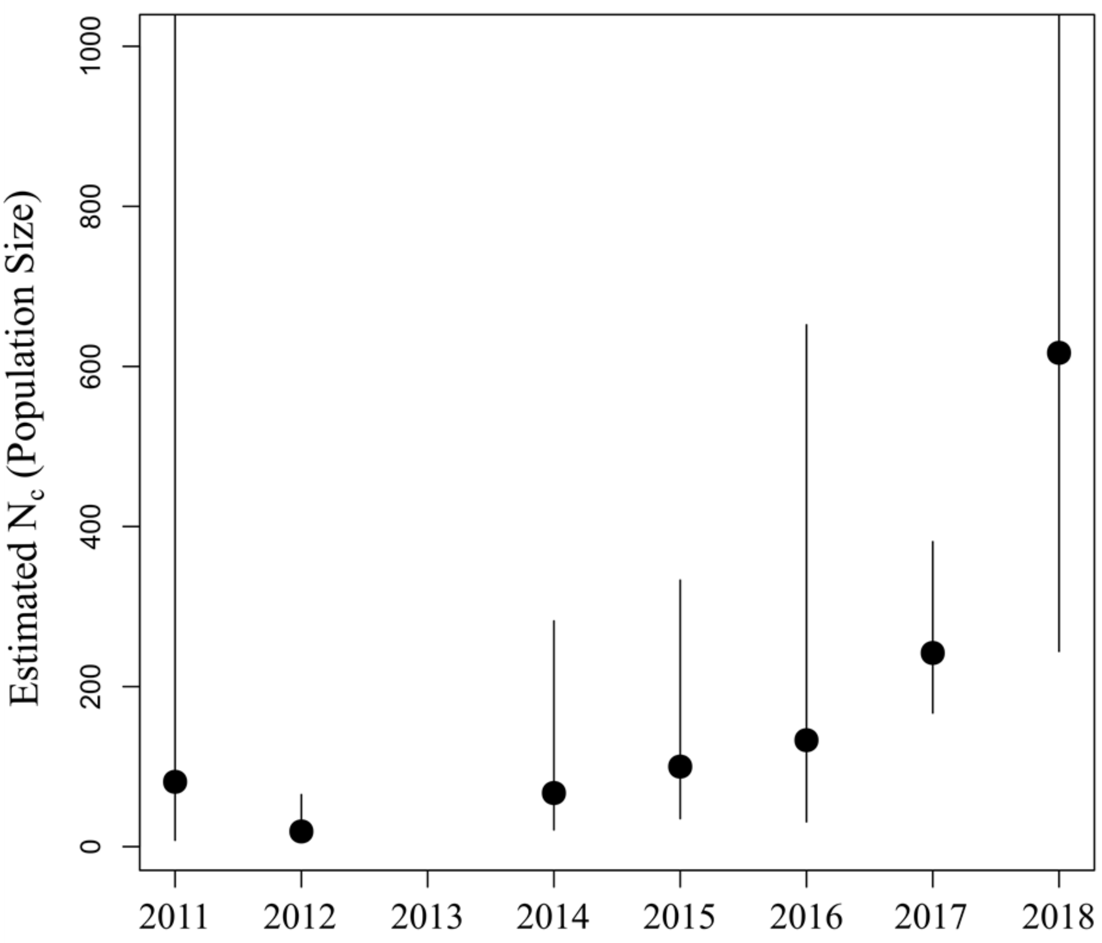


Figure 51. Population estimate (95% CI) for adult Colorado pikeminnow in the San Juan River. Figure and data adapted from San Juan River Basin Recovery Implementation Program (2017) by Diver and Mussman (2019).

Table 24. Adult Colorado pikeminnow population estimates and 95% confidence intervals (CI) for the Green, upper Colorado, and San Juan river subbasins for last 10 years of available data. Data from Bestgen et al. (2018 and unpublished data); Osmundson and White (2014); Elverud and Ryden (2018); Diver and Mussman (2019).

Year	Green River subbasin (509 RMI)			Upper Colorado River subbasin (182 RMI)			San Juan River subbasin (103 RMI)		
	N	Low CI	High CI	N	Low CI	High CI	N	Low CI	High CI
2003	3,131	2,655	3,710	661	452	990			
2004				688	511	946			
2005				889	746	1075			
2006	2,542	2,026	3,230						
2007	2,339	1,973	2,793						
2008	3,000	2,377	3,809	710	545	946			
2009				511	404	662			
2010				493	390	639			
2011	2,083	1,674	2,619				81	8	1,125
2012	1,787	1,440	2,242				19	7	65
2013	2,128	1,472	3,117	332					
2014				482			67	21	282
2015				429			100	35	333
2016	1243*	956	1,640				133	31	652
2017	842*	676	1,066				242	167	381
2018	885*	679	1,171				617	244	1,753
Mean	1,495			493			180		

5.2.4 Long-term population trajectory

The Colorado pikeminnow PVA (Miller, P. S. 2018) estimated population growth rates (lambda) from historic abundance estimates on the Green and upper Colorado river subbasins. The Green River data supported two models that fit the data, termed single-phase and dual-phase dynamics (Figure 52). The single-phase dynamic indicated a slowly declining population over a long period (since 1991). The dual-phase dynamic suggested the population was growing from 1991-2000, and began declining in 2001. The dual-phase model had stronger statistical support than the single-phase model, but both were well-supported. Recent estimates for 2016-2018 from Bestgen et al. (unpublished data) indicate a declining trend that more closely resembles the dual-phase model (Figure 49). In either case, these analyses estimate the population has been declining at a rate of 1.7-5.5% per year since at least 2000.

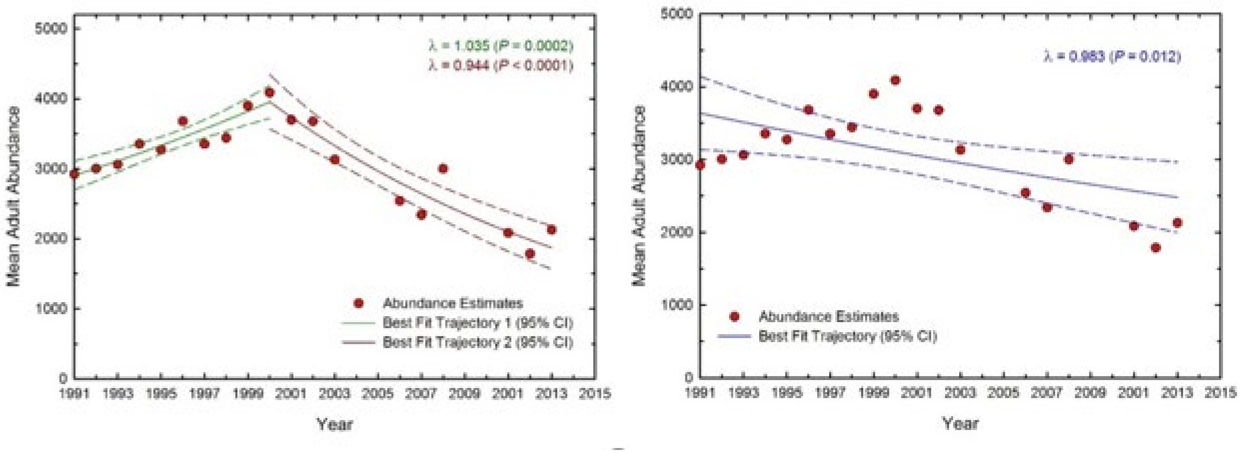


Figure 52. Adult Colorado pikeminnow abundance estimates for the Green River subbasin, with statistical trend analysis under the assumption of a dual-phase (left) or single-phase (right) demographic dynamics. Figures from Miller (2018) compiled from Bestgen *et al.* (2018).

The PVA applied the same single- and dual-phase models to the upper Colorado River subbasin, and neither model received significant statistical support (Figure 53; Miller, P. S. 2018). Of all the trends analyzed, there was some support for a population decline of 7% annually from 2005 to 2015 (the latter period of the dual-phase model). There was not statistical support for an increasing population prior to 2005 in the dual-phase model, nor for a slightly declining population across the entire dataset in the single-phase model.

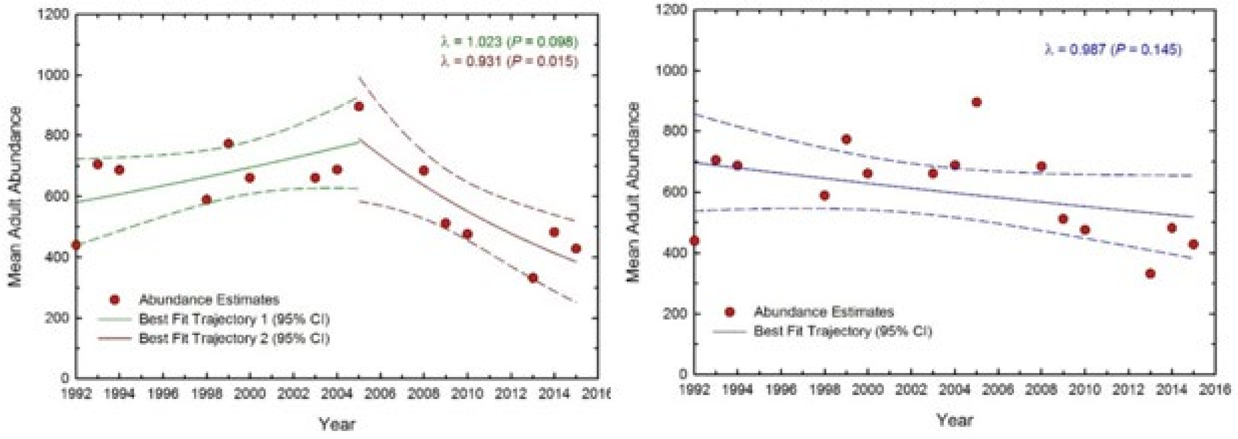


Figure 53. Adult Colorado pikeminnow estimates in the Upper Colorado River subbasin, with statistical trend analysis under the assumption of a dual-phase (left) or single-phase (right) demographic dynamics (P.S. Miller 2018 from Osmundson and White (2014) and Elverud and Ryden (2018) abundance estimates).

For the San Juan River subbasin, no estimates of population growth have been reported. The adult abundance in this population appears to have increased in recent years, but it is unclear what proportion of these adults, if any, are the result of wild-spawned fish that have recruited to adult size. The PVA did conclude, however, that without significant improvements in survival of early life stages, annual stocking will be required to maintain current adult abundances. This suggests that the current adult population is largely a result of stocking and not a product of increasing abundance of wild adults (Miller, P. S. 2018).

5.3 Lower Colorado River Basin Populations

Colorado pikeminnow have been extirpated from the lower Colorado River basin since the mid-1970s (Moyle 1976; Smith, G. R. *et al.* 1979; Minckley 1985; Mueller and Marsh 2002). The Gila River subbasin was designated as an experimental, nonessential population (50 CFR §1985), and 770,210 Colorado pikeminnow were stocked into the Salt and Verde rivers, tributaries to the Gila River, between 1985–1990 in an attempt to reestablish the species (Hendrickson 1993). Colorado pikeminnow have not been stocked into the Salt River since 1990. Stocking occurred sporadically between 1990 and 2002, and since then the Verde River has been stocked annually from 2002 to 2010 and again from 2015 to 2017. Between 2002–2017, 17,713 fish were stocked into the Verde River with annual stocking consisting of 266 to 2,384 individuals (Figure 54; S. Taylor, 2018 pers. comm.). For those fish stocked between 2002 and 2012 the mean length ranged from 300 to 400 mm (12 to 16 in) TL (Gill 2012). These fish were stocked upstream of Horseshoe Reservoir. Annual monitoring in the reservoir has resulted in the capture of two Colorado pikeminnow (2010), which were individuals stocked four months prior that same year (Salt River Project 2010). Fish surveys conducted in other sections of the Verde River (2003-2006, 2010, and 2012-2016) have not resulted in additional captures of Colorado pikeminnow (Weedman 2004b; Clark, A. 2006; Chmiel 2010a; Chmiel 2010b; Chmiel 2010c; Cummins 2013; Gill 2013). Fish surveys in the Salt River (2001-2004, 2009, and 2011) have not detected any of the Colorado pikeminnow stocked between 1981–1990 (Weedman 2004a; Evans, J. 2009; Gill 2011). The stocking program for Colorado pikeminnow in the Verde River ceased in 2018, and there are no plans to continue in the near future (AZGFD, pers. comm. 2019).

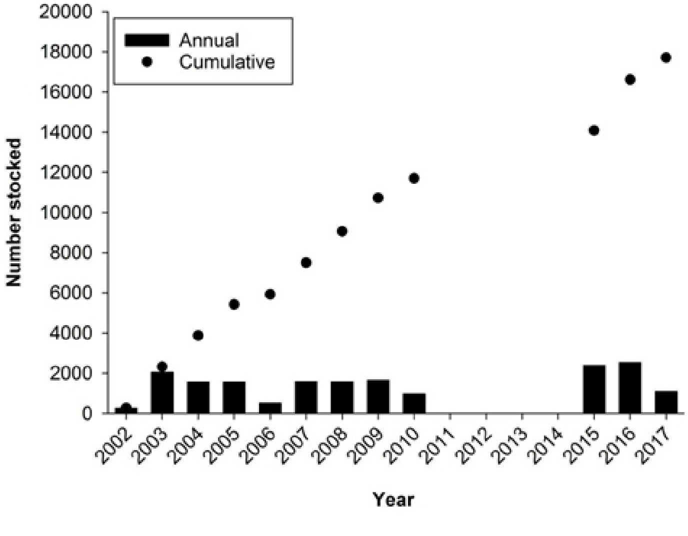


Figure 54. Annual and cumulative number of Colorado pikeminnow stocked to the Verde River, 2002-2017 (S. Taylor, pers. comm. 2018).

We are uncertain as to why stocked fish do not appear to survive in these rivers, which appear to contain suitable habitat such as pools and riffles for foraging and large river widths that may contain nursery habitat (Figure 55). Aspects such as shorter lengths of available riverine habitat as a result of water depletions and barriers, entrainment into diversions, and nonnative predatory fishes may contribute to the lack of apparent survival (Hendrickson 1993; Hyatt 2004).

Figure 55. Salt River (left) and Verde River (right) in the Gila River subbasin. Photos from Chmiel (2006) and Weedman (2004a).

Table 25. Current conditions for demographic factors of the six Colorado pikeminnow analysis units. Overall current condition scores were derived by adding condition values described in Table 19 above. The overall condition (sum of all scores) was then identified as functionally extirpated (1-3), low (4-8), moderate (9-13), or high (14-16). Note: overall condition cannot be more than one category higher than the lowest score for any of the factors.

Analysis unit	**Wild reproduction**	**Wild recruitment to sexual maturity**	**Adult Abundance**	**Long-term Population Trajectory**	**Overall condition**
Green River subbasin	Moderate 2009-2018: 5.1 / 100m	Low Recruit ratio = 21%; Adult mortality = 27%	Low 2009-2018: 1495	Low 2003-2018	Low (5)
Upper Colorado River subbasin	High 2009-2018: 14.3 / 100m	High Recruit ratio = 18%; Adult mortality = 17%	Low 2008-2017: 493	Low 2003-2018	Low (8)
San Juan River subbasin	Low 2009-2018: 0.15 / 100m	Extirpated No wild recruits detected	Low 2009-2018: 180	Moderate	Low (4)
Colorado River, Grand Canyon	**Ø**	**Ø**	**Ø**	**Ø**	**Ø** **Extirpated**
Lower Colorado River mainstem	**Ø**	**Ø**	**Ø**	**Ø**	**Ø** **Extirpated**
Gila River subbasin	**Ø**	**Ø**	**Ø**	**Ø**	**Ø** **Extirpated**

5.4 Current condition of habitat factors used to assess resiliency

The current condition for many of the habitat factors described and summarized in this section are the result of conservation measures described in Chapter 4. Because the effects of those conservation measures are described in Chapter 4, this section refers back to those summaries rather than repeating them here.

5.4.1 Peak flows—channel complexity and habitat maintenance

As discussed in Section 4.1.1, spring peak flows are considered the primary driver in creating backwaters in the Colorado River Basin (Grippo *et al.* 2017), and these backwaters are used as nursery habitat for Colorado pikeminnow larvae and age-0 fish (Bestgen and Hill 2016a). Both the magnitude and duration of peak flows can influence the number and size of backwaters. Peak flows of sufficient magnitude can also clean cobble bars of fine sediment, making them more suitable for spawning, egg hatching, and larval survival. High magnitude flows can also reverse channel narrowing and encroachment of vegetation that can lead to the simplification of the river channel (Section 4.1.7). The Colorado River Basin is a regulated system, and peak flows in most major rivers in the basin are affected at least in part by releases from large reservoirs (the Yampa and White rivers being significant exceptions). At times, these releases are based on recommendations to support Colorado pikeminnow populations. For this SSA, channel complexity and habitat maintenance were described for each reach based on the extent to which a variable flow regime has persisted similar to the natural hydrograph and whether those flows have led to improving or maintaining complex channel morphology. The successful implementation of channel maintenance peak flows based on flow recommendations was also considered in describing this factor. Because flow regimes are affected to a large extent by conservation measures such as reservoir operations to support flow recommendations, the current condition of flow regimes is described in Section 4.2.1 and summarized in Table 29.

Schmidt and Wilcock (2008) summarized channel narrowing throughout various reaches of the Colorado River Basin. They reported the Green River postdam width was 3-15% narrower than the predam width. For the upper Colorado River, the channel was 8-21% narrower above the Gunnsion River confluence and 8-20% narrower below this confluence. Lamarra and Lamarra (2016) concluded that the San Juan River also has experienced channel narrowing and a loss of complexity since the 1930s, as indicated by a decrease in total wetted area from ~2 million m^2 to ~600,000 m^2 in a 6.4 km (4 mi) reach and decreases in the number of islands and backwater area.

In the Grand Canyon reach of the Colorado River, Grams et al. (2007) estimated that the channel below Glen Canyon Dam had narrowed 6% between 1952 and 1984, mostly as a result of dam construction. Timing of peak flows in this reach are determined by high flow experiment criteria, which are largely based on the quantity, type, and location of sediment available for flow mobilization. A secondary benefit of the high flow experiments may be the restoration of some backwater type habitats, but these appear to be temporary (see Section 5.4.2 and Grams *et al.* (2010).

For the lower Colorado River mainstem, releases from the series of dams from Hoover Dam downstream are prioritized for flood control, water deliveries for irrigation and municipal water rights, and maximized power generation (Lower Colorado River Multi-Species Conservation Program 2004). Peak flows have occurred as a result of flood mitigation, but not for fish habitat or environmental flows, and are therefore irregular and unpredictable. In addition, many reaches in this subbasin have been channelized, dredged, riprapped, or leveed, reducing channel complexity and inhibiting flood flows from restoring or maintaining channel morphology.

In the Gila River subbasin, flows in the lower Salt and Verde rivers are controlled by a series of reservoirs in the Salt River Project. Above the Salt River Project reservoirs, flows in the Salt and Verde rivers are largely driven by precipitation patterns and, in the case of the Verde River, springs and tributary inflows (Arizona Department of Water Resources 2010). In their lower reaches, both rivers are regulated by a system of reservoirs managed for irrigation and municipal water deliveries. Where the two rivers join and flow into the Gila River, the entire streamflow is typically diverted to serve water supplies of the Phoenix metropolitan area. Downstream of the Phoenix area, the lower Gila River is considered intermittent or ephemeral (Arizona Department of Water Resources 2010) and flow in this reach originates from dam releases for flood control, precipitation events, and irrigation returns.

5.4.2 Base flows to provide nursery habitats

The work by Bestgen and Hill (2016a), Grippo *et al.* (2017), and Lamarra *et al.* (2018) support the hypothesis that there is a range of summer base flows that maximize backwater habitat as discussed in Sections 4.1.1 and 4.2.1. The PVA for Colorado pikeminnow also modeled the effects of base flow management on the species (Miller, P. S. 2018), and predicted a positive influence on adult abundance as a result of more consistent implementation of flow recommendations based on Bestgen and Hill (2016a). For this SSA we assessed whether nursery habitat was produced and maintained during the larval and age-0 growing season based on whether recommended summer base flow targets were met to maximize backwater and other nursery habitats. Base flow conditions and the resulting nursery habitat are provided through the implementation of flow experiments conducted within the flexibility of the current ROD, which was described in Section 4.2.1 and summarized in Table 29 and below. We partitioned this habitat factor into whether base flow recommendations from Bestgen and Hill (2016a) were maximized (≥75% of the time), commonly provided (74–50% of the time), or rarely provided (< 50% of the time) over the last ten years. The condition for extirpation was one where summer base flows were not regulated to stabilize backwater nursery habitat.

The most recent ten years of data for summer base flows are listed in Table 26, and show that base flows have been maintained within the recommended range for 7 of the last 10 years, for both the middle and lower Green River reaches. Despite mean August-September base flows within the recommended range, recruitment in 2016 and 2017 was low because flows were still high in late June and early July when Colorado pikeminnow larvae emerged from spawning bars and drifted into the nursery reaches (LaGory *et al.* 2019). These higher flows were a result of spring releases from Flaming Gorge Dam extending into the first portion of the larval drift period. For the upper Colorado River subbasin, base flows were maintained within the preferred range in 8 out of 10 years during 2009-2018 (Table 26). Base flow recommendations derived from age-0 Colorado pikeminnow densities have not been identified for the San Juan subbasin. There is some indication that individual backwater habitats are larger and total backwater area increases with flows at the higher end of the recommended range (>22 m^3/s [750 cfs]; Lamarra, V. A. *et al.* 2018), but these findings are preliminary and have not been incorporated into formal flow recommendations. Although base flows for the San Juan River have been managed within the existing base flow recommendations discussed earlier, the infrequent achievement of base flows that provide more nursery habitat lowered the condition of this resource.

Table 26. Mean August-September base flows for Green and Colorado river nursery reaches, 2009-2018. Revised base flow recommendations are listed in parentheses below each reach. Flows outside the recommended range are indicated in bold.

Year	middle Green River (1,700-3,000 cfs)	lower Green River (1,700-3,800 cfs)	Colorado River (3,000-6,400 cfs)
2009	2,479	2,785	3,870
2010	2,165	2,543	3,835
2011	**3,686**	**5,686**	5,540
2012	**1,406**	**1,338**	**2,605**
2013	**1,506**	**1,625**	3,715
2014	2,979	3,463	4,913
2015	2,118	2,328	3,995
2016	2,151	2,660	3,986
2017	2,762	2,998	4,314
2018	2,261	2,037	**2,433**

As mentioned in Section 4.2.1, flows are not managed to provide Colorado pikeminnow habitat in the Grand Canyon, the lower Colorado River, or the Gila River subbasins. In the Grand Canyon, flows are managed for hydropower production and other native fish resources, with periodic high flow experiments designed to facilitate sediment transport. While the high flow experiments can improve backwater habitat availability and area temporarily by building sandbars, erosion resulting from summer flow regimes reduced gains back to pre-experiment levels by the end of the year (Grams *et al.* 2010). These surveys also found that backwaters were more persistent during steady flow regimes, as compared to the maximum fluctuation of 227 m^3/s (8,000 cfs) within 24 hours. Flows in the lower Colorado River and Gila River subbasins are managed exclusively for consumptive water deliveries and hydropower. The Gila River subbasin in particular is highly modified and considered intermittent in the lower reaches (Section 5.4.1). It is unclear to what extent nursery habitats might be present in the lower Colorado River since extensive channelization and bank stabilization has occurred, but base flows are not provided with regard to native fishes.

5.4.3 Water temperature

Colorado pikeminnow require warm water temperatures in order to complete their life cycle. As described in Sections 3.1 and 4.1.2, spawning adults, eggs, and larvae require sufficiently warm water for successful reproduction and recruitment. Adults also require warm temperatures outside of the spawning period, and cold hypolimnetic releases from dams can preclude adult Colorado pikeminnow use in tailrace reaches below dams. For this SSA we assessed whether water temperatures reached and exceed 16–18°C in late spring to cue and support spawning adults and increased to 22–26°C (72-79°F) in the summer months to support growth of larval and age-0 fish. We qualitatively assessed to what extent temperatures were able to meet requirements for different life stages over the connected length of river habitat. Conditions for extirpation were those in which water temperatures did not meet thresholds required for any life stage. These data are presented in Section 4.2.1 and summarized in Table 29.

5.4.4 Complex, redundant riverine habitats

The availability and spatial arrangement of different types of suitable habitats can affect the ability of Colorado pikeminnow to forage, reproduce, and survive. Adult Colorado pikeminnow tend to occupy pools and deep, slow-moving runs for feeding and home range. Sufficient availability of these habitats will influence the carrying capacity of a river reach and can often be the product of available length of riverine habitat. Spawning adults deposit eggs in clean cobble and gravel substrates with sufficient water velocity to oxygenate eggs in the interstitial spaces. Larvae and age-0 fish drift into low velocity nursery habitats where higher food availability and warmer temperatures enhance growth before winter. These different habitats must be arranged in such a way as to allow adults to move between home range foraging areas and spawning areas. Spawning habitats need to be available annually, which can depend on flow conditions maintaining adequate substrate and fish passage, and these habitats must be situated upstream of suitable nursery habitats in order for larvae to be carried into conditions more conducive for recruitment. All of these habitat factors are required to a sufficient extent to sustain an adult population that successfully reproduces to maintain itself. The presence of redundant habitat types can mitigate the effects of less favorable environmental conditions in a particular reach and increases resiliency. Data summarizing the importance and availability of complex, redundant habitat can be found in Sections 4.1.3, 4.1.7, and 4.2.2 as well as Table 29.

This SSA rates the availability and extent of complex, redundant habitat as follows: An analysis unit was considered in high condition if it had a large extent of river with complex habitat, more than one spawning habitat, widespread and abundant nursery habitats, and multiple tributaries that provided access to a significant amount of suitable habitat. Moderate condition analysis units were those that had an intermediate length of complex riverine habitat, suitable spawning and nursery reaches that may be limited in number or extent, and some available tributary habitat. Analysis units were considered to be in low condition when a river had limited spawning habitat, nursery habitats were diffuse and marginal, and a low amount of tributary habitat. A river reach was described as extirpated when it had no suitable riverine habitat, consisting of low channel complexity, no spawning habitat, and no low velocity nursery habitat.

Valdez (2018) summarized the available data for Colorado pikeminnow habitat in the upper Colorado River basin for the PVA analyses. This data assimilation stated that Colorado pikeminnow inhabited 1,278 km (794 mi) of the Green River subbasin, 476 km (296 mi) of the upper Colorado River subbasin, and 347 km (216 mi) of the San Juan River subbasin. There are also 984, 574, and 290 km (611, 357, and 180 mi) of designated critical habitat within the Green, upper Colorado, and San Juan river subbasins, respectively.

Within the Green River subbasin, Colorado pikeminnow are known to spawn in two main locations in the lower Yampa River and in Desolation/Gray Canyons, with corresponding nursery reaches of >130 km (>81 mi) located below these spawning sites. There have also been occasional observations of spawning outside the main reaches, such as the White River (Webber *et al.* 2013). Both nursery reaches in the Green River subbasin contain zero velocity backwater habitats that are distributed regularly throughout the reach, with an estimated mean of 4.25 backwaters/RK in the middle Green River and 1.6 backwaters/RK in the lower Green River

(Day, K. S. *et al.* 1999; Trammell and Chart 1999b). Grippo *et al.* (2017) estimated backwater area in the middle Green River to be approximately 932—1865 m^2/RK in 2012, with an average of 0.93—1.2 backwater/RK. Trammell and Chart (1999b) found a mean annual density of 1.6 backwater habitats per RK and a mean annual area of 605.6 m^2/RK. Their study focused on a reach between RK 91.7 and 75.6 during 1992—1996. Finally, the Green River subbasin provides access to multiple tributary streams, including the Yampa (>224 km [>139 mi]), Duchesne (56 km [35 mi]), White (167 km [104 mi]), Price (142 km [88 mi]), and San Rafael (>60 km [37 mi]) rivers.

For the upper Colorado River subbasin, Colorado pikeminnow are believed to spawn over a larger reach of river primarily within the Grand Valley, although other sites have been suggested in the Gunnison River and below Westwater Canyon (McAda 2003). The lower 105 km (65 mi) of the Colorado River have been identified as the highest density of age-0 fish and are thought to represent the nursery reach for this subbasin. Despite the presence of larvae upstream of this reach in the 1990s (Anderson, R. 1998), more recent monitoring has not detected larvae in the Gunnison River or the Colorado River upstream of Westwater Canyon (Elverud 2018). Trammell and Chart (1999a) found 1.8 backwaters/RK in the upper reach and 1.4/RK in the lower reach of the Colorado River nursery reach. In addition, the upper Colorado River subbasin contains potential tributary habitat in the lower 97 km (60 mi) of the Gunnison River and 104 km (65 mi) of the Dolores River (Valdez, Mangan, McInerny *et al.* 1982), although access to the Gunnison River relies on fish being physically moved through the fish passage at the Redlands Diversion.

In the San Juan River subbasin, spawning activity has been suggested in two areas around RK 215-209 and RK 197. No specific nursery reach has been identified in the San Juan River subbasin, and larval fish have been found in the lower 251 RK (166 RM; Farrington *et al.* 2018). Lamarra and Lamarra (2013) found a decrease in total backwater area within the San Juan River from 1996 to 2012, but the number of backwaters had increased despite declines in total area from 2011 to 2012. Backwaters and lower velocity reaches were noted for the non-canyon reaches between RMI 130-68 where much larger backwater areas were observed. For RK 290-3, Lamarra and Lamarra (2013) measured 53,633 m^2 of backwater habitat in 2012 (187 m^2/RK). The San Juan River subbasin has tributary habitat available in the Animas River, and McElmo and Yellowjacket creeks, but diversion dams in the Animas River likely impede fish from moving upstream (U.S. Bureau of Reclamation 2007).

The Grand Canyon reach of the Colorado River extends ~476 km (~296 mi) from Glen Canyon Dam to the inflow area of Lake Mead, depending on lake levels. The reach is confined within the canyon and has a relatively steep mean gradient of 1.37 m/km, compared to nursery reach gradients of 0.3-0.6 m/km in the Green and upper Colorado rivers (Valdez 2018). Backwater habitats are present throughout the reach, with a maximum total area of 14,000 m^2 estimated in a 389 km (242 mi) reach (36 m^2/RK; Figure 56; Grams *et al.* 2010). More recent data during 2016—2018 found approximately one backwater per mile throughout the Grand Canyon (M. Dodrill, unpublished data). Tributary habitat is limited and mainly consists of small creeks, with the exception of the Little Colorado River.

The lower Colorado River is characterized by a series of dams and impoundments, with cold tailrace reaches of river that warm as they approach the downstream reservoir inflow. The reaches of river between dams are relatively short, with a maximum extent of ~63 km (~39 mi). In addition, dredging, levee construction, and channelization have simplified the river channel and reduced potential spawning and nursery habitat.

Potential Colorado pikeminnow habitat was identified for the Gila River subbasin with the designation of experimental, nonessential populations that allowed for stocking of the species in the Verde and Salt rivers (50 CFR 30188). These reaches were bounded by impoundments downstream and what was considered a lack of suitable habitat at their upstream extents. Based on maps in Hendrickson (1993) these reaches constitute ~185 km (~115 mi) of the Verde River and ~90 km (~56 mi) of habitat in the Salt River. Reservoirs and their dams form barriers that isolate these river reaches from the rest of the Gila River subbasin, and as mentioned in Section 5.4.1, the river only flows intermittently in the lower portion of the basin.

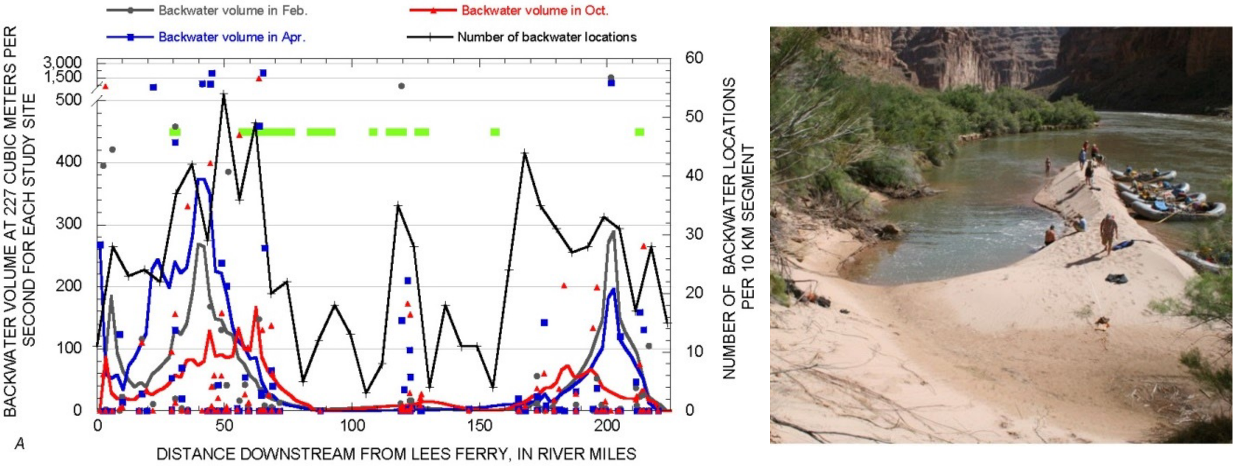


Figure 56. Backwater distribution, volume, and number in the Colorado River, Grand Canyon. Figure and photo from Grams *et al.* (2010). Green squares represent locations of known humpback chub aggregations.

5.4.5 Availability of prey influenced by nonnative fishes

Due to Colorado pikeminnow's evolutionary history where it was the sole large predator, the increase in nonnative predatory fishes in its range has reduced the resiliency of extant Colorado pikeminnow populations. However, the interaction is complex depending on the ecology, abundance, and distribution of a nonnative species and whether conservation management is effective in minimizing the effects of problematic species. We partitioned this metric into high, moderate, low, and an extirpated condition, respectively characterized as: 1) nonnative fish impacts are minimal and do not influence population dynamics enough to cause detectable changes in abundance, 2) nonnative fishes cause detectable, negative impacts to populations, but Colorado pikeminnow are persisting, 3) nonnative fishes have caused a detectable decline in native fish abundance that is believed to negatively impact Colorado pikeminnow, and 4) nonnative fishes are predominant throughout a reach and preclude the presence of Colorado pikeminnow.

Nonnative fishes that impose the greatest predatory pressure in the upper Colorado River basin are large-bodied species including smallmouth bass, northern pike, and walleye (Johnson *et al.* 2008; Martinez *et al.* 2014). Smallmouth bass is considered abundant throughout the Green River subbasin (Figure 57), and densities have generally been lower in the upper Colorado River subbasin (Figure 58). The species has not established a population in the San Juan River subbasin and has been infrequently collected during annual fish surveys (n = 3 between 2007–2016; Schleicher 2018).

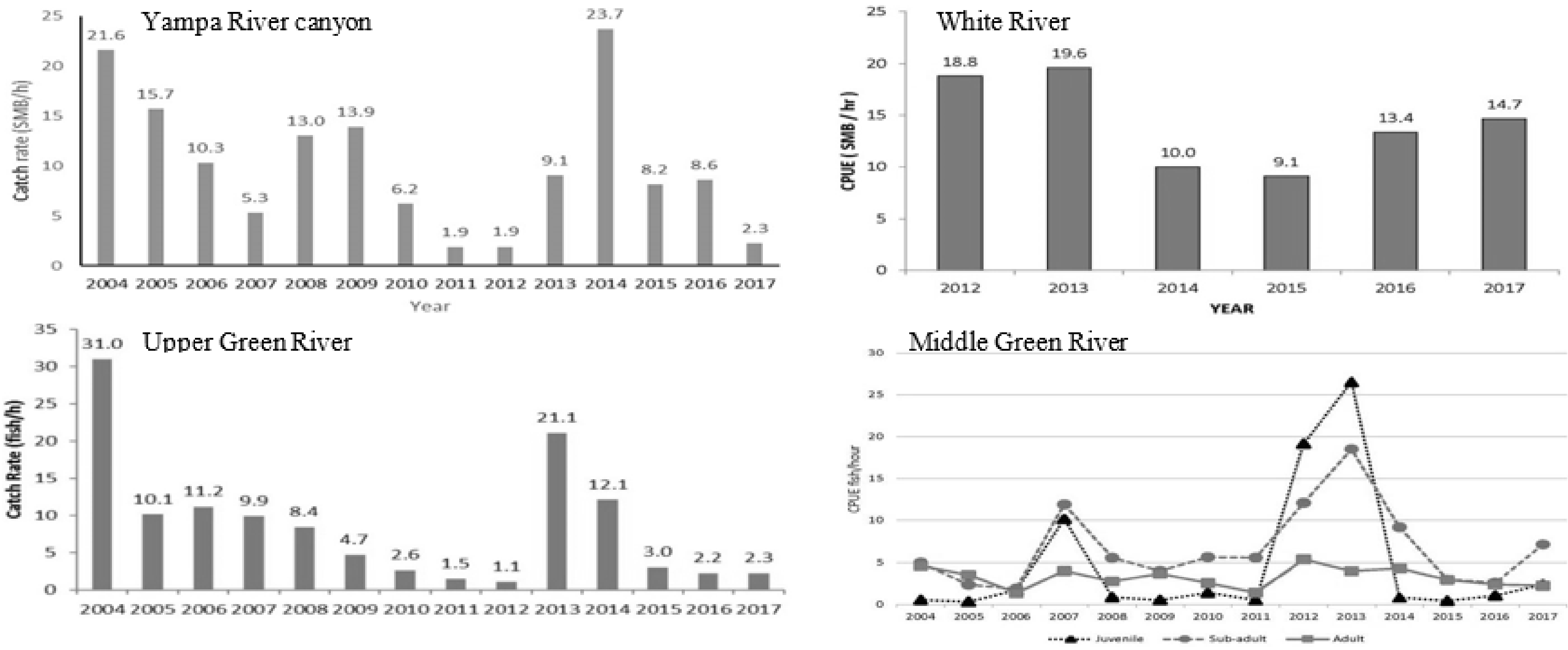
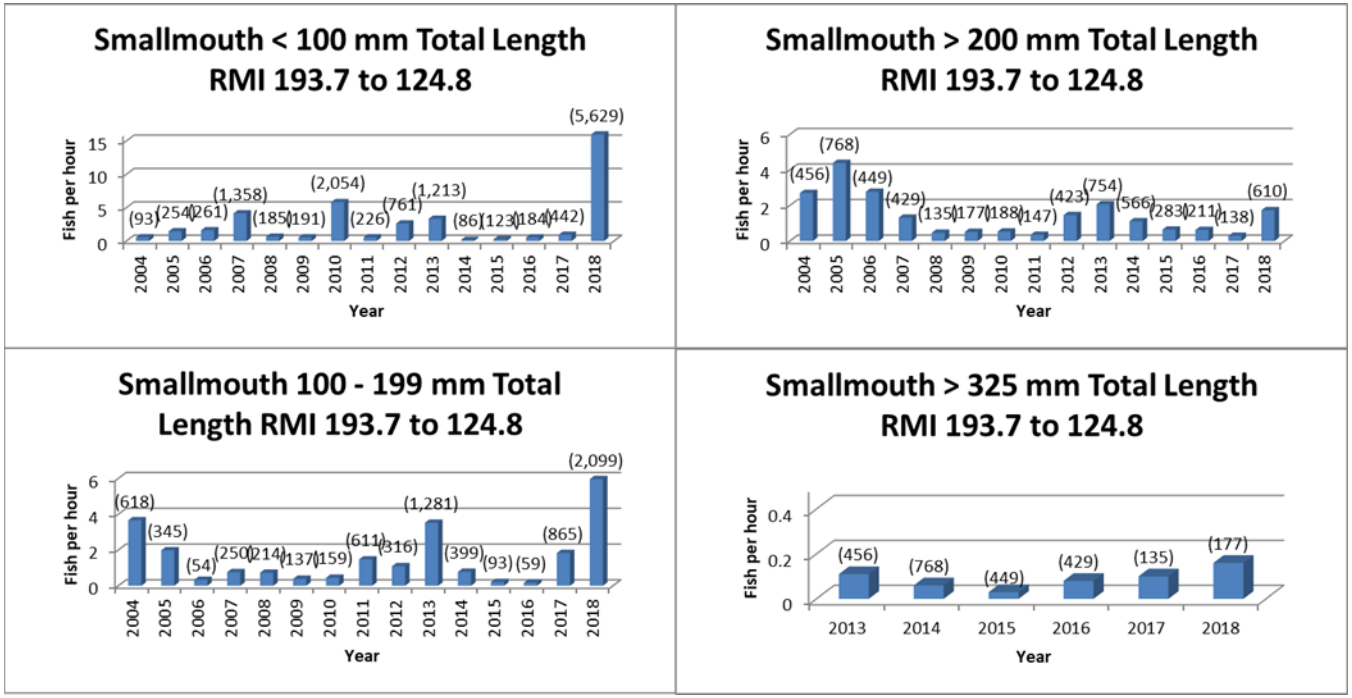


Figure 57. Smallmouth bass (SMB) catch per electrofishing hour (CPUE) in the Green River subbasin. Upper panels from Jones, M. T. (2017) and Smith, C. *et al.* (2017), lower panels from Jones, M. T. and Caldwell (2017) and Staffeldt *et al.* (2017).


Smallmouth < 100 mm Total Length RMI 193.7 to 124.8

Smallmouth > 200 mm Total Length RMI 193.7 to 124.8

Smallmouth 100 - 199 mm Total Length RMI 193.7 to 124.8

Smallmouth > 325 mm Total Length RMI 193.7 to 124.8

Figure 58. Smallmouth bass catch per effort in the upper Colorado River (Francis and Ryden 2018).

Northern pike and walleye are two other large-bodied nonnative piscivorous fishes that have established populations in the Green and upper Colorado River subbasins (Johnson *et al.* 2008; Martinez *et al.* 2014). Northern pike is commonly captured in the upper Yampa River (Green River subbasin; Figure 59; Bestgen *et al.* 2018), while walleye have been captured consistently in the middle and lower Green River and the lower Colorado River. Neither northern pike nor walleye have been collected in annual adult monitoring the San Juan River subbasin (Schleicher 2018).

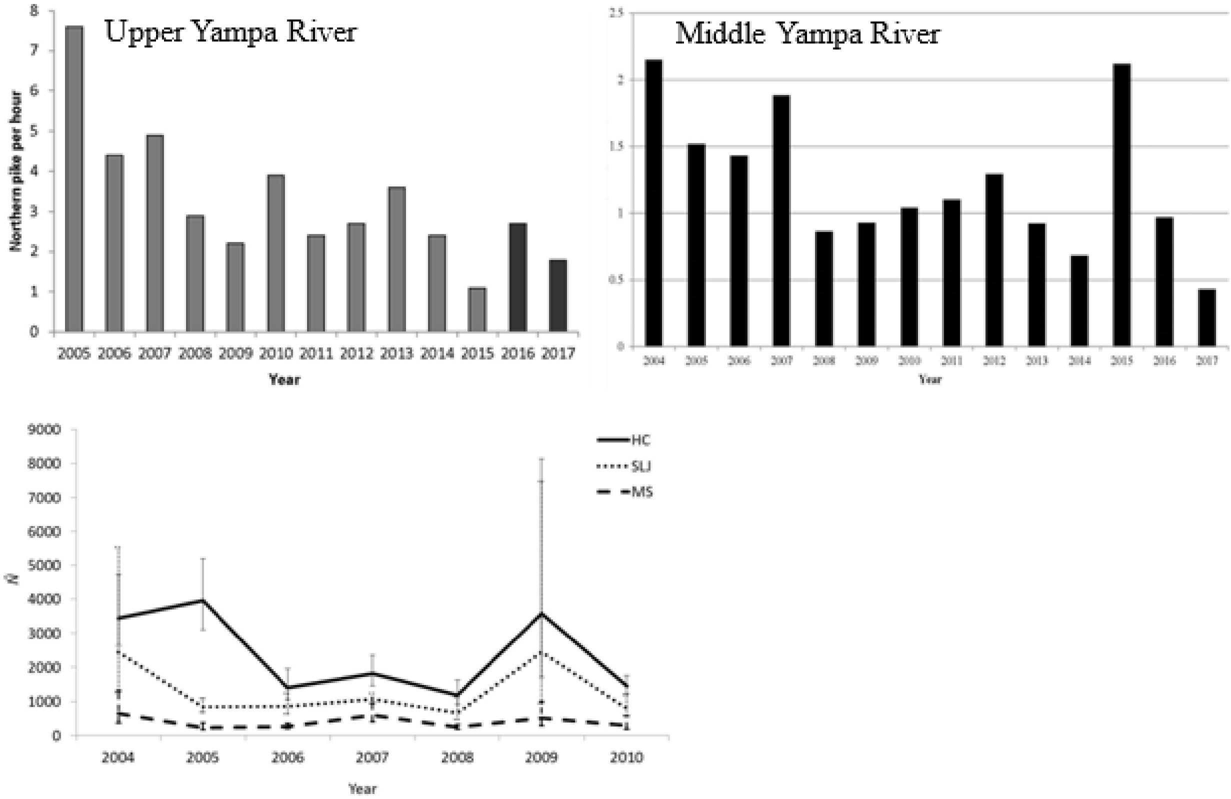


Figure 59. Northern pike catch per hour and population estimates (95 % CI) in the Yampa River; upper panels Eyre (2017) and Smith and Jones (2017) and population estimates (bottom panel) in three river sections (HC=Hayden-Craig; SLJ=South Beach, Little Yampa Canyon and Juniper; MS=Maybell-Sunbeam; Zelasko *et al.* 2015).

Although the San Juan River subbasin has relatively few large-bodied nonnative highly predatory species, common carp *Cyprinus carpio* and channel catfish *Ictalurus punctatus* are present. At times, channel catfish is the second most abundant species collected while common carp captures have been low (Figure 60; Franssen *et al.* 2016). Channel catfish's predatory impact may be lower than other large-bodied nonnative fish fishes (Johnson *et al.* 2008; Patton *et al.* 2015). In the Yampa River (Green River subbasin), channel catfish consumed the least amount of fish at 0.22 kg/km/yr, whereas smallmouth bass consumed a mean of 15.2 kg/km/yr of small-bodied fishes, and northern pike consumed a mean of 13.7 kg/km/yr (Johnson *et al.* 2008; Patton *et al.* 2015). In an analysis of 1,120 channel catfish stomachs collected from the San Juan River, incidence of piscivory was estimated at 8.2% (n = 92; Patton *et al.* 2015). However, given the high abundance of channel catfish in the San Juan River, a low rate of piscivory could potentially have a negative impact on the Colorado pikeminnow population there.

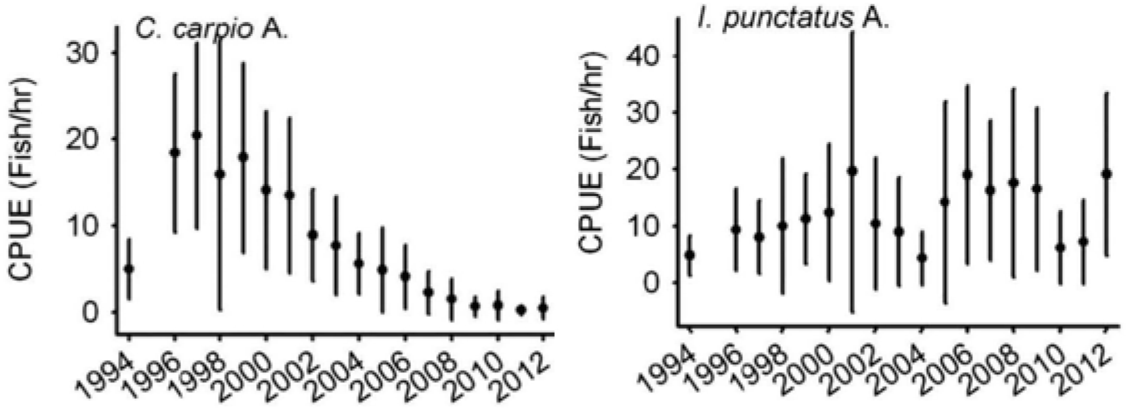


Figure 60. San Juan River catch per unit effort (CPUE) during electrofishing surveys for adult (A.) common carp *Cyprinus carpio* and channel catfish *Ictalurus punctatus* (adapted from Franssen *et al.* 2016).

In the lower Colorado River basin, nonnative large-bodied fishes dominate the fish assemblage with the exception of the Grand Canyon reach. Nonnative fishes in the Grand Canyon reach are mostly salmonids that are present in cooler, upstream portions of the river (Figure 61; Rogowski and Boyer 2019). In 2018, the sub-adult and adult community survey resulted in the collection of few other nonnative species, and these were collected in low numbers: bluegill *Lepomis macrochirus* (n = 1), fathead minnow (n = 29), western mosquitofish *Gambusia affinis* (n = 1), plains killifish *Fundulus zebrinus* (n = 1), red shiner (n = 14), and striped bass *Morone saxatilis* (n = 4). Recent small-bodied fish surveys in western Grand Canyon (the most downstream reach) indicate nonnative fishes are relatively rare, and consist of trout, fathead minnow, plains killifish, western mosquitofish, red shiner, green sunfish, and common carp (Kegerries *et al.* 2018). Native fish species in this reach have become abundant, particularly for flannelmouth sucker, speckled dace, and humpback chub, suggesting that nonnative fish impacts are low.

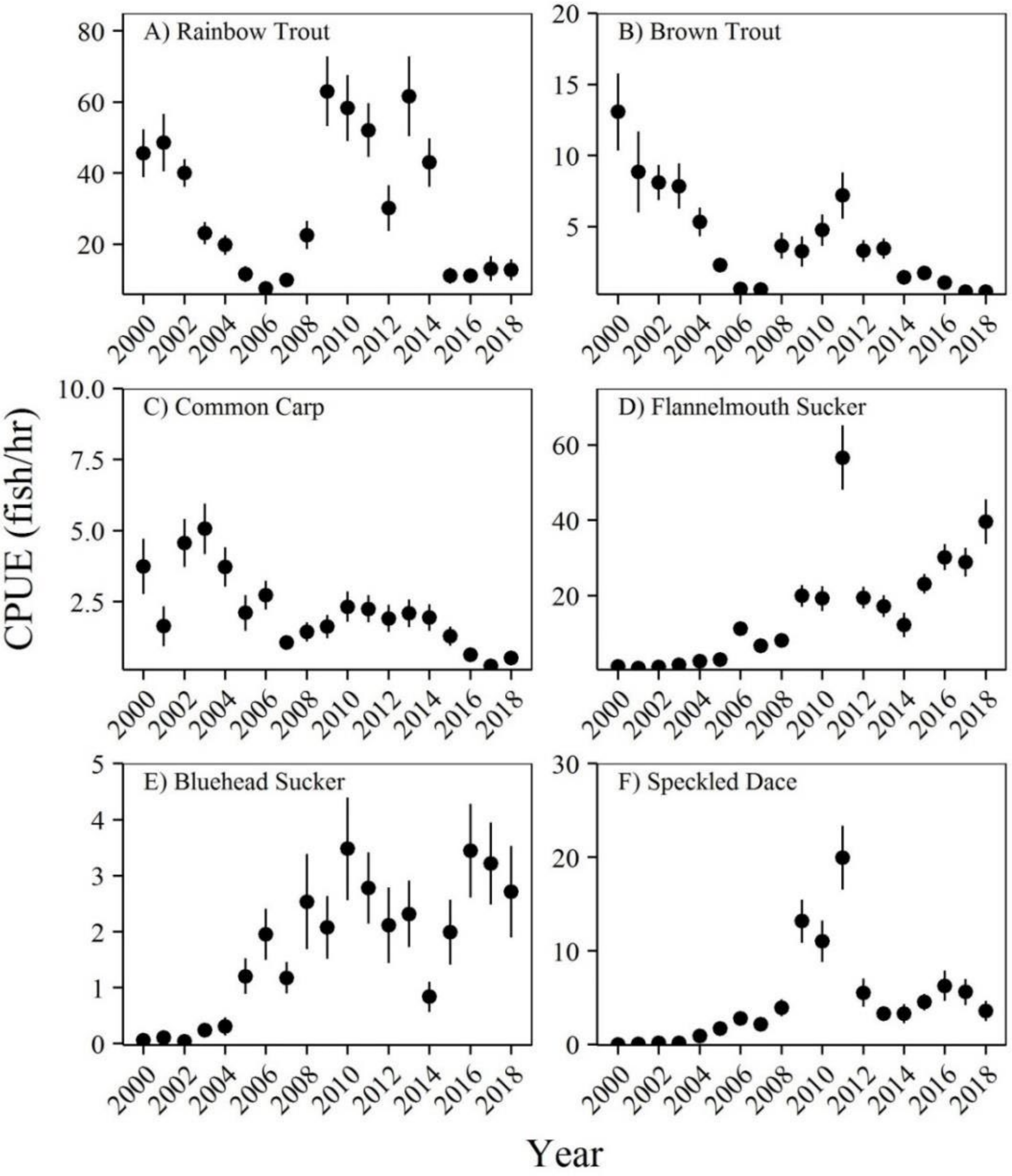


Figure 61. Mean catch per unit effort (CPUE) of the six most common fish species captured during river-wide electrofishing and hoop net surveys in the Grand Canyon reach from Lees Ferry to Pearce Ferry (Rogowski and Boyer 2019). Error bars are 95% confidence intervals.

In the lower Colorado River mainstem where Colorado pikeminnow have been extirpated, the fish assemblage is predominately nonnative species. This is partially because the fish assemblage from Davis Dam downstream to Lake Havasu (~19 RK [12 RM]) is managed as a recreational sport fishery composed of nonnative species (Figure 62; Nevada Department of Wildlife 2014). In 2014, approximately 48% of fishes captured consisted of sportfish. Of these species, the largest captured was striped bass, which had mean length of 841 mm TL (33 in; range: 675–1050 mm [27 – 41 in]). Another 24% of fishes captured were identified as nonnative nongame species with common carp composing 22% of those fishes (Nevada Department of Wildlife 2014). In more downstream reaches of the lower Colorado River mainstem (Parker to Laguna dams) fish surveys in separate river segments totaling 282 RK (175 RM) resulted in the captures of 21 species, 19 which were nonnative (Schooley *et al.* 2008). These species comprised 90% (n = 21,987) of the fishes captured. The most common nonnative fish species were those from the genus *Lepomis* and represented 35% of the catch, followed by largemouth bass *Micropterus salmoides* (19%) and common carp (12%). Razorback sucker are stocked within this reach of river and short-term mortality was estimated to be >70% with long-term mortality estimated at >90%. In large part, the high mortality was attributed to predation by nonnative fishes (Schooley *et al.* 2008).

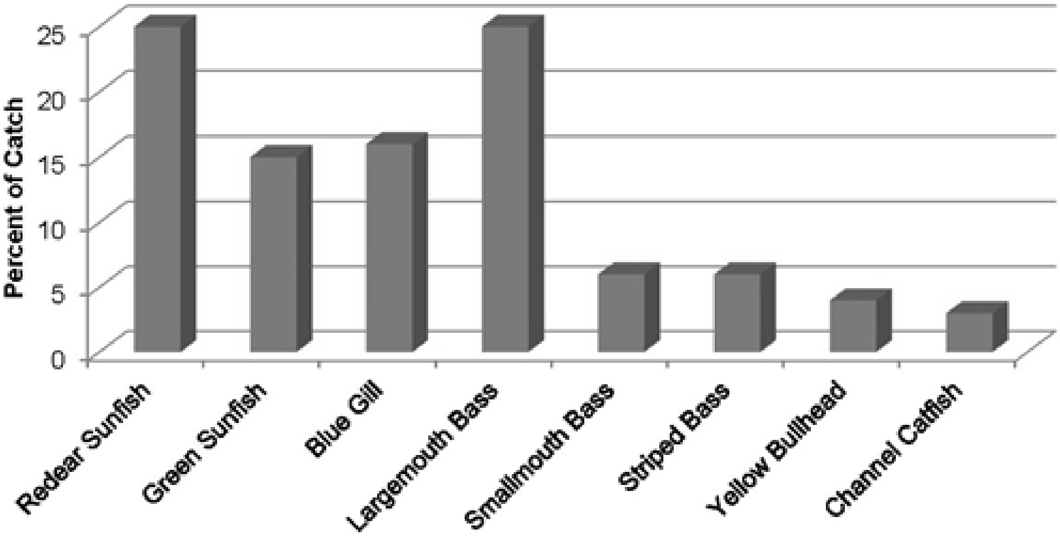


Figure 62. Species composition of select nonnative fishes captured from in the lower Colorado River mainstem (Davis Dam downstream to Lake Havasu; Nevada Department of Wildlife 2014).

In the Gila River subbasin where Colorado pikeminnow have been stocked, flathead catfish *Pylodictis olivaris* is present in addition to the other large-bodied nonnative piscivores documented in the Colorado River Basin. In some portions of the Gila River subbasin flathead catfish may be abundant enough to preclude native fishes from persisting in their historical range (Hendrickson 1993; Hedden *et al.* 2016). In the Verde River, fish surveys conducted in the middle section indicated nonnative fishes were abundant and there were more nonnative than native fish species (Table 27; Gill 2012; Cummins 2012a; Cummins 2012b). The largest largemouth bass individuals captured were 450–499 mm (18-20 in) TL, common carp exceeded 650 mm (26 in) TL, and flathead catfish were captured at maximum lengths of 400–449 mm TL (16-18 in). However, fish surveys in the more upstream sections of the Verde River indicated native fishes composed a greater proportion of the catch in some reaches than nonnative fishes (Paretti *et al.* 2017). Similar to the Verde River, the fish assemblages in the Salt River above its reservoirs are mostly nonnative catfish (Weedman 2004a; Evans, J. 2009; Gill 2011). Surveys from 2004–2011 resulted in captures of fishes that were 99.9–100.0% nonnative. In some areas, flathead catfish composed up to 50% of the large-bodied fishes captured.

Table 27. Abundance (#/hr) and composition of fishes captured during electrofishing surveys in the Verde River. Data summarized from Gill (2010; 2012; 2013) and Cummins (2012a; 2012b).

River Section	Year	Large-mouth Bass	Common Carp	Small-mouth Bass	Flathead Catfish	Nonnative species to total	Nonnative % composition
Middle Verde (3 sites)	2012	47.0 12.1 1.6	14.2 35.7 100.8	114.0 58.1 23.2	6.5 14.0 8.0	9 of 13 7 of 10 8 of 10	73 98 96
Below Horseshoe Reservoir (gill netting)	2013	present	present	____	Present	8 of 8	100
Below Bartlett Reservoir	2010	5.3	7.9	____	____	4 of 7	3

Table 28. Habitat factors and parameters used to compare health (resiliency) among Colorado pikeminnow analysis units.

Condition Category	Peak flows—channel complexity and habitat maintenance	Base flows—nursery habitat[14]	Water temperature	Complex, redundant lotic habitats	Prey availability influenced by nonnative fishes
High	Variable flow regime similar to the natural hydrograph such that channel complexity is maintained at high levels or improving; the channel is essentially unconstrained	Maximized production	Water temperatures support all life stages throughout the reach	Long river reaches with complex habitat, multiple spawning habitats, nursery habitats are widespread and abundant, and access to multiple tributaries with significant amount of habitat	Nonnative fish impacts are minimal and do not influence population dynamics enough to cause detectable changes in abundance
Moderate	Some flow variability allows for approximating the natural hydrograph in most years; channel complexity has been reduced and the channel constrained	Commonly provided	Suitable for adults but insufficient for spawning or larval development in some years or in specific extent	Intermediate length river reaches with complex habitat, spawning and nursery reaches are suitable but limited in number/extent; some tributary habitat available	Nonnative fishes cause detectable negative impacts to populations, but Colorado pikeminnow are persisting
Low	Peak flows sufficient to maintain or improve channel complexity are rare; complexity is low and the channel is constrained	Rarely provided	Suitable for adults but not for spawning or recruitment in most years or over most of the reach	A river with limited spawning habitat, nursery habitats available but diffuse and marginal, and limited tributary habitat available	Nonnative fishes cause a detectable decline in Colorado pikeminnow abundance
Functionally Extirpated	Flows are not variable and do not resemble a natural hydrograph; no channel complexity or maintenance is achieved by peak flows; the channel lacks complexity and/or has been modified to fully constrain the river	Not provided	Water temperatures insufficient to support any life stage year round throughout the reach	No suitable riverine habitat: low channel complexity, no spawning habitat, no zero to low velocity nursery habitats	Nonnative fishes are predominant throughout the reach and preclude Colorado pikeminnow presence

---

[14] Maximizes, commonly, and rarely approximates meeting summer base flow recommendations that result in production of nursery habitat ≥75%, 74-50%, and <50% of recommended targets or over the last 10 years if a target period is not given.

Table 29. Summary of current conditions for habitat factors. Overall current condition scores were derived by averaging extirpated (0), low (1-orange), moderate (2-yellow), and high (3-green) condition values. The overall condition was then identified as extirpated (0.0-0.75), low (0.76-1.5), moderate (1.51-2.25), or high (2.26-3).

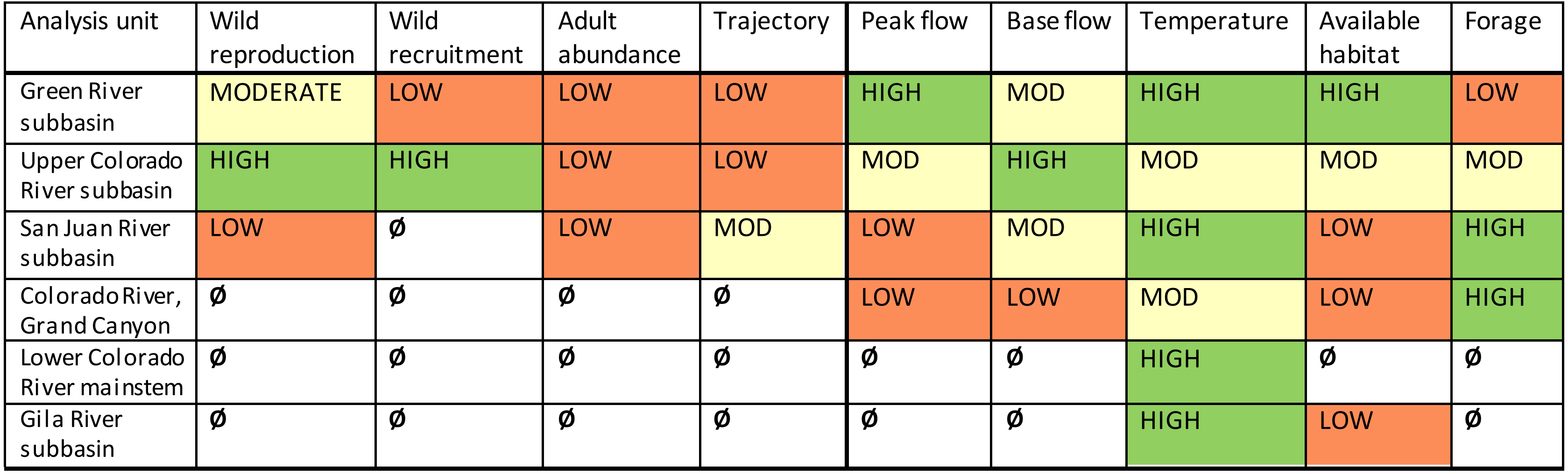
Analysis Unit	**Channel/habitat maintenance-peak flow**	**Nursery habitat—base flow**	**Water temperature**	**Complex, redundant habitat**	**Forage base influenced by nonnative fishes**	**Overall habitat condition**
Green River subbasin	Peak flow magnitude in Reach 2 has been achieved in 9/10 years; in Reach 3, 8/10 years	2009-2018 base flows for both middle and lower Green have been in revised range 7 of 10 years (5 of 10 if looking at larval onset)	Tributary inputs and dam management provide warm temperatures that support spawning, egg hatching, and recruitment through age-0 for two spawning/nursery reaches	Two spawning reaches with nursery reaches downstream; two large tributaries available; smaller tributaries accessible; 1,278 km (794 mi) river available	Riverine populations of walleye, smallmouth bass, and northern pike; nursery habitats contain nonnative cyprinids	HIGH (2.4)
Upper Colorado River subbasin	From 2009-2018 recommended peak flow magnitudes achieved in 4/10 years for 15-Mile Reach. Recommended peak flow magnitude achieved in 7/10 years at state line but 4/10 for durations above half- and bank-full	PVA indicates base flow targets largely met each year Base flows met 2009-2018 in 8 out of 10 years at state line gauge	Temperatures currently support spawning, egg hatching, and recruitment through age-0 for spawning/nursery reach but some critical habitat may not be occupied because of temperatures	One spawning reach with downstream nursery reach; large tributary accessible via fish ladder; 476 km (296 mi) river available but some nursery habitat may have been abandoned or lost	Smallmouth bass and walleye; nonnative cyprinids	MODERATE (2.2)
San Juan River subbasin	6 and 10 year recurrence interval peak flows not achieved since 2008 (0 out of last 10 years)	Median base flows 500-1000 cfs (14-28 m^3/s); from 2005-2016 base flows >750 cfs (>21 m^3/s) 4/12 years	Temperatures currently support spawning, egg hatching, and recruitment through age-0	347 km (216mi) of river habitat, including tributaries; nursery habitats more diffuse and limited in spatial extent, young fish may be lost over waterfall, numerous diversions in upper reaches and tributaries	High abundance channel catfish; relatively few other nonnative predators	MODERATE (2.0)

Colorado River, Grand Canyon	High flow experiments conducted for sediment transport, typically in autumn; sediment is drastically reduced and relies on tributary inputs; channel constrained	Flows managed for hydropower with large fluctuations; backwater habitats not persistent	(Valdez *et al.* 2013) concluded insufficient water temperatures for complete life cycle; recent expansion of humpback chub and flannelmouth sucker associated with warmer temperatures suggest the lower canyon may be reaching temperatures predicted to support CPM life history in ~60 RMIs (~97 RKMs)	Approx. 476 km (296 mi) river between Glen Canyon Dam and Lake Mead, but potential barrier at Pearce Ferry; warm, small tributaries present; spawning and nursery habitats limited	Nonnative salmonids in upper reaches; nonnative warmwater fishes near Lake Mead; largely native fishes in lower river	MODERATE (1.6)
Lower Colorado River mainstem	Flows highly regulated; streambank stabilized or channelized for long distances **Ø-Extirpated**	Base flows managed for hydropower and water deliveries **Ø-Extirpated**	River segments characterized by cold tailraces below dams; potentially water warm enough for nursery habitat	Reach characterized by series of dams and reservoirs; longest reach of riverine habitat is <63 km (<39 mi; section 4.2.2) **Ø-Extirpated**	Multiple, large predator species: striped bass, flathead catfish, largemouth bass, sunfishes; other native fishes largely absent	**Ø** **Extirpated** **(0.6)**
Gila River subbasin	**Ø-Extirpated**	**Ø-Extirpated**	Water temperatures appear suitable	Approx. 101 km (63 mi) available in the Verde River and 64 km (40 mi) in the Salt River; reaches characterized by numerous barriers and dewatered segments	Multiple predator species in high abundances: largemouth bass, smallmouth bass, and flathead catfish	**Ø** **Extirpated** **(0.5)**

5.5 Summary of Current Demographic and Habitat Factors

When demographic and habitat factors are evaluated in combination (Table 30), habitat conditions are generally rated in higher condition than demographic factors. The overall conditions table also displays a summary of key demographic factors and resources that influence the species' viability. Assessing overall condition can be used to identify potential limiting factors that are driving the species' condition, or to identify areas where conservation measures might improve resource conditions or demographic factors. In this instance, factors like nonnative fish impacts to native fish communities for the Green River subbasin and peak flow frequency in the San Juan River subbasin point to possible habitat conditions that could be influencing Colorado pikeminnow populations' current condition. High densities of nonnative fishes, compounded by their diversity and distribution in different parts of the basin, are believed to reduce reproduction and recruitment of populations in the Green River subbasin. Base flow management is also a factor that can influence reproduction and recruitment to the juvenile stage. These reductions in reproduction and recruitment in turn lead to long-term declines in adult abundance. In the San Juan River subbasin, the decreasing frequency of achieving recommended peak flows has been implicated in channel simplification and habitat maintenance necessary to support nursery habitats. As a result, early life stage demographic factors are in a low condition for this population. Regardless of habitat condition ratings, demographic factors are extensively monitored in the three subbasins where Colorado pikeminnow occurs, such that demographic data should adequately represent the species' status.

Table 30. Summary of demographic and habitat factor condition ratings for Colorado pikeminnow analysis units.



Analysis unit	Wild reproduction	Wild recruitment	Adult abundance	Trajectory	Peak flow	Base flow	Temperature	Available habitat	Forage
Green River subbasin	MODERATE	LOW	LOW	LOW	HIGH	MOD	HIGH	HIGH	LOW
Upper Colorado River subbasin	HIGH	HIGH	LOW	LOW	MOD	HIGH	MOD	MOD	MOD
San Juan River subbasin	LOW	Ø	LOW	MOD	LOW	MOD	HIGH	LOW	HIGH
Colorado River, Grand Canyon	Ø	Ø	Ø	Ø	LOW	LOW	MOD	LOW	HIGH
Lower Colorado River mainstem	Ø	Ø	Ø	Ø	Ø	Ø	HIGH	Ø	Ø
Gila River subbasin	Ø	Ø	Ø	Ø	Ø	Ø	HIGH	LOW	Ø

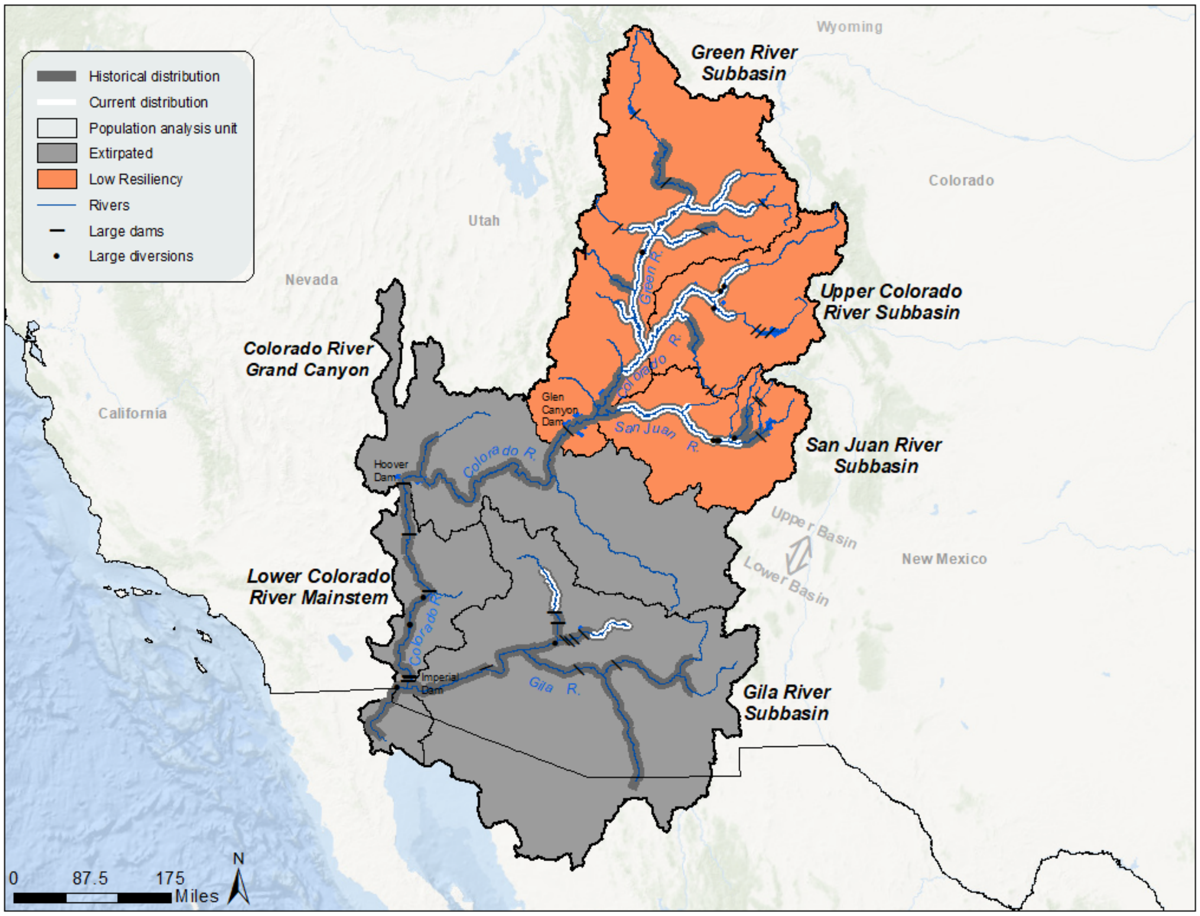


Figure 63. Current condition of Colorado pikeminnow analysis units.

5.6 Current – Species' Redundancy

Colorado pikeminnow is currently distributed in the upper Colorado River basin as two connected populations rated as moderate health, and another disconnected population rated as low health. The species' current distribution continues to be disconnected from the lower Colorado River basin where it is functionally extirpated. Designated critical habitat in the upper basin is estimated to represent around 29% of the species' historic range (U.S. Fish and Wildlife Service 1994). Osmundson (2011) estimated that suitable habitat in mainstem rivers of the upper Colorado River basin had been reduced by 39%, when accounting for barriers and thermally suitable water. This loss has reduced the available habitat where Colorado pikeminnow can survive and/or reproduce. For example, physical and thermal barriers have eliminated spawning reaches in the upper Green River near Flaming Gorge and throughout the Gunnison River. Historically these areas would have served as additional sites for reproduction, adding redundancy in years where environmental conditions were not suitable at other sites. In the upper Colorado River basin Colorado pikeminnow currently occupies approximately 2,101 kilometers (1,306 miles) of habitat, including smaller tributaries that were not included in Osmundson's estimates of mainstem habitat. Colorado pikeminnow in the Green and upper Colorado River subbasins may demonstrate metapopulation dynamics with a low amount of movement (6.5 fish annually) between populations (Osmundson, D. B. and White 2017a). This amount of movement keeps the two populations from genetically differentiating over time but is not enough exchange for one population to affect the demographics of the other (Osmundson, D. B. and White 2014; Miller, P. S. 2014). The San Juan River subbasin population is fragmented from the Green and upper Colorado River subbasin populations by Lake Powell as well as by an impassable waterfall at the inflow of the San Juan River into Lake Powell (see section 4.2.2). The isolation of the San Juan River subbasin from the Green and upper Colorado rivers may make it more prone to extirpation due to a large catastrophic event. As an example, a plume of wastewater spilled from a gold mine in the headwaters of the Animas River in 2015, while apparently benign to fish, was detected as far downstream as Lake Powell (Environmental Protection Agency 2017). While this specific incident did not appear to negatively affect fish in the San Juan River, it raises the possibility that a similar incident closer to the mainstem river could have widespread negative consequences. All three populations of Colorado pikeminnow in the upper Colorado River basin not only use mainstem rivers but are also present in tributaries, with the highest use of tributaries by river length and fish abundance occurring in the Green River subbasin. These tributaries, however, have often been more extensively altered by water development, and may only serve as suitable habitat for adult fish on a seasonal basis. While tributaries such as the White River support adult populations, they do not support substantial levels of spawning or contain nursery habitat.

In summary, Colorado pikeminnow currently exist in three populations limited to the upper basin. Two of these populations are connected but lack sufficient movement for one to repopulate the other in the event of a major decline or catastrophic event. These two populations are sustained by reproduction of wild fish in three primary spawning reaches on the mainstem large rivers. The third population is small, maintained primarily through stocking, and currently disconnected from the other populations by large distances across Lake Powell and an impassable waterfall. The species has been extirpated from the lower basin, save some stocking in the Gila subbasin that has not resulted in long term survival or a measurable population.

5.7 Current – Species' Representation

A thorough assessment of genetic diversity for extant Colorado pikeminnow populations has not occurred. However, the partial analyses that have been conducted indicate genetic variation between populations and diversity overall is likely low. While the assessment of allozymes, a measure of the expression of proteins from a gene (rather than a quantification of allelic diversity), is an outdated method for assessing genetic diversity, such investigations can provide some understanding of similarity between populations. The two Colorado pikeminnow allozyme studies concluded that populations of Colorado pikeminnow in the upper Colorado River basin are a single genetic population (Ammerman and Morizot 1989; Morizot *et al.* 2002). The mean F_{ST} was 0.019 for samples collected from the Yampa, Green, upper Colorado, and San Juan rivers (Morizot *et al.* 2002). An F_{ST} is the proportion of the total genetic variance contained in a subpopulation (the $_{S}$ subscript) relative to the total genetic variance (the $_{T}$ subscript). Values can range from 0 to 1 with 1 indicative of complete differentiation between populations.

While these allozyme studies suggest Colorado pikeminnow is a single, panmictic population in the Upper Basin, Hardy-Weinberg equilibrium results from these studies also suggest that genetic divergence once existed between the Green and Colorado River subbasins (Ammerman and Morizot 1989; Morizot *et al.* 2002). The Hardy-Weinberg equilibrium theory is an expectation of the allele frequency in a population where evolutionary forces are not at play. The expected distribution of allele frequency is 25% for homozygous alleles (pp), 25% for homozygous alleles (qq), and 50% heterozygosity (pq). For Colorado pikeminnow the allozyme studies indicated 11 significant deviations from Hardy-Weinberg equilibrium (Ammerman and Morizot 1989; Morizot *et al.* 2002). Ten of the eleven deviations were the result of lower heterozygosity than average (Morizot *et al.* 2002). While heterozygosity was low, five rare and private alleles, two in the Green River and three from the upper Colorado River, were detected. Habitat modification and early augmentation efforts using hatchery fish in the early 1980s have likely contributed to the mixing of what may have been historically divergent populations (Morizot *et al.* 2002).

The allozyme studies indicated that Colorado pikeminnow from the San Juan River prior to intensive stocking had the lowest genetic variability of all upper Colorado River basin populations (Morizot *et al.* 2002). This may have changed in recent decades. All Colorado pikeminnow stocked into the San Juan River are progeny from wild broodstock collected from the Green and upper Colorado subbasins (Ammerman and Morizot 1989; Morizot *et al.* 2002; Borley and White 2006; Diver *et al.* 2019) and are produced consistent with a genetic management plan (Crist and Ryden 2003). In recent years, the San Juan River has only been stocked with offspring produced from fish captured in the Colorado River. Genetic testing confirmed a close similarity between fish captured in the San Juan River and the founding Colorado River broodstock (Diver *et al.* 2019).

A direct measure of allele frequency (i.e., genetic diversity) has occurred for Colorado pikeminnow from the upper Colorado River basin using mitochondrial DNA (mtDNA). The investigation resulted in the detection of 2 alleles (called haplotypes) from 41 fish which were either first generation wild fish or the result of paired spawning in the hatchery (Borley and White 2006). As a comparison to other endangered fish, 27 haplotypes were identified in razorback sucker larvae captured in Lake Mohave (Dowling *et al.* 2005) and 15 from Rio Grande silvery minnow *Hybognathus amarus* larvae produced in the Rio Grande (Osborne *et al.* 2012). While there is a low level of Colorado pikeminnow genetic variation within and among extant populations, this may have predated the extirpation of lower Colorado River basin populations and population fragmentation in the upper Colorado River basin. The mtDNA analysis used museum specimens collected during the early 1930s and suggested a genetic bottleneck occurred prior to that time (Borley and White 2006). It is possible, however, that this low mtDNA diversity is an artifact of low sample size or a genetic bottleneck in the collection of broodstock from which many of the sampled fish were derived.

The most recent study of Colorado pikeminnow genetics was conducted to compare hatchery broodstock for the San Juan River basin with wild stocks collected for broodstock augmentation efforts and through opportunistic tissue sampling (Diver *et al.* 2019). This study examined twenty-four microsatellite loci. Wild adults from the Green River did not differ significantly from Hardy-Weinberg or linkage disequilibrium expectations. Samples from wild larvae did differ from Hardy-Weinberg expectations, but not consistently among cohorts or populations. These results could reflect small numbers of adults contributing to a particular year class at a specific spawning site. Wild larvae and juveniles sampled from the upper Colorado and Yampa rivers had the highest genetic diversity, followed by Green River adult samples, perhaps as a result of adults migrating to the spawning sites that produced these younger fish. The authors also found some indication that there could be genetic structure between the Green and upper Colorado river subbasin populations, but the limited number of samples were not sufficient to resolve this issue.

The primary goal of the Diver et al. (2019) study was to assess the San Juan River subbasin broodstock and wild larvae in order to effectively manage reintroduction efforts. The results of the study showed that only a single lineage derived from ten wild upper Colorado River adults is currently being used for propagation of fish stocked into the San Juan River. Genetic analyses of these fish showed significant deviation from Hardy-Weinberg equilibrium and linkage disequilibrium, indicating that some evolutionary processes have acted on the broodstock. This is not surprising given the small number of founders for this lineage and the potential for genetic drift. The San Juan River broodstock also formed a genetic cluster separate from wild populations and possibly representative of a less common Colorado River genetic substructure. All wild larvae collected from the San Juan River grouped with the hatchery broodstock and exhibited lower indices of genetic diversity. The study concluded that existing broodstock should not be used to augment populations in the Green and upper Colorado subbasins.

The combined results of genetic studies suggest that genetic structure may have existed between the Green and upper Colorado populations, but currently there is not strong evidence of substructure between the two subbasins. The San Juan River population has been augmented using mixed stocks from the Green and upper Colorado subbasins, but this population does not reflect the genetic composition or diversity found in wild populations of those rivers. In essence, Colorado pikeminnow representation is comprised of Green and upper Colorado river subbasin genetic diversity, and it is unclear to what extent those two populations might be unique.

There is also evidence that Colorado pikeminnow may exhibit behavioral diversity in spawning strategies. Individuals in the Green and San Juan subbasin populations historically have displayed site fidelity to spawning reaches and migrated to reproduce at those sites. The upper Colorado River subbasin population is believed to be less site specific in its spawning, and individuals often spawn over much larger reaches of river. Stocked individuals in the San Juan subbasin have recently exhibited less spawning site fidelity and have spawned over a larger extent of river than previously known. Preserving differences in spawning behaviors could be adaptive for the species, allowing adults to take advantage of available habitats when environmental conditions make specific spawning sites less suitable or unavailable due to low flows. Conversely, spawning at specific sites consistently can ensure larvae are situated upstream of suitable nursery habitats, thus maximizing their survival and recruitment. Colorado pikeminnow stocked into the San Juan subbasin were derived from broodstock collected from the upper Colorado river subbasin, so representation of the species is limited to two populations. It is unclear to what extent, if any, Colorado pikeminnow in the lower Colorado River basin may have been unique genetically, behaviorally, or in their habitat use. Populations that used the most upstream extent of river reaches have also been extirpated (Flaming Gorge, Gunnison, upper Yampa), and it is not known whether these populations were unique or adapted to the cooler river temperatures they may have experienced.

CHAPTER 6 – FUTURE SCENARIOS AND COLORADO PIKEMINNOW VIABILITY

This section of the SSA considers how resiliency might change for each Colorado pikeminnow analysis unit under various future scenarios as well as forecasts the species' redundancy and representation for each scenario. Since Colorado pikeminnow is either extirpated or functionally extirpated from the lower Colorado River basin, and it is not apparent that habitat conditions are likely to change within the next 10-20 years, we predicted resiliency for the lower Colorado River basin analysis units would remain in an extirpated condition. The conclusion that lower basin habitat conditions are unlikely to change in the near future was based on the description of habitat in the lower Colorado River mainstem that stated:

> Present conditions in the LCR [lower Colorado River mainstem] are significantly different from historical conditions…The river is no longer free flowing and does not constitute a continuous ecosystem because of the many impoundments along its length. In addition, the hydrologic regime does not support extreme fluctuations mainly because of the presence of large, mainstem dams farther upstream, resulting in reduced natural backwaters and reduced periods of inundation in adjacent floodplain lowlands….The LCR is one of the most highly controlled rivers in North America. The flow regime and channel of the LCR has been extensively modified for hydropower, flood control, and water supply. As a consequence, LCR flow and elevation are highly controlled by dams and diversions (Facilities), levees, and stabilized banks. Modifications to the LCR have been occurring continuously over the past century and the most significant effects occurred at the time the Facilities were constructed or shortly thereafter. The existence of these Facilities in the past, and their continued presence through the next 50 years, will continue to affect the physical characteristics of the LCR (Lower Colorado River Multi-Species Conservation Program 2004).

We also based our decision to keep LCRB analysis units in an extirpated condition based on the recent 20-year reauthorization of Glen Canyon Dam operations (U.S. Department of the Interior 2016), which although adaptive, does not appear to include considerations for Colorado pikeminnow in the Grand Canyon reach. In the Gila River subbasin, the middle portion of the Verde River has been recommended for sportfish management (Cummins 2012a; Cummins 2012b), and plans to install barriers to protect upstream native fishes in this system (Stewart W. 2018, pers. comm.) will make it more difficult to establish a population since habitat connectivity will be further reduced. Finally, stocking efforts in this basin ceased in 2018, with no plans to continue in the near future (AZGFD, pers. comm.).

To forecast the resiliency of each of the upper Colorado River basin Colorado pikeminnow populations we used the output of a population viability analysis (PVA; Miller, P. S. 2018). For this SSA we selected PVA models we thought best represented each scenario for a continuation of existing trends and conditions, a modest increase in conservation measures or their effectiveness, and a considerable increase in conservation outcomes. However, many more scenarios were modeled in the PVA, and we suggest that report be read in concert with this SSA. For the Green and upper Colorado River subbasins, the PVA assessed two alternative hypotheses pertaining to underlying interannual population demographic changes. These hypotheses were termed "dual" and "single" phase dynamics. For this SSA we present the model runs using both single and dual phase dynamics to show a range of possible outcomes (Figure 52 and Figure 53).

We predicted Colorado pikeminnow resiliency, redundancy, and representation under four plausible future scenarios. The first scenario was the Status Quo, which was modeled in the PVA as the condition of Colorado pikeminnow when conservation actions continue with the same level of effectiveness as has occurred over the last decade with no change in the influence of stressors. The second scenario forecasted the response of Colorado pikeminnow to a reduction in conservation actions or their effectiveness, which we suggest could be an increase in the influence a stressor(s) has on populations or a reduction in conservation actions. This scenario was not modeled because the PVA team considered such a scenario to lead to a reduction in outcomes compared to the status quo models. The status quo models generally predicted low abundances, so any reduction from those models would encompass a small range of possible outcomes. The last two scenarios forecast the response of Colorado pikeminnow to slight and considerable increases in conservation efficacy. Based on model trajectories for each of the four scenarios we predicted and described what might occur to each population's demographic parameters as identified in the current condition assessment (Table 25). Once we forecasted each population's resiliency, we predicted the overall effect on the species' redundancy and representation.

Some of the changes applied to demographic parameters in the PVA were based on future management of habitat parameters, namely summer base flows to improve recruitment, increased survival through nonnative fish reductions, and increased habitat availability from more extensive use of fish passages. Miller (2018) recognized that the functional relationships between these management actions and demographic responses are unknown. In other words, it is not clear the level of an activity that must occur (such as nonnative fish reduction) to elicit a given response in a population (e.g. improved survival of young). The PVA models change underlying demographic rates based on expected responses to habitat parameters, and do not specifically incorporate changes in habitat or resources. Because of this, the underlying demographic rates used in each PVA model could be used to predict a response to changes in any of the stressors or management actions that influence reproduction, recruitment, survival, or carrying capacity. Other habitat parameters considered in the current conditions chapter are not expected to change in the forty year period used here. For example, large mainstem impoundments are likely going to persist, so availability of habitat is not expected to change dramatically from present. Also, factors such as peak flows are inherently variable in natural river systems, and where flow management is possible, there are often agreements to maintain flows to benefit listed fishes. For these reasons, this section of the SSA only considers demographic changes to extant populations for predicting future outcomes, with the understanding that underlying habitat factors could influence the demographic parameters leading to a population's response.

We predicted Colorado pikeminnow viability over the next 40 years. We chose this forecast timeframe because we expect any near term (10 years) continuation of the Status Quo or alterations to conservation management to require at least three generations (approximate generation period of 13 years) to detect consistent trends in demographics. We also have a high level of uncertainty regarding availability of water for suitable flow regimes and our ability to control nonnative predators that will result in positive growth rates. There are also underlying gaps in knowledge (e.g., the extent of riverine habitat required to support a self-sustaining, viable population). Because of these uncertainties and the Colorado pikeminnow's generation time, we think we can be most confident with a 40-year forecast period. Since the PVA modelling extended to 100 years into the future, a brief summary of those results is also presented here, but uncertainty in conditions that far into the future should be acknowledged when interpreting the PVA projections.

6.1 Future scenarios

(1) Status Quo: Colorado pikeminnow recovery actions continue at levels within the last decade– There is no change in the effect of stressors, the impact of conservation actions, the extent of available river, changes in the ecosystem's carrying capacity, etc.

(2) Conservation Reduction: Conservation measures for Colorado pikeminnow are reduced in application or effectiveness– This could occur through funding reductions or a lapse in reauthorizing recovery programs. It assumes elimination of some management actions and research oriented towards understanding how to effectively recover Colorado pikeminnow given the high potential for decreased water availability, future water development, and increased nonnative fish pressures. This scenario also represents the development of a novel threat introduced into the system that would reduce the effectiveness of conservation management such as the introduction of a new piscivorous species, disease, etc.

(3) Conservation Increase: Colorado pikeminnow conservation measures are increased, new actions occur, or better implementation results in slight increases in efficacy as described for each population in this scenario's forecast– This determination was made based on some conservation measures being implemented, attempted, or planned as of the writing of this SSA, however population responses have not been determined for newly implemented actions (e.g., fish barrier at the Green River canal). In addition new estimates of first summer survival from 2015-2017 (Farrington *et al.* 2018; Zeigler *et al.* 2018) may indicate underlying demographic parameters have recently changed from Status Quo in the San Juan River subbasin population.

(4) Considerable Conservation: Colorado pikeminnow conservation measures result in considerable increases in efficacy for each population as described in this scenario's forecast.

6.2 Scenario 1 – Status Quo forecast

Under the Status Quo scenario, factors (conservation measures and stressors) that are currently influencing extant Colorado pikeminnow populations continue at current rates. For example, in this scenario nonnative predatory fishes are removed at a similar rate as achieved within the recent past, and the PVA used survival and recruitment rates consistent with observed abundance estimates that are at least partially a by-product of current nonnative fish impacts. Flow regimes continue at the same frequency and magnitude resulting in similar habitat production, maintenance, and complexity, and the overall influence of these factors are again captured in reproduction and recruitment rates that are consistent with recent observations. In this scenario, there are no changes to the extent of available habitat, rate of entrainment into water system diversions, or water temperatures. For the San Juan River subbasin, 400,000 age-0 fish continue to be stocked annually.

For the upper Colorado River subbasin, the PVA modeling for this scenario incorporated the potential for large offspring production events termed "spawning spikes" (Miller, P. S. 2018). A spawning spike was observed in 2015 and long-term monitoring suggested the frequency of such an event was 1 out of 23 years (4.3%). The Status Quo PVA model for this subbasin population predicted the mean adult abundance when no, very low, low, medium, and full spawning spikes occurred at this frequency (Figure 64). For this SSA, we forecast Colorado pikeminnow's resiliency for the upper Colorado River subbasin population using the medium spawning spike because that was the level used in all subsequent PVA scenarios. This decision was based on input from the PVA team and their acknowledgement that while infrequent, these events likely occurred at some interval and had significant effects on reproduction and recruitment.

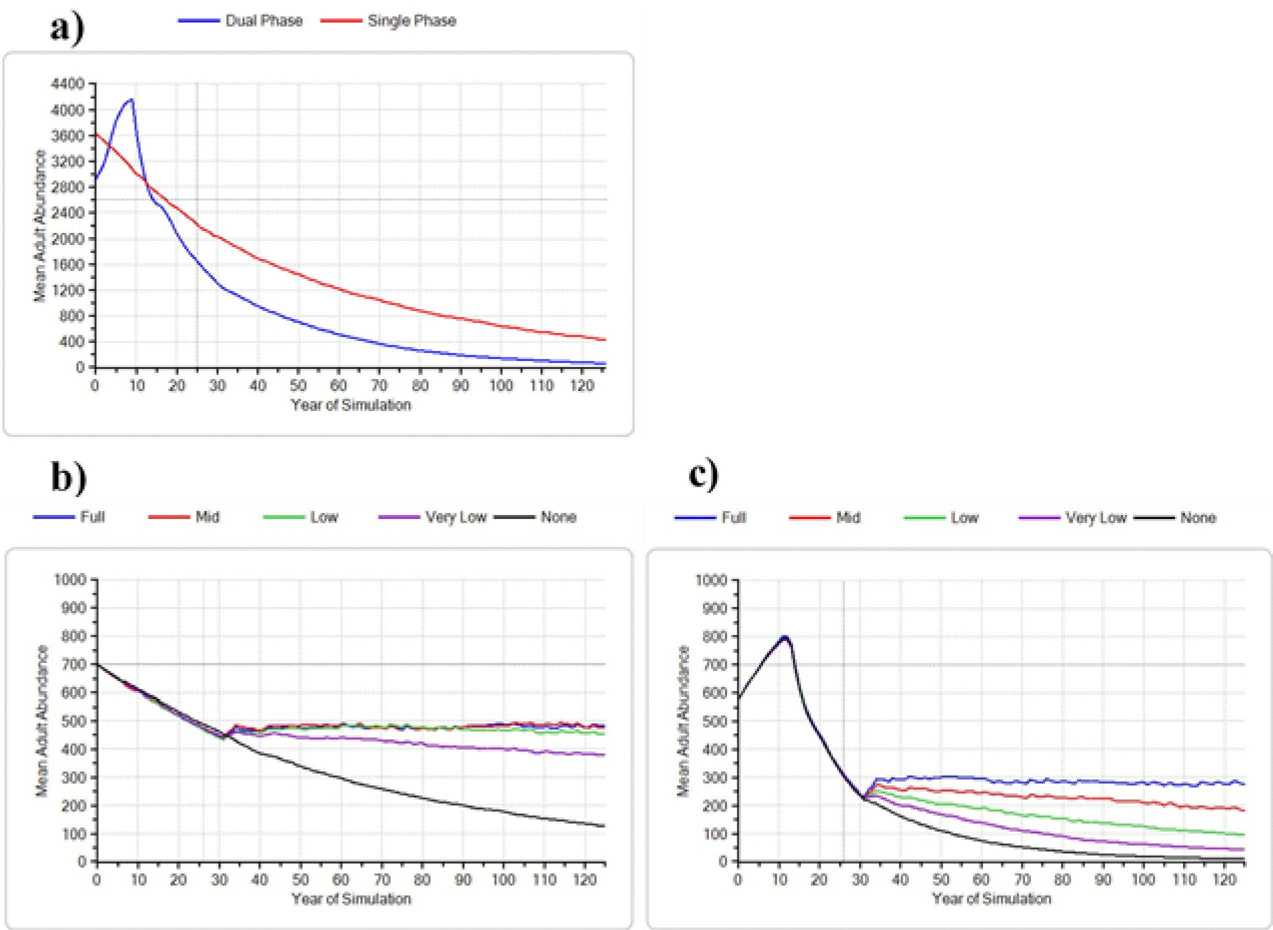


Figure 64. Colorado pikeminnow mean adult abundance under scenario 1 – Status Quo as modeled by a population viability analysis for two Colorado pikeminnow analysis units (Miller, P. S. 2018). a) Green River subbasin models using single (red) and dual (blue) phase dynamics. b) upper Colorado River subbasin projections for the single phase model incorporating varying influences of spawning spikes and c) upper Colorado River subbasin projections for the dual phase model incorporating varying influences of spawning spikes. Years 0-25 represent model results based on observed data through 2018, therefore future projections begin in model year 25 and year 65 would be forty years into the future.

For the Status Quo scenario, the PVA incorporated demographic parameters that reproduced observed historical population trends for the Green and upper Colorado River subbasins. These then were used to predict mean adult abundance for those analysis units (Miller, P. S. 2018). For the San Juan River subbasin, the PVA used inferences from the historically low adult abundance and reproduction to assign underlying demographic rates for this scenario.

Under the Status Quo scenario, the abundance of adults in both the Green and upper Colorado river subbasins is predicted to decline (Figure 64; Miller, P. S. 2018) with the San Juan River subbasin population remaining stable at current abundance due to sustained stocking (Figure 65e). The Green River subbasin population is predicted to decline at either 1-2% or 6-7% per year depending on the underlying model used (single- or dual-phase model, respectively). This would result in adult abundance declining to roughly 50-75% of the current magnitude in forty years, and produce a low condition rating for this population (Table 31). It is also interesting to note that the most recent abundance estimates for the Green River subbasin indicate the population has declined to less than 1,000 adults (K. Bestgen, unpublished data), which is more consistent with the dual-phase model projections.

For the mid-level "spawning spike" model, adult abundances in the upper Colorado River subbasin would be approximately 40% lower than the most recent three year estimates with a declining growth rate according to the dual-phase model (Figure 64). Other dual-phase models using various magnitudes of spawning spikes produce different trajectories, illustrating the importance of this phenomenon. Models that did not include spawning spikes resulted in adult abundances of less than 100 to around 300 individuals after forty years. Three of the five single-phase models project the adult population for the upper Colorado River subbasin to remain essentially stable over time. In summary, six of ten models indicated the upper Colorado River subbasin population would decline, and this population was only projected to remain stable if spawning spikes continued. Due to stocking, the adult abundance in the San Juan River would remain at current levels over the next 40 years. Although the abundance of adults in two of three populations would decline, we predicted reproduction under this scenario would continue at current frequency (annually) for each population. Considering the adult abundance in the Green River subbasin would significantly decline, we would expect this to be the result of low recruitment. This would likely be the result of decreases in age-0 abundance as has been observed in recent years. Similarly, we predicted a reduction in abundance of age-0 fish in the upper Colorado River subbasin because although spawning spikes might occur, the average abundance of age-0 would decrease and produce the predicted declines in adult numbers. Age-0 abundance in the San Juan River subbasin would also continue to be low rather than undetectable. Since adult abundance would be similar between current conditions and this Status Quo scenario for the San Juan river subbasin, we expect the abundance of stocked recruits to remain the same over a 40-year period. Declines in the majority of adult projections for the Green and upper Colorado river subbasins suggest recruit abundances in those reaches would not be sufficient to offset adult mortalities. Under the Status Quo scenario, we predict that population augmentation would be required to maintain all three analysis units, so some demographic parameters would be the result of stocking and not wild-produced fish. Overall, the three extant analysis units would be in a low resiliency condition within 40 years given the Status Quo future scenario.

If predictions from the Status Quo scenario are realized, redundancy would be reduced. Two of the three analysis units are predicted to become less resilient, reducing overall redundancy. However, the PVA did not predict the extirpation of any population (Miller, P. S. 2018) and thus the overall occupied range would not be reduced (Figure 67). In the Status Quo scenario, the current level of representation would be reduced through a loss of allelic diversity as the Green River subbasin population contracts and stocking is implemented in all subbasins.

After 100 years, the PVA projections indicate the Green River subbasin population would continue to decline to roughly 200-400 adults. For the upper Colorado River subbasin, the PVA models encompass a much wider range of potential outcomes after 100 years as a result of different spawning spike magnitudes. Under the single-phase dynamic, this population ranges from approximately 100 adults (no spike) to about 500 adults (full spike). For the dual-phase dynamic, the upper Colorado River subbasin adult abundances range from near extirpation to just under 300 individuals. Again, the San Juan subbasin adult population was not predicted to change after 100 years because stocking would continue indefinitely in this scenario.

Table 31. Colorado pikeminnow resiliency described by projections of population demographics under scenario 1 – Status Quo. Future condition scores were derived by summing scores for each factor. The overall condition was then identified as functionally extirpated (1-3), low (4-8), moderate (9-13), or high (14-16).

	Demographic Factors				
Analysis unit	**Wild reproduction**	**Wild recruitment to sexual maturity**	**Adult Abundance**	**Long-term Population Trajectory**	**Overall condition**
Green River	LOW (1)	LOW (1)	LOW (1)	LOW (1)	LOW (4)
Upper Colorado River	LOW/MODERATE (1.5)	LOW (1)	LOW (1)	LOW (1)	LOW (4.5)
San Juan River	LOW (1)	Ø	LOW (1)	MODERATE (2)	LOW (4)
Colorado River, Grand Canyon	Ø	Ø	Ø	Ø	Ø
Lower Colorado River mainstem	Ø	Ø	Ø	Ø	Ø
Gila River subbasin	Ø	Ø	Ø	Ø	Ø

6.3 Scenario 2 – Conservation Reduction forecast

Under the Conservation Reduction scenario, we forecast the condition of Colorado pikeminnow when either the level or efficacy of conservation actions are reduced. Conservation reduction could be in the form of reduced or lapsed funding and a commensurate decrease in conservation actions. It could also occur if a stressor becomes more influential such as an increase in the abundance of nonnative predatory fishes or a decrease in the flow regime's ability to produce and sustain habitat. Conservation reduction could also occur if a new stressor began to influence

Colorado pikeminnow populations, like the introduction of a new predatory fish species or disease.

The effects of climate change can be evaluated in this scenario. One predicted outcome of increased temperatures is more consumptive demand for water and potentially less runoff without commensurate increases in precipitation (Udall and Overpeck 2017), which could decrease the frequency that summer base flows are provided to support age-0 Colorado pikeminnow recruitment compared to the status quo models. The Green River status quo PVA model assumed base flows were provided in only 10% of years, based on observed frequencies for the middle and lower Green River in 2000—2013. This status quo projection produced continued declines in adult abundance over the next 40—100 years. In the upper Colorado River, base flow management was assumed to be within the recommended range 85—100% of years since 2005. The PVA model reduced base flow implementation for this subbasin (not shown), which resulted in decreased adult abundances under both the single- and dual-phase dynamics. For the dual-phase dynamic, the adult population was reduced by half (Miller, P. S. 2018).

This scenario was not completely modeled in the PVA, except as noted above, but we used results from Status Quo to predict Colorado pikeminnow’s condition. Under the Reduced Conservation scenario, we predicted adult abundance in the Green and upper Colorado river subbasins would decline at a greater rate than modeled under the Status Quo and would result in a low rating for all populations (Table 32). In such an instance, adults would still be present in the Green and upper Colorado river subbasins, with reproduction detected at a low level and undetectable in the San Juan River subbasin. We predicted recruitment into age-0 or older age classes would not be detectable in any of the three populations. Given these population demographics, to maintain the species in the wild, stocking would have to occur more than once a generation for all populations. Overall, we predicted the three extant Colorado pikeminnow populations would become functionally extirpated within 40 years of a reduction in conservation.

Under the Conservation Reduction scenario, redundancy and representation would be reduced. All three populations would become extirpated or functionally so (Table 32; Figure 67). In this scenario, the current level of representation would be reduced by a potential bottleneck within the functionally extirpated Green and upper Colorado river subbasin populations and replacement of wild stocks with fish derived from limited genetic diversity produced through hatchery propagation.

Table 32. Future Colorado pikeminnow demographic resiliency conditions under scenario 2 – Conservation Reduction. Future condition scores were derived by summing scores for each factor. The overall condition was then identified as functionally extirpated (1-3), low (4-8), moderate (9-13), or high (14-16).

	Demographic Factors				
Analysis unit	**Wild reproduction**	**Wild recruitment to sexual maturity**	**Adult Abundance**	**Long-term Population Trajectory**	**Overall condition**
Green River	**Ø**	**LOW (1)**	**LOW (1)**	**LOW (1)**	**Ø (3)**

Demographic Factors					
Upper Colorado River	**Ø**	**LOW (1)**	**LOW (1)**	**LOW (1)**	**Ø (3)**
San Juan River	**Ø**	**Ø**	**LOW (1)**	**LOW (1)**	**Ø (2)**
Colorado River, Grand Canyon	**Ø**	**Ø**	**Ø**	**Ø**	**Ø**
Lower Colorado River mainstem	**Ø**	**Ø**	**Ø**	**Ø**	**Ø**
Gila River subbasin	**Ø**	**Ø**	**Ø**	**Ø**	**Ø**

6.4 Scenario 3 – Conservation Increase forecast

Under the Conservation Increase scenario, we forecast the future demographic conditions of Colorado pikeminnow when conservation measures are slightly increased in magnitude or efficacy. This could result from increases in age-specific survival rates due to increased effectiveness of nonnative fish control measures, improvements of entrainment reduction devices, more frequent implementation of recommended flows, an increase in habitat carrying capacity, increased connectivity of habitat through fish passage use, etc. We do not currently know the numerical and functional relationships between such conservation measures and Colorado pikeminnow demographics; however, the PVA modeling varied demographic parameters that represented the potential response to increases in conservation (Miller, P. S. 2018) based on available data. As a result, the PVA adjusts a relatively limited set of demographic parameters, which could be the end result of a variety of mechanisms, individually or in concert. So while several different actions could lead to demographic improvements, the effect of those actions is usually seen in the same few parameters, such as survival, reproduction, and carrying capacity.

To forecast the future condition of Colorado pikeminnow 40 years after an increase in conservation we used PVA analyses for each extant Colorado pikeminnow population that slightly increased underlying population demographic dynamics (Figure 65; Miller, P. S. 2018). For the Green River subbasin, we chose the population viability analysis model projections that incorporated pairs of conservation measures that included increased survival of young stages of Colorado pikeminnow (age-0 through 4) through more effective nonnative predator control (5% NNP), reduced mortality of all age classes through successful exclusion of fish from the Green River canal (canal-low), or increased recruitment through more frequent implementation of revised base flows (50% flow). These combinations were chosen because a fish exclusion device was installed in the Green River canal in spring 2019, improved base flow implementation is being attempted through experimental dam releases, and new strategies are being deployed and revised for nonnative fish control, including the screening of more reservoirs that can serve as sources of nonnative fishes into the river. We used models for the upper Colorado River subbasin where survival was increased by a 5% increment for ages 0-4 as a result of improved nonnative fish control, and adult carrying capacity was increased as a result of habitat expansion from improved use of fish passages. Range expansion could also be a result of warming water temperatures due to climate change. For the San Juan River subbasin we chose the model which incorporated the fewest changes from Status Quo. This was the model that increased production of age-0 fish from 5 to 50 per successful spawning female and increased survival of age 0-4 fish by 25% (e.g. age-0 survival increased from 10% to 12.5%). This model also assumes that current stocking rates and practices continue as a conservation measure.

Under the PVA models selected for the Conservation Increase scenario, Colorado pikeminnow adult abundance would demonstrate a positive growth rate in all three extant populations (Figure 65; Miller, P. S. 2018). After forty years, adult abundance in the Green River subbasin would approach or exceed 3,100 individuals in all of the models, with the dual-phase models requiring more time to reach this threshold. All pairs of improved flows, reduced canal entrainment, and/or reduced nonnative fish predation produced similar trajectories and magnitudes for each underlying dynamic, indicating that reductions in mortality and improved recruitment should lead to increasing populations in this basin. As a result, for this scenario we would predict annual reproduction, increased age-0 abundance, and increasing sub-adult recruitment. With increasing population growth, stocking would likely not be necessary or considered.

For the upper Colorado River subbasin, model projections under a slight conservation increase scenario result in substantial increases in adult abundance. In the forty year timeframe, this population would maintain an adult abundance around 500 adults for the dual-phase dynamic. The single-phase model predicts adult abundances over 1,000 individuals for this subbasin. Population increases appear to result from the inclusion of a moderate spawning spike in addition to increased survival in young age classes. The addition of increased carrying capacity to this model scenario is a product of expanded habitat use from more successful fish passage at Grand Valley Water Users and Redlands diversions. The degree of expanded carrying capacity does not significantly affect the projection results. This carrying capacity factor interacts with the spawning spike because it supports increased recruitment of fish from those spawning events. For this population, we would expect demographic parameters such as reproduction and recruit abundance to increase from current conditions and would categorize those factors as high. Age-0 abundance would be highly variable annually, and while spawning spikes would contribute to overall abundance, these spikes are thought to be infrequent and may not lead to consistently high values for this parameter. Regardless, an increasing adult population would suggest age-0 abundance and recruitment are greater than the long term mean. Stocking would likely not occur.

The increased conservation scenario for the San Juan subbasin population resulted in an initial increase in adult abundance, which then stabilized at just over 200 individuals. This scenario also reveals the importance of continued annual stocking in maintaining this population, since using the same parameters with a cessation of stocking after fifteen years produced an abrupt decline in adult abundance to near extirpation (not shown; Miller, P. S. 2018). While adult abundance for the San Juan population would still be considered low, population stability and recruit abundance would be low due to a reliance on stocked fish, reproduction would occur annually, and age-0 abundance would increase compared to current conditions. Despite improvements in some demographic factors, most of the fish older than age-0 would still be the result of stocking efforts (see Table 20).

The 100 year projections for all three populations generally stabilize at levels near the forty year projections. The primary difference is that dual-phase models require more time to reach higher abundances. The Green River population exceeds 3,100 adults in all models after 100 years. In 100 years the upper Colorado River population only exceeds 760 adults in the single-phase models, and it approaches that threshold for the dual-phase models, stabilizing at around 600 adults. The San Juan population remains stable at approximately 200 adults in the long term projections.

Overall, the results of this scenario would place Colorado pikeminnow populations in higher categories of health than the Status Quo predictions, with two populations in high health and one in low health (Table 33). These ratings would be higher than current conditions for the Green and upper Colorado subbasins, and the same as the current condition for the San Juan subbasin. Thus, redundancy would be increased slightly compared to what is currently observed since the same three populations would persist in their current locations but at higher abundances. Representation would increase as all three populations grow and support more individuals, particularly in the upper Colorado River basin where the PVA assumed higher carrying capacity as a result of range expansion.

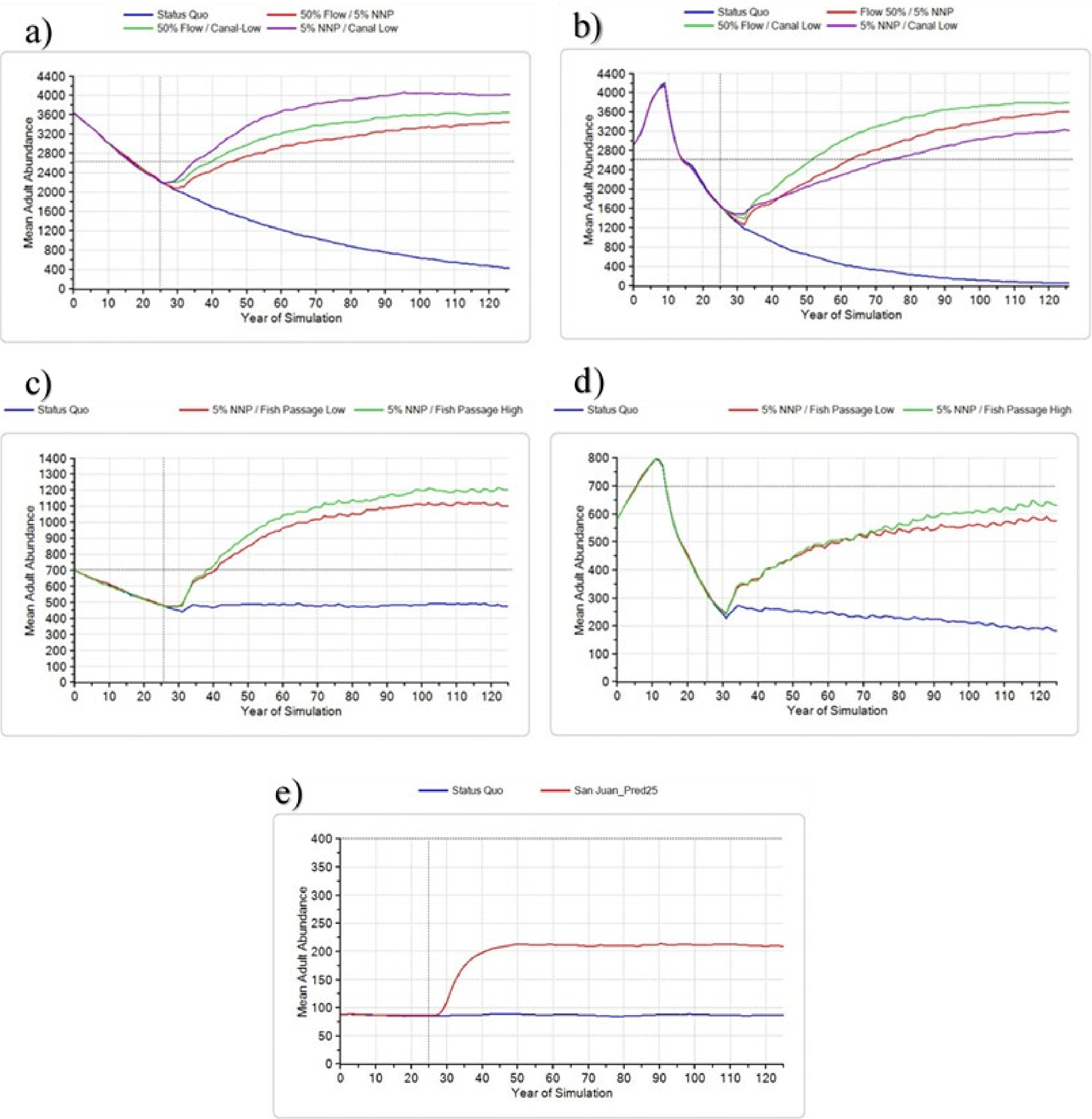


Figure 65. Colorado pikeminnow mean adult abundance under scenario 3 – Increased Conservation as modeled for a population viability analysis (PVA) for each extant Colorado pikeminnow population (Miller, P. S. 2018). Green River subbasin models for the single- (a) and dual-phase (b) dynamics. Upper Colorado River subbasin models for the single- (c) and dual-phase (d) dynamics. San Juan River subbasin models (e).

Table 33. Colorado pikeminnow demographic resiliency under scenario 3 – Conservation increase. Future condition scores were derived by summing scores for each factor. The overall condition was then identified as functionally extirpated (1-3), low (4-8), moderate (9-13), or high (14-16).

	Demographic Factors				
Analysis unit	**Wild reproduction**	**Wild recruitment to sexual maturity**	**Adult Abundance**	**Long-term Population Trajectory**	**Overall condition**
Green River	HIGH (3)	HIGH (3)	MOD/HIGH (3/6)	HIGH (4)	HIGH (14.5)
Upper Colorado River	HIGH (3)	HIGH (3)	MOD/HIGH (3/6)	HIGH (4)	HIGH (14.5)
San Juan River	LOW (1)	LOW (1)	LOW (1)	MODERATE (2)	LOW (5)
Colorado River, Grand Canyon	Ø	Ø	Ø	Ø	Ø
Lower Colorado River mainstem	Ø	Ø	Ø	Ø	Ø
Gila River subbasin	Ø	Ø	Ø	Ø	Ø

6.5 Scenario 4 – Considerable Conservation forecast

Under the Considerable Conservation scenario, we forecast the future demographic conditions of Colorado pikeminnow if conservation measures are significantly increased in magnitude or efficacy. This could result from combinations of even greater increases in recruitment, survival, and carrying capacity than predicted under the Conservation Increase scenario. This might be a combination of new technology to reduce the number or effects of nonnative predators on Colorado pikeminnow survival, installation of more effective fish exclusion devices that preclude fish entrainment into canals, an increase in the frequency of meeting flow recommendations, and increases in habitat carrying capacity and connectivity from increased use of fish passages. Again, it is important to state that we do not currently know the numerical and functional relationships between such increases in conservation and Colorado pikeminnow demographics; however, the PVA modeling varied changes in the underlying demographic dynamics that could represent such considerable increases in conservation (Miller, P. S. 2018).

To forecast the future condition of Colorado pikeminnow 40 years after implementation of a Considerable Conservation scenario we used PVA models for each extant Colorado pikeminnow population that in combination significantly increased demographic parameters (Figure 66; Miller, P. S. 2018). For the Green River subbasin, we chose the PVA model where revised recommended base flows are achieved in 50% of years, nonnative fish management results in a 5% increase in annual survival for ages 0-4 fish, and reducing entrainment at the Green River canal decreases mortality by 1.76% across all age classes. For the upper Colorado River subbasin we used the PVA model that increased age 0-4 fish survival by 10% and increased the available habitat through improved effectiveness of fish passages on the Colorado and Gunnison rivers. For the San Juan River subbasin we used the “ideal management” model that resulted in a population which did not require augmentation. This model was optimized when the mean rate of successful spawning among adult females increased from 70% to 80%, mean age-0 production among successfully breeding females was no less than 60 individuals per female, and mortality rates among age 0-6 fish decreased for each age class (Table 34). This model was conducted with two different carrying capacities for the San Juan River: 400 and 800 adults. While these different carrying capacities did not change the population trajectories, they did impose a maximum limit beyond which the population could not grow. Science panel members indicated that carrying capacity estimates for the San Juan River have been determined by available forage and habitat. If forage fish densities were increased by reducing nonnative fishes, or if habitat improvements occurred, the carrying capacity would increase.

Table 34. Age-specific mortality rates used in the Colorado pikeminnow population viability analysis for the San Juan River’s ideal management scenario (Miller, P. S. 2018).

Age class	Initial mortality rate	Future scenario mortality rate
0-1	90	75
1-2	80	65
2-3	70	55
3-4	60	40
4-5	50	30
5-6	40	25
6-7	30	22
7+	18	18

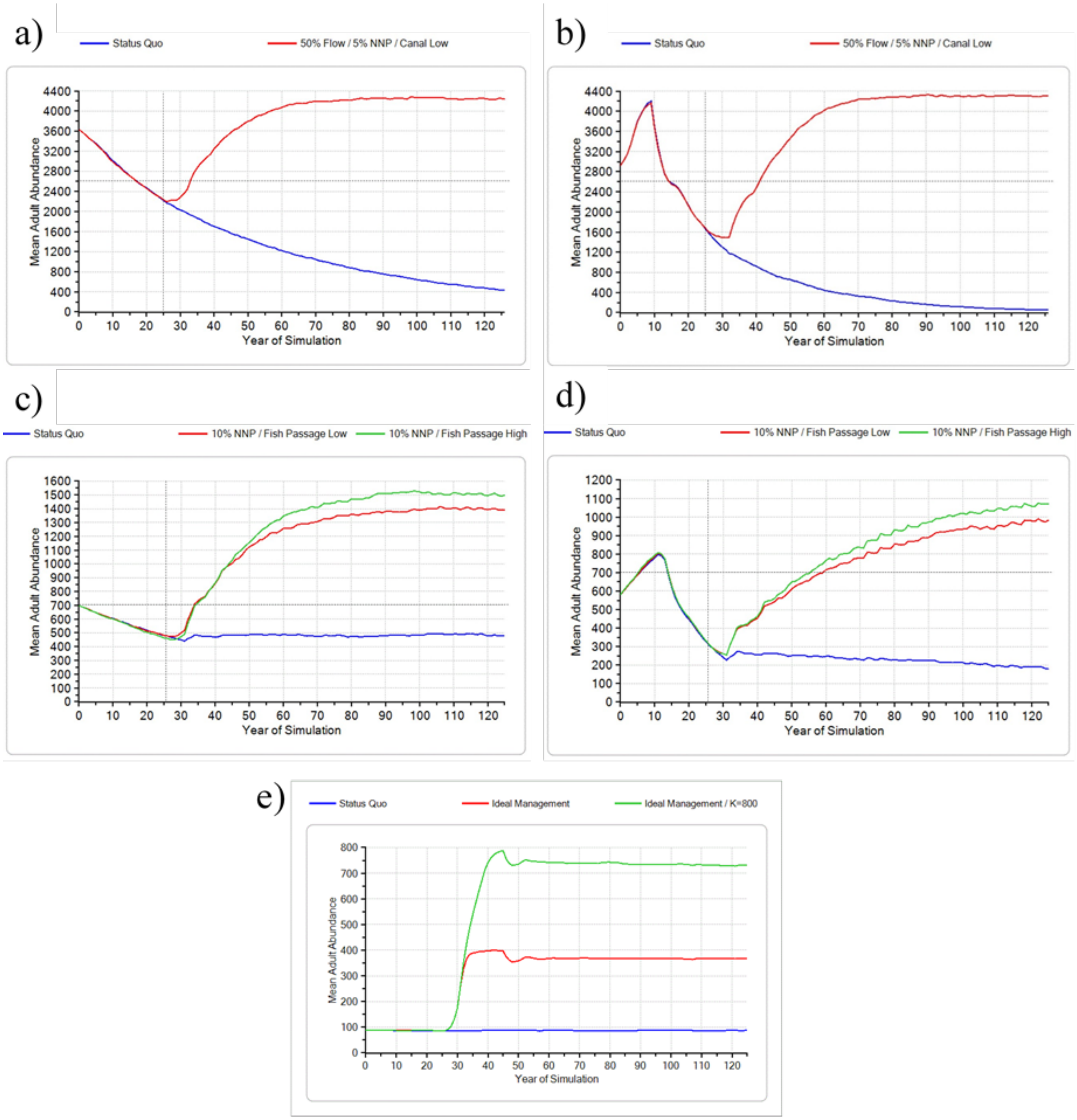


Figure 66. Colorado pikeminnow mean adult abundance under scenario 4 – Considerable Conservation as modeled a population viability analysis (PVA) for each extant Colorado pikeminnow population (Miller, P. S. 2018). Green River subbasin models for the single- (a) and dual-phase (b) dynamics. Upper Colorado River subbasin models for the single- (c) and dual-phase (d) dynamics. San Juan River subbasin models (e).

Under the PVA modeling adopted for this SSA's Considerable Conservation scenario, positive population growth rates would be expected in all three extant populations. The Green and upper Colorado river subbasin populations are predicted to exceed thresholds to be considered resilient, while the San Juan River subbasin population is predicted to reach a steady adult abundance of just over 350 or 750 individuals after stocking ceases, depending on the carrying capacity used

(Figure 66; Miller, P. S. 2018). For this scenario, we expect Colorado pikeminnow adult abundance to have reached a high level of health for the Green and upper Colorado populations and result in high levels for each population demographic parameter (Table 35). Reproduction would be high, and we predicted the 10-year mean age-0 abundance would be high since increased adult abundance and potential spawning spikes would be expected to result in high recruit abundance for this subbasin. The increase in adults would change the San Juan River subbasin adult abundance from a low to high condition when using a carrying capacity of 800 adults. We predicted reproduction would remain high and the increase in adult abundance along with the changes in the underlying demographic parameters to result in a moderate abundance of age-0 fish. Since the population would be self-sustaining, recruit abundance was presumed to be high and population augmentation unnecessary. Overall, we forecast resiliency to be high for all three populations under the Considerable Conservation scenario.

At the end of the 100 year simulations, most of the models reach stable adult abundances for all three populations. Only the dual-phase models for the upper Colorado River population suggest slight rates of increase. The Green and upper Colorado river populations would exceed thresholds to be considered resilient, whereas the San Juan would be stable at an abundance approximately four times larger than the most recent ten year mean abundance.

In 40 years, under the Considerable Conservation scenario, redundancy and representation would be increased from current conditions. All three populations would become more resilient, increasing overall redundancy. However, overall occupied range would not increase (Figure 67). In the Considerable Conservation scenario, allelic diversity could be increased through increased metapopulation dynamics between the more resilient Green and upper Colorado river basin populations. However, the San Juan River population would continue to be disconnected from the other two extant populations, be small and tend toward a loss of genetic diversity over time.

Table 35. Colorado pikeminnow demographic resiliency under scenario 4 – Considerable Conservation increase. Future condition scores were derived by summing scores for each factor. The overall condition was then identified as functionally extirpated (1-3), low (4-8), moderate (9-13), or high (14-16).

Demographic Factors					
Analysis unit	**Wild reproduction**	**Wild recruitment to sexual maturity**	**Adult Abundance**	**Long-term Population Trajectory**	**Overall condition**
Green River	**HIGH (3)**	**HIGH (3)**	**HIGH (6)**	**HIGH (4)**	**HIGH (16)**
Upper Colorado River	**HIGH (3)**	**HIGH (3)**	**HIGH (6)**	**HIGH (4)**	**HIGH (16)**
San Juan River	**HIGH (3)**	**HIGH (3)**	**MOD/HIGH (3/6)**	**HIGH (4)**	**HIGH (14.5)**
Colorado River, Grand Canyon	**Ø**	**Ø**	**Ø**	**Ø**	**Ø**
Lower Colorado River mainstem	**Ø**	**Ø**	**Ø**	**Ø**	**Ø**
Gila River subbasin	**Ø**	**Ø**	**Ø**	**Ø**	**Ø**

6.6 Future scenario status assessment summary

We used the best available information to forecast the future condition of the Colorado pikeminnow. Our goal was to describe the viability of the species in a manner that addresses the needs of the species in terms of resiliency, representation, and redundancy. We considered four plausible future scenarios that may result from changes in conservation efficacy. Our results describe a range of possible conditions in terms of populations' resiliency and resultant species redundancy and representation (Figure 67). Colorado pikeminnow faces a variety of risks from habitat fragmentation, entrainment through diversions, reduction in habitat-regulating flows, contamination of water, and predation by nonnative predatory fishes. Although the influence of these stressors has been reduced through conservation measures, they continue to affect the future viability of Colorado pikeminnow. General themes regarding Colorado pikeminnow population dynamics also emerged from the PVA modeling. Specifically, increases in reproduction and survival of younger age classes tended to improve population growth rates and lead to higher abundances, regardless of whether these increases were the result of reduced nonnative fish predation, decreased mortality from entrainment into a canal, or improved base flow management to provide nursery habitat. Improving adult survival also increased adult abundances over status quo projections. For the upper Colorado River population, the inclusion of a spawning spike at some regular interval improved model projections in most cases, and this phenomenon interacted with other parameters, such as increased carrying capacity resulting from improved fish passage, to produce synergistic effects. Miller (2018) pointed out that the spawning spike could drive the population to carrying capacity, limiting its potential to produce even greater abundances. Increasing carrying capacity by opening up new habitat through fish passages allows more fish from a spawning spike to recruit into the adult population, and improved population projections. Given the effect of the spawning spike on model projections, it is important to note that future conditions could be different than presented above if assumptions about the frequency or magnitude of this event are incorrect. Finally, PVA models for the San Juan River showed the reliance of this population on continued stocking unless underlying demographic parameters for reproduction and survival improve. Without such improvement, all the models that ceased stocking resulted in a decreased population, and in some instances, extirpation (Miller, P. S. 2018).

Under scenario 1 – Status Quo, we would expect Colorado pikeminnow's viability to be characterized by a loss of resiliency, representation, and redundancy after forty years. All populations would be in a low resiliency condition. We anticipate all extant populations would persist, but at low abundances. This would not reduce the range of the species but would result in a greater risk of extirpation through a reduction in redundancy. We expect representation would be reduced through a loss of allelic diversity through significant declines in the Green River subbasin population.

Under scenario 2 – Conservation Reduction, we would expect Colorado pikeminnow's viability to be characterized by more dramatic losses of resiliency, representation, and redundancy after forty years compared to the status quo forecasts. All populations would be in a functionally "extirpated" condition. Although it is unlikely two populations would be completely extirpated this risk would exist for the San Juan River subbasin. The loss of the San Juan River subbasin population would result in a loss of redundancy and representation for this species.

Under scenario 3 – Conservation Increase, after forty years we would expect Colorado pikeminnow's viability to be characterized by higher levels of resiliency and representation than exhibited under the Status Quo. Two of the three extant populations would be in high condition and one in low condition. We would anticipate all of the current populations to persist with redundancy remaining the same as current conditions, and representation would be expected to increase with higher abundance in two populations.

Under scenario 4 – Considerable Conservation, we would expect Colorado pikeminnow's viability to be characterized by higher levels of resiliency than exhibited under the current conditions or any future scenario. All three populations would be in a high condition after forty years. We would anticipate redundancy and representation to increase commensurate with the increase in each population's resiliency.

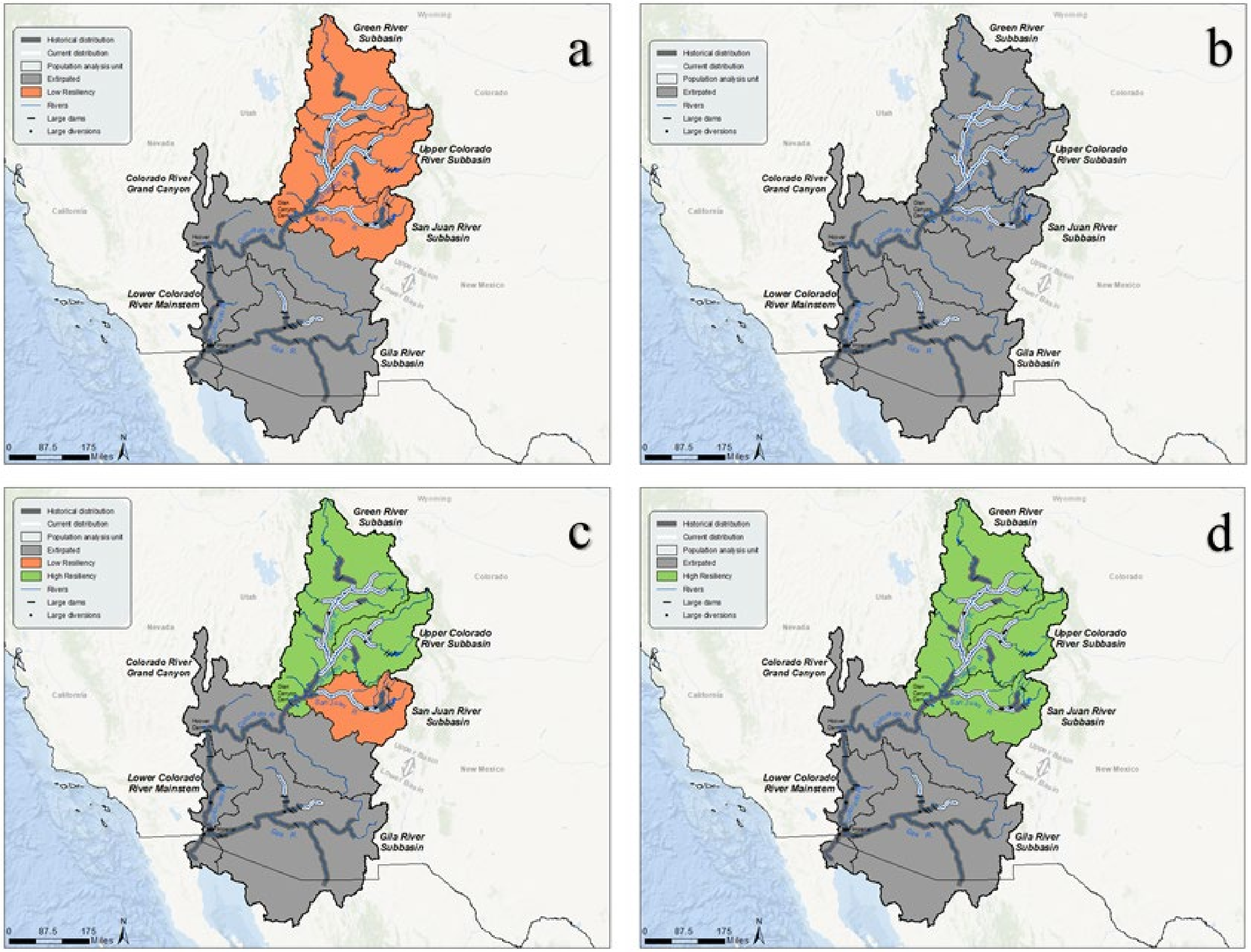


Figure 67. Upper Colorado River basin Colorado pikeminnow population resiliency (green = high health, yellow = moderate, orange = low, and grey = extirpated) under four future scenarios (40-year period): a) status quo b) conservation reduction c) conservation increase and d) considerable conservation increase.

LITERATURE CITED

Ahrens, Z., and M. T. Jones. 2017. Green River Company Canal salvage. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number C29a-138 Annual Report.

Allred, T. M., and J. C. Schmidt. 1999. Channel narrowing by vertical accretion along the Green River near Green River, Utah. Geological Society of America Bulletin 111(12):1757-1772.

Ammerman, L. K., and D. C. Morizot. 1989. Biochemical genetics of endangered Colorado squawfish populations. Transactions of the American Fisheries Society 118(4):435-440.

Anderson, D. M., T. W. Econopouly, J. Mohrman, M. T. Jones, M. J. Breen, and T. E. Chart. 2019. Review of fish studies with interim flow recommendations for endangered fishes of the White River, Colorado and Utah. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Draft Report.

Anderson, R. 1998. Evaluation of Gunnison River flow manipulation upon larval production of Colorado squawfish in the Gunnison and Colorado River, Colorado. Draft Report. Fort Collins, CO.

Anderson, R., and G. Stewart. 2003. Riverine fish flow investigations. Colorado Division of Wildlife, Fort Collins, CO. Federal Aid Project F-289-R6 Job Progress Report.

Archer, E., T. A. Crowl, and M. A. Trammell. 2000. Abundance of age-0 native fish species and nursery habitat quality and availability in the San Juan River, New Mexico, Colorado, and Utah. Final report. State of Utah, Department of Natural Resources, Salt Lake City, Utah. Publication Number 00-9.

Arizona Department of Water Resources. 2010. Arizona Water Atlas Volume I: Executive Summary.

Ault, T. R., J. S. Mankin, B. I. Cook, and J. E. Smerdon. 2016. Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest. Science Advances 2(10):e1600873.

Bark, R. C., E. L. Best, K. N. Bloom, and K. W. Frizell. 2013. Ridges Basin Dam sleeve valve passage analysis of nonnative fish and embryos at increasing depths and pressures. U.S. Bureau of Reclamation, Denver, CO. Technical Memorandum Number 86-68290-12-01.

Barkstedt, J. M., J. R. Campbell, B. R. Kesner, J. D. Schooley, and P. C. Marsh. 2008. Survival of razorback sucker stocked into the lower Colorado River. U.S. Bureau of Reclamation, Boulder City, NV. Draft 2007 Annual Report for Agreement Number 06FC300002.

Bassett, S. 2015. San Juan River historical ecology assessment: changes in channel characteristics and riparian vegetation. U.S. Bureau of Reclamation, Sante Fe, NM.

Baxter, G. T., and J. R. Simon. 1970. Wyoming Fishes. Wyoming Game and Fish Department, Cheyenne, Wyoming.

Berry, C. R. 1988. Effects of cold shock on Colorado squawfish larvae. The Southwestern Naturalist 33(2):193-197.

Bestgen, K. R. 2018. Evaluate effects of flow spikes to disrupt reproduction of smallmouth bass in the Green River downstream of Flaming Gorge Dam. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Larval Fish Laboratory Contribution 214.

Bestgen, K. R. 1996. Growth, survival, and starvation resistance of Colorado squawfish larvae. Environmental Biology of Fishes 46:197-209.

Bestgen, K. R., D. W. Beyers, J. A. Rice, and G. B. Haines. 2006. Factors affecting recruitment of young Colorado pikeminnow: synthesis of predation experiments, field studies, and individual-based modeling. Transactions of the American Fisheries Society 135(6):1722-1742.

Bestgen, K. R., J. A. Hawkins, G. C. White, K. D. Christopherson, J. M. Hudson, M. H. Fuller, D. C. Kitcheyan, R. Brunson, P. Badame, G. B. Haines, J. A. Jackson, C. D. Walford, and T. A. Sorensen. 2007. Population status of Colorado pikeminnow in the Green River Basin, Utah and Colorado. Transactions of the American Fisheries Society 136(5):1356-1380.

Bestgen, K. R., and A. A. Hill. 2016a. Reproduction, abundance, and recruitment dynamics of young Colorado pikeminnow in the Green and Yampa rivers, Utah and Colorado, 1979-2012. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number FR BW-Synth Final Report.

Bestgen, K. R., and A. A. Hill. 2016b. River regulation affects reproduction, early growth, and suppression strategies for invasive smallmouth bass in the upper Colorado River basin. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Numbers FR-115 and 140 Final Report.

Bestgen, K. R., R. T. Muth, and M. A. Trammell. 1998. Downstream transport of Colorado squawfish larvae in the Green River drainage: temporal and spatial variation in abundance and relationships with juvenile recruitment. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number 32 Final Report.

Bestgen, K. R., C. D. Walford, G. C. White, J. A. Hawkins, M. T. Jones, P. A. Webber, M. J. Breen, J. A. Skorupski, J. Howard, K. Creighton, J. Logan, K. Battige, and F. B. Wright. 2018. Population status and trends of Colorado pikeminnow in the Green River sub-basin, Utah and Colorado, 2000-2013. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 128 Final Report.

Bestgen, K. R., C. Walford, and D. Tuttle III. 2017. Evaluating effects of non-native predator removal on native fishes in the Yampa River, Colorado. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 140 Annual Report.

Bestgen, K. R., and M. A. Williams. 1994. Effects of fluctuating and constant temperatures on early development and survival of Colorado squawfish. Transactions of the American Fisheries Society 123(4):574-579.

Bliesner, R., E. de la Hoz, P. B. Holden, and V. A. Lamarra. 2009. Hydrology, geomorphology, and habitat studies. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. 2008 Annual Report.

Borley, K., and M. M. White. 2006. Mitochondrial DNA variation in the endangered Colorado pikeminnow: a comparison among hatchery stocks and historic specimens. North American Journal of Fisheries Management 26(4):916-920.

Bottcher, J. L., T. E. Walsworth, G. P. Thiede, P. Budy, and D. W. Speas. 2013. Frequent usage of tributaries by the endangered fishes of the upper Colorado River basin: observations from the San Rafael River, Utah. North American Journal of Fisheries Management 33(3):585-594.

Boyer, J. M., and A. Cutler. 2004. Gunnison River Aspinall Unit temperature study - phase II. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 107 Final Report.

Brandenburg, W. H., McKinstry, M. C., Cheek, C., MacKinnon, P., Norman, R., Ubing, C., Vermeyen, T., Dudley, R. K., Platania, S. P., Clark-Barkalow, S. L., Bestgen, K. R., Ulibarri, M., and Knight, W. 2017. Evaluation of the Hogback fish weir— transport and entrainment of fishes. Upper Colorado River Basin Researchers Meeting.

Breen, M. J., and C. M. Michaud. 2018. Annual fall monitoring of young-of-year Colorado pikeminnow. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 138 Annual Report.

Breton, A. R., J. A. Hawkins, K. R. Bestgen, D. L. Winkelman, and G. C. White. 2013. Escapement rates of translocated smallmouth bass (*Micropterus dolomieu*) from Elkhead Reservoir to the Yampa River. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 161 Final Report.

Breton, A. R., D. L. Winkelman, K. R. Bestgen, and J. A. Hawkins. 2015. Population dynamics modeling of introduced smallmouth bass in the upper Colorado River basin. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 161 Final Report.

Breton, A. R., D. L. Winkelman, J. A. Hawkins, and K. R. Bestgen. 2014. Population trends of smallmouth bass in the upper Colorado River basin with an evaluation of removal effects.

Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 161 Final Report.

Burdick, B. D. 1997. Minimum flow recommendation for passage of Colorado squawfish and razorback sucker in the 2.3-mile reach of the lower Gunnison River: Redlands Diversion Dam to the Colorado River confluence. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 57 Final Report.

Burnette, M. F., and A. C. Gibb. 2013. Do changes in morphology and prey-capture movements facilitate a dietary transition in juvenile Colorado pikeminnow, *Ptychocheilus lucius*? Evolutionary Biology 40(2):261-275.

Carlson, C. A., and Muth, R. T. 1989. The Colorado River: lifeline of the American Southwest. Pages 220-239 *in* D. P. Dodge, editor. Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences 106, Ottawa, Canada.

Carroll, C., J. A. Vucetich, M. P. Nelson, D. J. Rohlf, and M. K. Phillips. 2010. Geography and recovery under the U.S. Endangered Species Act. Conservation Biology 24(2):395-403.

Cathcart, C. N., M. C. McKinstry, P. D. MacKinnon, and C. M. Ruffing. 2019. A tribute to tributaries: endangered fish distributions within critical habitat of the San Juan River, U.S.A. North American Journal of Fisheries Management 39(5):1015-1025.

Cathcart, C. N., C. A. Pennock, C. A. Cheek, M. C. McKinstry, P. D. MacKinnon, M. M. Conner, and K. B. Gido. 2018. Waterfall formation at a desert river–reservoir delta isolates endangered fishes. River Research and Applications 34(8):948-956.

Chmiel, M. 2010a. Verde River Trip Report August 24-26, 2010.

Chmiel, M. 2010b. Verde River Trip Report July 6-8, 2010.

Chmiel, M. 2010c. Verde River Trip Report June 15-16, 2010.

Chmiel, M. 2006. Verde River Trip Report June 20-22, 2006.

Christensen, N., A. Wood, N. Voisin, D. Lettenmaier, and R. Palmer. 2004. The effects of climate change on the hydrology and water resources of the Colorado River Basin. Climatic Change 62(1):337-363.

Clark, A. 2006. Verde River Trip Report August 15-17, 2006.

Clark, S. R., M. M. Conner, S. L. Durst, and N. R. Franssen. 2018. Age-specific estimates indicate potential deleterious capture effects and low survival of stocked juvenile Colorado pikeminnow. North American Journal of Fisheries Management 38(5):1059-1074.

Coggins, L. G., M. D. Yard, and W. E. Pine. 2011. Nonnative fish control in the Colorado River in Grand Canyon, Arizona: an effective program or serendipitous timing? Transactions of the American Fisheries Society 140(2):456-470.

Colorado Natural Heritage Program. 2019. The species tagging, research and monitoring system (STReaMS), Available: https://streamsystem.org/.

Conrad, K. 2017. Grand Valley Water Users' Association OM&R for fish screen and fish passage. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number C-23 Annual Report.

Crist, L. W., and D. W. Ryden. 2003. Genetics management plan for the endangered fishes of the San Juan River. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Final Report.

Crowley, B., and D. W. Ryden. 2018. Retrieval of fish from the Grand Valley Irrigation Company and Grand Valley Water Users canals. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number C-29a Annual Report.

Crowley, B., and D. W. Ryden. 2017. Retrieval of fish from the Grand Valley Irrigation Company and Grand Valley Water Users canals. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number C-29a Annual Report.

Cummins, G. 2013. Verde River trip report, June 25-26, 2013. Arizona Game and Fish Department, Phoenix, AZ.

Cummins, G. 2012a. Verde River fish survey report: Tuzigoot Bridge to Beasley Flat, July 10-13, 2012. Arizona Game and Fish Department, Phoenix, AZ.

Cummins, G. 2012b. Verde River trip report, June 5-7, 2012. Arizona Game and Fish Department, Phoenix, AZ.

Cutler, A. 2006. Navajo Reservoir and San Juan River temperature study. U.S. Bureau of Reclamation, Salt Lake City, UT. San Juan River Basin Recovery Implementation Program. Final Report

Day, H. February 21, 2018. Four Corners Power Plant non- native fish control structure. Biology Committee Meeting. San Juan River Basin Recovery Implementation Program.

Day, K. S., K. D. Christopherson, and C. Crosby. 2000. Backwater use by young-of-the-year chub (*Gila spp.*) and Colorado pikeminnow (*Ptychocheilus lucius*) in Desolation and Gray canyons of the Green River, Utah. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number FG-39 Final Report.

Day, K. S., K. D. Christopherson, and C. Crosby. 1999. Report B: An assessment of young-of-the-year Colorado pikeminnow (*Ptychocheilus lucius*) use of backwater habitats in the

Green River, Utah. *in* Flaming Gorge Studies: Assessment of Colorado pikeinnow nursery habitat in the Green River. Utah Division of Wildlife Resources, Salt Lake City, UT.

Dayton, P. K., M. J. Tegner, P. B. Edwards, and K. L. Riser. 1998. Sliding baselines, ghosts, and reduced expectations in kelp forest communities. Ecological Applications 8(2):309.

de Graaf, M., van de Weerd, Gerco H, and J. W. M. Osse. 2010. Diversification of prey capture techniques among the piscivores in Lake Tana's (Ethiopia) Labeobarbus species flock (Cyprinidae). African Zoology 45(1):32-40.

Dennis, A. S. 1991. Initial climate change scenario for the western United States. U.S. Bureau of Reclamation, Denver, Colorado.

Diver, T., A. Harrison, and W. Wilson. 2019. Genetic evaluation and history of captive broodstock populations of endangered Colorado pikeminnow (*Ptychocheilus lucius*). San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Draft Report.

Diver, T., and S. Mussman. 2019. Using molecular techniques to quantify the effective number of breeders (Nb) for razorback sucker and Colorado pikeminnow in the San Juan River. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Draft Report.

Diver, T., and W. Wilson. 2018. Using molecular techniques to determine effective number of breeders (Nb) for razorback sucker and Colorado pikeminnow in the San Juan River. San Juan River Basin Recovery Implementation Program, Albuquerque, NM.

Dowling, T. E., P. C. Marsh, A. T. Kelsen, and C. A. Tibbets. 2005. Genetic monitoring of wild and repatriated populations of endangered razorback sucker (*Xyrauchen texanus*, Catostomidae, Teleostei) in Lake Mohave, Arizona-Nevada. Molecular Ecology 14(1):123-135.

Duncan, D., and Clarkson, R. W. 2013. Gila River Basin Native Fishes Conservation Program. Pages 376-380 *in* G. J. Gottfried, P. F. Ffolliott, B. S. Gebow, L. G. Eskew, and L. C. Collins, compilers. Merging science and management in a rapidly changing world: Biodiversity and management of the Madrean Archipelago III and 7th Conference on Research and Resource Management in the Southwestern Deserts. USDA Forest Service Proceedings RMRS-P-67. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Fort Collins, CO.

Duran, B. R., B. A. Hines, N. R. Franssen, and S. L. Durst. 2018. An experimental approach to nonnative species monitoring and control in the San Juan River: 2016-2017. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Draft Report.

Durst, S. L., and N. R. Franssen. 2014. Movement and growth of juvenile Colorado pikeminnows in the San Juan River, Colorado, New Mexico, and Utah. Transactions of the American Fisheries Society 143(2):519-527.

Ellis, M. M. 1914. Fishes of Colorado. The University of Colorado Studies 11(1):1-136.

Elverud, D. 2018. Monitoring multi-life stages of the fish community in the lower Gunnison and upper Colorado Rivers, with emphasis on Colorado pikeminnow and razorback sucker populations, in response to reoperation of the Aspinall Unit and implementation of the Selenium Management Plan. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 163 Annual Report.

Elverud, D., and D. W. Ryden. 2018. Monitoring the Colorado pikeminnow population in the mainstem Colorado River via periodic population estimates. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 127 Annual Report.

Elverud, D., and D. W. Ryden. 2015. Monitoring the Colorado pikeminnow population in the mainstem Colorado River via periodic population estimates. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 127 Annual Report.

Elverud, D., D. W. Ryden, and D. B. Osmundson. 2014. Monitoring the Colorado pikeminnow population in the mainstem Colorado River via periodic population estimates. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 127 Annual Report.

Environmental Protection Agency. 2017. Frequent questions related to gold king mine response, Available: https://www.epa.gov/goldkingmine/frequent-questions-related-gold-king-mine-response.

EPRI. 2015. A case study assessment of trace metal atmospheric emissions and their aquatic impacts in the San Juan River basin. Phase 1: Four Corners Power Plant. Electric Power Research Institute, Palo Alto, CA.

Evans, J. 2009. Fisheries survey of upper Salt River, June 1st-5th, 2009. Arizona Game and Fish Department, Phoenix, AZ.

Evans, P. 1993. A "recovery" partnership for the upper Colorado River to meet ESA § 7 needs. Natural Resources & Environment 8(1):24-72.

Evermann, B. W., and C. D. Rutter. 1894. The fishes of the Colorado River. Bulletin of U.S. Fisheries Commission 14:473-488.

Eyre, T. 2017. Middle Yampa River northern pike removal and evaluation; smallmouth bass removal and evaluation. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 98a Annual Report.

Fagan, W. F., P. J. Unmack, C. Burgess, and W. L. Minckley. 2002. Rarity, fragmentation, and extinction risk in desert fishes. Ecology 83(12):3250-3256.

Farrington, M. A., R. K. Dudley, J. L. Kennedy, S. P. Platania, and G. C. White. 2018. Colorado pikeminnow and razorback sucker larval fish survey in the San Juan River during 2017. San Juan River Basin Recovery Implementation Program, Albuquerque, NM.

Fogarty, M. J., M. P. Sissenwine, and E. B. Cohen. 1991. Recruitment variability and dynamics of exploited marine populations. Tree 6(8):241-246.

Francis, T. A. 2018. Annual operation and maintenance of the fish passage structure at the Government Highline Diversion Dam on the upper Colorado River and Price Stubb Fish Passage. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number C4b-GVP Annual Report.

Francis, T. A., and D. W. Ryden. 2018. Removal of non-native fish in the upper Colorado River between Grand Valley Water User's Dam [Government Highline Diversion Dam] near Palisade, Colorado, and Potash, Utah. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 126 Annual Report.

Franssen, N. R. May 22, 2018. Update on opening PNM fish passage from March-May. Biology Committee Meeting. San Juan River Basin Recovery Implementation Program.

Franssen, N. R., and S. L. Durst. 2014. Prey and non-native fish predict the distribution of Colorado pikeminnow (*Ptychocheilus lucius*) in a south-western river in North America. Ecology of Freshwater Fish 23(3):395-404.

Franssen, N. R., S. L. Durst, K. B. Gido, D. W. Ryden, V. A. Lamarra, and D. L. Propst. 2016. Long-term dynamics of large-bodied fishes assessed from spatially intensive monitoring of a managed desert river. River Research and Applications 32(3):348-361.

Franssen, N. R., E. I. Gilbert, K. B. Gido, and D. L. Propst. 2019. Hatchery-reared endangered Colorado pikeminnow (*Ptychocheilus lucius*) undergo a gradual transition to piscivory after introduction to the wild. Aquatic Conservation: Marine and Freshwater Ecosystems 29(1):24-38.

Fresques, T. D., R. C. Ramey, and G. J. Dekleva. 2013. Use of small tributary streams by subadult Colorado pikeminnows (*Ptychocheilus lucius*) in Yellow Jacket Canyon, Colorado. The Southwestern Naturalist 58(1):104-107.

Friedman, J., G. Auble, P. Shafroth, M. Scott, M. Merigliano, M. Freehling, and E. Griffin. 2005. Dominance of non-native riparian trees in western USA. Biological Invasions 7(4):747-751.

Furr, D. W. 2018. San Juan River razorback sucker (*Xyrauchen texanus*) and Colorado pikeminnow (*Ptychocheilus lucius*) population augmentation: 2017. San Juan River Basin Recovery Implementation Program, Albuquerque, NM.

Gaston, K. J., and T. M. Blackburn. 2000. Pattern and process in macroecology. Blackwell Science, Oxford, U.K.

Gido, K. B., and D. L. Propst. 2012. Long-term dynamics of native and nonnative fishes in the San Juan River, New Mexico and Utah, under a partially managed flow regime. Transactions of the American Fisheries Society 141(3):645-659.

Gilbert, C. H., and N. B. Scofield. 1898. Notes on a collection of fishes from the Colorado Basin in Arizona. Proceedings of the United States National Museum 20:487-499.

Gilbert, E., S. L. Durst, A. James, J. Davis, T. Sinclair, and N. R. Franssen. 2018. Cranial morphological scaling and relative prey size limitations for a native predator in an invaded system. Environmental Biology of Fishes 101(6):1067-1076.

Gill, C. 2013. Verde River – Below Horseshoe Reservoir survey report July 30- August 1, 2013. Arizona Game and Fish Department, Mesa, Arizona.

Gill, C. 2012. Trip report for the Verde River fisheries survey, Childs to Sheep Bridge, May 21 – 25, 2012. Arizona Game and Fish Department, Mesa, AZ.

Gill, C. 2011. Fisheries survey of the Upper Salt River: May 9th – 13th, 2011. Arizona Game and Fish Department, Mesa, AZ.

Gill, C. 2010. Verde River – Bartlett Lake to Box Bar survey report September 21, 2010. Arizona Game and Fish Department, Mesa, AZ.

Girard, C. 1856. Researches upon the cyprinoid fishes inhabiting the fresh waters of the United States, west of the Mississippi Valley, from specimens in the Museum of the Smithsonian institution. Proceedings of the Academy of Natural Sciences of Philadelphia 8:165-213.

Gleick, P. H., and E. L. Chalecki. 1999. The impacts of climatic changes for water resources of the Colorado and Sacramento-San Joaquin river basins. JAWRA Journal of the American Water Resources Association 35(6):1429-1441.

Gobalet, K. W., T. A. Wake, and K. L. Hardin. 2005. Archaeological record of native fishes of the lower Colorado River: how to identify their remains. Western North American Naturalist 65(3):335-344.

Good, D., K. Moran, J. Brooks, M. Wernke, K. Sayer, E. Manzanaras, and D. McKelvie. 2007. Hogback Diversion Dam – fish screen project. U.S. Bureau of Reclamation, Farmington, NM. Value Engineering Final Report.

Grams, P. E., and J. C. Schmidt. 2002. Streamflow regulation and multi-level flood plain formation: channel narrowing on the aggrading Green River in the eastern Uinta Mountains, Colorado and Utah. Geomorphology 44(3):337-360.

Grams, P. E., J. C. Schmidt, and M. E. Andersen. 2010. 2008 high-flow experiment at Glen Canyon Dam—morphologic response of eddy-deposited sandbars and associated aquatic backwater habitats along the Colorado River in Grand Canyon National Park: U.S. Geological Survey Open-File Report 2010-1032. U.S. Geological Survey, Reston, VA.

Grams, P. E., J. C. Schmidt, and D. J. Topping. 2007. The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956-2000. Geological Society of America Bulletin 119(5-6):556-575.

Grippo, M., K. E. LaGory, D. Waterman, J. W. Hayse, L. J. Walston, C. C. Weber, A. K. Magnusson, and X. H. Jiang. 2017. Relationships between flow and the physical characteristics of Colorado pikeminnow backwater nursery habitats in the middle Green River, Utah. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number FR BW-Synth Final Report.

Guenther, C. D. 2017. Operation and maintenance of the fish screen and fish passage facility at the Grand Valley Irrigation Company Diversion in Palisade. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number C-29 Annual Report.

Haines, G. B., D. W. Beyers, and T. Modde. 1998. Estimation of winter survival, movement, and dispersal of young Colorado squawfish in the Green River, Utah. Larval Fish Laboratory, Colorado State University, Fort Collins, CO. Larval Fish Laboratory Contribution 36.

Haines, G. B., B. Irving David, and T. Modde. 2004. White River base flow study for endangered fishes, Colorado and Utah, 1995-1996. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 65 Final Report.

Hamman, R. L. 1986. Induced spawning of hatchery-reared Colorado squawfish. The Progressive Fish-Culturist 48(1):72-74.

Harvey, M. D., and E. J. Wick. 1993. A physical process-biological response model for spawning habitat formation for the endangered Colorado squawfish. Rivers 4(2):114-131.

Hawkins, J. A., C. Walford, and A. A. Hill. 2009. Smallmouth bass control in the middle Yampa River, 2003–2007. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 125 Final Report.

Hedden, S. C., and K. B. Gido. 2020. Incidence and consumption of endangered fishes by channel catfish (*Ictalurus punctatus*) in the San Juan River. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Draft Report.

Hedden, S. C., K. B. Gido, and J. E. Whitney. 2016. Introduced flathead catfish consumptive demand on native fishes of the Upper Gila River, New Mexico. North American Journal of Fisheries Management 36(1):55-61.

Hendrickson, D. A. 1993. Evaluation of the razorback sucker (*Xyrauchen texanus*) and Colorado squawfish (*Ptychocheilus lucius*) reintroduction programs in central Arizona based on surveys of fish populations in the Salt and Verde rivers from 1986 to 1990. Arizona Game and Fish Department, Phoenix, AZ. Nongame and Endangered Wildlife Program Report.

Hinck, J. E., V. S. Blazer, N. D. Denslow, T. S. Gross, K. R. Echols, A. P. Davis, T. W. May, C. E. Orazio, J. J. Coyle, and D. E. Tillitt. 2006. Biomonitoring of environmental status and trends (BEST) program: environmental contaminants, health indicators, and reproductive biomarkers in fish from the Colorado River Basin. U.S. Geological Survey, Report 2006-5163, Reston, Va.

Holden, P. B. 1999. Flow recommendations for the San Juan River. San Juan River Basin Recovery Implementation Program, Albuquerque, New Mexico.

Holden, P. B., and Wick, E. J. 1982. Life history and prospects for recovery of Colorado squawfish. Fishes of the upper Colorado River system: Present and future, Bethesda, MD: Western Division, American Fisheries Society, 98-108.

Hyatt, M. W. 2004. Assessment of Colorado pikeminnow and razorback sucker reintroduction programs in the Gila River Basin. Arizona Game and Fish Department, Phoenix, AZ.

Irving, D. B., and T. Modde. 2000. Home-range fidelity and use of historic habitat by adult Colorado pikeminnow (*Ptychocheilus lucius*) in the White River, Colorado and Utah. Western North American Naturalist 60(1):16-25.

Jacobi, G. Z., and M. D. Jacobi. 1981. Fish Stomach Content Analysis. Sante Fe, New Mexico.

Johnson, B. M., P. J. Martinez, J. A. Hawkins, and K. R. Bestgen. 2008. Ranking predatory threats by nonnative fishes in the Yampa River, Colorado, via bioenergetics modeling. North American Journal of Fisheries Management 28(6):1941-1953.

Johnson, B. M., B. Wolff, and P. J. Martinez. 2014. Chemically fingerprinting nonnative fishes in reservoirs. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number C-18/19 Final Report.

Jones, K. E. 2017. Operation and maintenance of the fish screen and maintenance of the fish passage at the Redlands Water and Power Company Diversion Dam. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 116/C-33 Annual Report.

Jones, M. T. 2017. Smallmouth bass control in the lower Yampa River. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 110 Annual Report.

Jones, M. T., and J. Caldwell. 2017. Nonnative fish control in the Green River. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 123a Annual Report.

Jordan, D. S. 1891. Report of explorations in Colorado and Utah during the summer of 1889, with an account of the fishes found in each of the river basins examined. Bulletin of the United States Fish Commission IX:1-40.

Jordan, D. S., and Evermann, B. W. 1896. The fishes of North and Middle America. Smithsonian Institution, Monograph 47, Washington, D.C.

Kaeding, L. R., and D. B. Osmundson. 1988. Interaction of slow growth and increased early-life mortality: an hypothesis on the decline of Colorado squawfish in the upstream regions of its historic range. Environmental Biology of Fishes 22(4):287-298.

Karp, C. A., and H. M. Tyus. 1990. Behavioral interactions between young Colorado squawfish and six fish species. Copeia 1990(1):25-34.

Kegerries, R., B. Albrecht, R. Rogers, H. Mohn, W. H. Brandenburg, A. L. Barkalow, S. L. Wood, M. McKinstry, B. Healy, J. Stolberg, and E. Omana-Smith. 2018. Razorback sucker *Xyrauchen texanus* research and monitoring in the Colorado River inflow areas of Lake Mead and the lower Grand Canyon, Arizona and Nevada. U.S. Bureau of Reclamation, Salt Lake City, UT.

Keller, D., S. Bellagamba, and D. M. Anderson. 2018. Protecting flows in the Price River. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number FR-171 Annual Report.

Kennedy, T. A., J. D. Muehlbauer, C. B. Yackulic, D. A. Lytle, S. W. Miller, K. L. Dibble, E. W. Kortenhoeven, A. N. Metcalfe, and C. V. Baxter. 2016. Flow management for hydropower extirpates aquatic insects, undermining river food webs. BioScience 66(7):561-575.

Kirsch, P. H. 1889. Notes on a Collection of Fishes Obtained in the Gila River, at Fort Thomas, Arizona, by Lieut. W L Carpenter. Proceedings of United States National Museum XI:555-558.

Kitcheyan, D. C., and G. B. Haines. 2004. Overwinter survival and movement of young-of-year Colorado pikeminnow in the Green River, Utah, 1999-2002. Pages A1-A73 *in* D. C. Kitcheyan, and G. B. Haines, editors. Evaluation of the effects of stage fluctuations on overwinter survival and movement of young Colorado pikeminnow in the Green River, Utah, 1999-2002. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

Korman, J., M. Kaplinski, and T. S. Melis. 2011. Effects of fluctuating flows and a controlled flood on incubation success and early survival rates and growth of age-0 rainbow trout in a large regulated river. Transactions of the American Fisheries Society 140(2):487-505.

Koster, W. J. 1960. *Ptychocheilus lucius* (Cyprinidae) in the San Juan River, New Mexico. The Southwestern Naturalist 5(3):174-175.

LaGory, K. E., K. R. Bestgen, H. Patno, J. Wilhite, D. W. Speas, and M. A. Trammell. 2019. Evaluation and suggested revisions of flow and temperature recommendations for endangered fish in the Green River downstream of Flaming Gorge Dam. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number FR-173 Draft Report.

Lamarra, D., and V. A. Lamarra. 2016. Spatial and temporal trends in San Juan River habitat. San Juan River Recovery Implementation Program, Albuquerque, New Mexico.

Lamarra, V. A., and D. Lamarra. 2018. San Juan River habitat monitoring: 2017. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Annual report.

Lamarra, V. A., and D. Lamarra. 2013. San Juan River 2013 habitat monitoring. Logan, UT. U.S.Bureau of Reclamation Contract No. INR11PX40083 Final Report.

Lamarra, V. A., Lamarra, D., Durst, S. L., and Franssen, N. R. 2018. Effects of spring discharge, time, and flows-at-mapping on backwater and secondary channel habitats in the San Juan River (1993-2016). Annual Meeting of the San Juan River Basin Recovery Implementation Program.

Lamarrra, V. L. 2015. Current flow recommendations: an historical perspective. San Juan River Environmental Flows Workshop. San Juan River Basin Recovery Implementation Program.

Lower Colorado River Multi-Species Conservation Program. 2018. Final implementation report, fiscal year 2019 work plan and budget, fiscal year 2017 accomplishment report. U.S. Bureau of Reclamation, Boulder City, Nevada.

Lower Colorado River Multi-Species Conservation Program. 2004. Lower Colorado River Multi-Species Conservation Program, Volume II: Habitat Conservation Plan. Lower Colorado River Multi-Species Conservation Program, Sacramento, CA.

Lyons, D., M. A. Farrington, S. P. Platania, and D. Gori. 2016. San Juan and Animas rivers diversion study. San Juan River Basin Recovery Implementation Program, Albuquerque, NM.

Manners, R. B., J. C. Schmidt, and M. L. Scott. 2014. Mechanisms of vegetation-induced channel narrowing of an unregulated canyon river: Results from a natural field-scale experiment. Geomorphology 211:100-115.

Martinez, P. J., K. Wilson, P. Cavalli, H. Crockett, D. W. Speas, M. A. Trammell, B. Albrecht, and D. W. Ryden. 2014. Upper Colorado River basin nonnative and invasive aquatic species prevention and control strategy. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

McAbee, K. 2017a. Colorado River summer base flow scenario for PVA consideration. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

McAbee, K. 2017b. Scenario 4: increased adult survival via screening a problematic irrigation structure. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

McAda, C. W. 2003. Flow recommendations to benefit endangered fishes in the Colorado and Gunnison Rivers. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number 54 Final Report.

McAda, C. W. 1983. Colorado squawfish, *Ptychocheilus lucius* (Cyprinidae), with a channel catfish, *Ictalurus punctatus* (Ictaluridae), lodged in its throat. The Southwestern Naturalist 28(1):119-120.

McAda, C. W., and L. R. Kaeding. 1991. Movements of adult Colorado squawfish during the spawning season in the upper Colorado River. Transactions of the American Fisheries Society 120(3):339-345.

McAda, C. W., and R. J. Ryel. 1999. Distribution, relative abundance, and environmental correlates for age-0 Colorado pikeminnow and sympatric fishes in the Colorado River. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number 45 Final Report.

McCabe, G. J., D. M. Wolock, G. T. Pederson, C. A. Woodhouse, and S. McAfee. 2017. Evidence that recent warming is reducing Upper Colorado River flows. Earth Interactions 21(10):1-14.

McGarvey, D. J., J. M. Johnston, and M. C. Barber. 2010. Predicting fish densities in lotic systems: a simple modeling approach. Journal of the North American Benthological Society 29(4):1212-1227.

McKinstry, M., Cathcart, N., Cheek, C., and MacKinnon, P. 2016. Small antennas downstream of San Juan River waterfall. Colorado River Aquatic Biologists Meeting.

Melis, T. S. 2011. Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona. U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia.

Michaud, C., T. A. Francis, M. Partlow, M. Fiorelli, and M. T. Jones. 2018. Evaluation of walleye removal in the upper Colorado River basin. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number 123d Annual Report.

Miller, P. S. 2018. Population viability analysis for the Colorado pikeminnow (*Ptychocheilus lucius*): an assessment of current threats to species recovery and evaluation of management alternatives. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

Miller, P. S. 2014. A population viability analysis for the Colorado pikeminnow (*Ptychocheilus lucius*) in the San Juan River. Conservation Breeding Specialist Group (IUCN/SSC), Apple Valley, MN.

Miller, R. R. 1961. Man and the changing fish fauna of the American Southwest. Papers of the Michigan Academy of Science, Arts and Letters 46:365-404.

Minckley, W. L. 1991. Native fishes of the Grand Canyon region: an obituary? *in* National Research Council, editor. Colorado River Ecology and Dam Management: Proceedings of a symposium May 24-25, 1990 Santa Fe, NM. National Academy Press, Washington, D.C., 124-177.

Minckley, W. L. 1985. Native fishes and natural aquatic habitats in U.S. Fish and Wildlife Service Region II west of the continental divide. U.S. Fish and Wildlife Service, Albuquerque, NM.

Minckley, W. L. 1973. Fishes of Arizona. Sims Publishing Co, Phoenix, AZ.

Minckley, W. L., and J. E. Deacon. 1968. Southwestern fishes and the enigma of "endangered species". Science 159(3822):1424-1432.

Minckley, W. L. and P. C. Marsh. 2009. Inland fishes of the greater Southwest: chronicle of a vanishing biota. University of Arizona Press, Tucson, Arizona.

Modde, T., and C. Keleher. 2003. Flow recommendations for the Duchesne River with a synopsis of information regarding endangered fishes. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 84 Final Report.

Modde, T., W. J. Miller, and R. Anderson. 1999. Determination of habitat availability, habitat use, and flow needs of endangered fishes in the Yampa River between August and October. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number CAP-9 Final Report.

Mohrman, J., and D. M. Anderson. 2017. Procedures for releasing and administering water from Elkhead Reservoir to augment Yampa River flows for endangered fish. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

Morizot, D. C., J. H. Williamson, and G. J. Carmichael. 2002. Biochemical Genetics of Colorado Pikeminnow. North American Journal of Fisheries Management 22(1):66-76.

Moyle, P. B. 1976. Inland Fishes of California. University of California Press, Berkeley, California.

Mueller, G. A., and P. C. Marsh. 2002. Lost, a desert and its native fishes: a historical perspective of the Lower Colorado River. U.S. Government Printing Office, Denver, CO. Information and Technology Report USGS/BRD/ITR-2002-0010.

Muth, R. T., L. W. Crist, K. E. LaGory, J. W. Hayse, K. R. Bestgen, T. P. Ryan, J. K. Lyons, and R. A. Valdez. 2000. Flow and temperature recommendations for endangered fishes in the

Green River downstream of Flaming Gorge Dam. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number FG-53 Final Report.

Muth, R. T., and D. E. Snyder. 1995. Diets of young Colorado squawfish and other small fish in backwaters of the Green River, Colorado and Utah. The Great Basin Naturalist 55(2):95-104.

Nash, L. L., and P. H. Gleick. 1991. Sensitivity of streamflow in the Colorado basin to climatic changes. Journal of Hydrology 125:221-241.

National Park Service. 2013. Grand Canyon National Park, Glen Canyon National Recreation Area: Comprehensive fisheries management plan: Environmental assessment. National Park Service, Grand Canyon, AZ.

Natural Resources Conservation Service. 2014. Final Environmental Impact Statement (FEIS) for the rehabilitation of the Green River diversion. USDA NRCS Utah, Salt Lake City, UT.

Nelson, J. S., E. J. Crossman, H. Espinosa-Perez, C. R. Gilbert, R. N. Lea, and J. D. Williams. 1998. Recommended changes in common fish names: pikeminnow to replace squawfish (*Ptychocheilus* spp.). Fisheries 23(9):37.

Nelson, J. S., T. C. Grande, and M. V. H. Wilson. 2016. Fishes of the world, 5th edition. John Wiley & Sons, Hoboken, NJ.

Nesler, T. P., R. T. Muth, and A. F. Wasowicz. 1988. Evidence for baseline flow spikes as spawning cues for Colorado squawfish in the Yampa River, Colorado. Pages 68-79 *in* R. D. Hoyt, editor. American Fisheries Society, Symposium 5, Bethesda, Maryland.

Nevada Department of Wildlife. 2015. Federal aid job progress report F-20-50: Colorado River below Davis Dam, Southern Region. Nevada Department of Wildlife, Las Vegas, NV.

Nevada Department of Wildlife. 2014. Federal aid job progress report F-20-50: Colorado River below Davis Dam, Southern Region. Nevada Department of Wildlife, Las Vegas, NV.

Osborne, M. J., E. W. Carson, and T. F. Turner. 2012. Genetic monitoring and complex population dynamics: insights from a 12-year study of the Rio Grande silvery minnow. Evolutionary Applications 5(6):553-574.

Osmundson, B., and J. D. Lusk. 2019. Field assessment of Colorado pikeminnow exposure to mercury within its designated critical habitat in Colorado, Utah, and New Mexico. Archives of Environmental Contamination and Toxicology 76:17-30.

Osmundson, B., T. W. May, and D. B. Osmundson. 2000. Selenium concentrations in the Colorado pikeminnow (*Ptychocheilus lucius*): relationship with flows in the upper Colorado River. Archives of Environmental Contamination and Toxicology 38(4):479-485.

Osmundson, D. B. 2011. Thermal regime suitability: assessment of upstream range restoration potential for Colorado pikeminnow, a warmwater endangered fish. River Research and Applications 27(6):706-722.

Osmundson, D. B. 2006. Proximate causes of sexual size dimorphism in Colorado pikeminnow, a long-lived cyprinid. Journal of Fish Biology 68(5):1563-1588.

Osmundson, D. B. 1999. Longitudinal variation in fish community structure and water temperature in the upper Colorado River. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 48-A Final Report.

Osmundson, D. B., and K. P. Burnham. 1998. Status and trends of the endangered Colorado squawfish in the upper Colorado River. Transactions of the American Fisheries Society 127(6):957-970.

Osmundson, D. B., P. Nelson, K. Fenton, and D. W. Ryden. 1995. Relationships between flow and rare fish habitat in the "15-Mile Reach" of the upper Colorado River. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Final Report.

Osmundson, D. B., R. J. Ryel, and T. E. Mourning. 1997. Growth and survival of Colorado squawfish in the upper Colorado River. Transactions of the American Fisheries Society 126(4):687-698.

Osmundson, D. B., R. J. Ryel, M. E. Tucker, B. D. Burdick, W. R. Elmblad, and T. E. Chart. 1998. Dispersal patterns of subadult and adult Colorado squawfish in the upper Colorado River. Transactions of the American Fisheries Society 127(6):943-956.

Osmundson, D. B., and G. C. White. 2017a. Long-term mark-recapture monitoring of a Colorado pikeminnow *Ptychocheilus lucius* population: assessing recovery progress using demographic trends. Endangered Species Research 34:131-147.

Osmundson, D. B., and G. C. White. 2017b. Long-term mark-recapture monitoring of a Colorado pikeminnow *Ptychocheilus lucius* population: assessing recovery progress using demographic trends (supplement). Endangered Species Research 34:S1-S6.

Osmundson, D. B., and G. C. White. 2014. Population structure, abundance and recruitment of Colorado pikeminnow of the upper Colorado River, 1991-2010. U. S. Fish and Wildlife Service, Grand Junction, CO. Project Number 127 Final Report.

Paretti, N. V., A. M. Brasher, S. L. Pearlstein, D. M. Skow, B. Gungle, and B. D. Garner. 2017. Preliminary synthesis and assessment of environmental flows in the Middle Verde River watershed, Arizona. U.S. Geological Survey, Reston, VA.

Patton, T. M., J. Morel, and M. C. McKinstry. 2015. Extent of predation by non-native channel catfish on native and endangered fishes in the San Juan River, New Mexico and Utah. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Draft Report.

Pennock, C. A., S. L. Durst, B. R. Duran, B. A. Hines, C. N. Cathcart, J. E. Davis, B. J. Schleicher, and N. R. Franssen. 2018. Predicted and observed responses of a nonnative channel catfish population following managed removal to aid the recovery of endangered fishes. North American Journal of Fisheries Management 38(3):565-578.

Peters, J. C. 1978. Modification of intakes at Flaming Gorge Dam, Utah, to improve water temperature in the Green River. U.S. Bureau of Reclamation, Denver, CO.

Pimental, R., R. V. Bulkley, and H. M. Tyus. 1985. Choking of Colorado squawfish, *Ptychocheilus luciu*s (Cyprinidae), on channel catfish, *Ictalurus punctatus* (Ictaluridae), as a cause of mortality. The Southwestern Naturalist 30(1):154-158.

Pinnegar, J., and G. Engelhard. 2008. The ‘shifting baseline’ phenomenon: a global perspective. Reviews in Fish Biology and Fisheries 18(1):1-16.

Pitlick, J., M. M. van Steeter, B. Barkett, R. Cress, and M. Franseen. 1999. Geomorphology and hydrology of the Colorado and Gunnison rivers and implications for habitats used by endangered fishes. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Final Report.

Platania, S. P. 1990. Biological summary of the 1987 to 1989 New Mexico-Utah ichthyofaunal study of the San Juan River. New Mexico Department of Game and Fish, Santa Fe, NM.

Platania, S. P., K. R. Bestgen, M. A. Moretti, D. L. Propst, and J. E. Brooks. 1991. Status of Colorado squawfish and razorback sucker in the San Juan River, Colorado, New Mexico, and Utah. The Southwestern Naturalist 36(1):147-150.

Portz, D., and H. Tyus. 2004. Fish humps in two Colorado River fishes: a morphological response to cyprinid predation? Environmental Biology of Fishes 71(3):233-235.

Quartarone, F., and C. Young. 1995. Historical accounts of upper Colorado River Basin endangered fish. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado.

Rakowski, C. L., and J. C. Schmidt. 1999. The geomorphic basis of Colorado pikeminnow nursery habitat in the Green River near Ouray, Utah. Pages A1-A145 *in* M. A. Trammell, and K. D. Christopherson, editors. Flaming Gorge Studies: Assessment of Colorado pikeminnow nursery habitat in the Green River. Utah Division of Wildlife Resources, Salt Lake City, UT.

Redford, K. H., G. Amato, J. Baillie, P. Beldomenico, E. L. Bennett, N. Clum, R. Cook, G. Fonseca, S. Hedges, F. Launay, S. Lieberman, G. M. Mace, A. Murayama, A. Putnam, J. G. Robinson, H. Rosenbaum, E. W. Sanderson, S. N. Stuart, P. Thomas, and J. Thorbjarnarson. 2011. What does it mean to successfully conserve a (vertebrate) species? BioScience 61(1):39-48.

Renfro, L. E., S. P. Platania, and R. K. Dudley. 2006. An assessment of fish entrainment in the Hogback diversion canal, San Juan River, New Mexico, 2004. U.S. Bureau of Reclamation, Salt Lake City, UT.

Roehm, G. W. 2004. Management plan for endangered fishes in the Yampa River basin and environmental assessment. U.S. Fish and Wildlife Service, Denver, CO.

Rogowski, D. L., and J. K. Boyer. 2019. Colorado River fish monitoring in the Grand Canyon, Arizona—2018 annual report. Grand Canyon Monitoring and Research Center, Flagstaff, AZ.

Rogowski, D. L., R. J. Osterhoudt, H. E. Mohn, and J. K. Boyer. 2018. Humpback chub (*Gila cypha*) range expansion in the western Grand Canyon. Western North American Naturalist 78(1):26-38.

Ryden, D. W. 2017. Annual operation and maintenance of the fish passage structure at the Government Highline Diversion Dam on the Upper Colorado River and Price Stubb Fish Passage. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number C4b-GVP Annual Report.

Ryden, D. W. 2000. Adult fish community monitoring on the San Juan River, 1991-1997. U.S. Fish and Wildlife Service, Grand Junction, CO. Final Report.

Ryden, D. W., and L. A. Ahlm. 1996. Observations on the distribution and movements of Colorado squawfish, *Ptychocheilus lucius*, in the San Juan River, New Mexico, Colorado, and Utah. The Southwestern Naturalist 41(2):161-168.

Ryden, D. W., and J. R. Smith. 2002. Colorado pikeminnow with a channel catfish lodged in its throat in the San Juan River, Utah. The Southwestern Naturalist 47(1):92-94.

Salt River Project. 2017. Horseshoe and Bartlett Reservoirs habitat conservation plan. U.S. Fish and Wildlife Service, Phoenix, AZ. 2016 Annual Report.

Salt River Project. 2010. Horseshoe and Bartlett Reservoirs habitat conservation plan. U.S. Fish and Wildlife Service, Phoenix, Arizona. 2010 Annual Report.

Salt River Project. 2008. Habitat Conservation Plan--Horseshoe and Bartlett Reservoirs. U.S. Fish and Wildlife Service, Phoenix, AZ.

San Juan River Basin Recovery Implementation Program. 2017. Population abundance estimates for Colorado pikeminnow and razorback sucker in the San Juan River. San Juan River Basin Recovery Implementation Program, Albuquerque, NM.

San Juan River Basin Recovery Implementation Program. 2006. San Juan River standardized monitoring program five year integration report. San Juan River Basin Recovery Implementation Program, Albuquerque, NM.

Schleicher, B. J. 2018. Long term monitoring of sub-adult and adult large-bodied fishes in the San Juan River: 2017. San Juan River Basin Recovery Implementation Program, Albuquerque, New Mexico.

Schmidt, J. C., and P. R. Wilcock. 2008. Metrics for assessing the downstream effects of dams. Water Resources Research 44(4).

Schooley, J. D., B. R. Kesner, J. R. Campbell, J. M. Barkstedt, and P. C. Marsh. 2008. Survival of razorback sucker in the lower Colorado River. U.S. Bureau of Reclamation, Boulder City, NV. January 2006-April 2008 Final Report.

Seethaler, K. 1978. Life history and ecology of the Colorado squawfish (*Ptychocheilus lucius*) in the upper Colorado River basin. Master's thesis. Utah State University, Logan, Utah.

Seethaler, K., McAda, C. W., and Wydoski, R. S. 1979. Endangered and threatened fish in the Yampa and Green rivers of Dinosaur National Monument. Pages 605-612 *in* R. M. Linn, editor. Proceedings of the First Conference on Scientific Research in the National Parks. National Park Service, Transactions and Proceedings Series 5, Washington, DC.

Smith, C. and M. T. Jones. 2017. Upper Yampa River northern pike management and monitoring. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number 98b Annual Report.

Smith, C., M. T. Jones, M. J. Breen, R. R. Staffeldt, and J. Logan. 2017. Smallmouth bass control in the White River. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number 167 Annual Report.

Smith, D. R., N. L. Allan, C. P. McGowan, J. A. Szymanski, S. R. Oetker, and H. M. Bell. 2018. Development of a species status assessment process for decisions under the U.S. Endangered Species Act. Journal of Fish and Wildlife Management 9(1):302-320.

Smith, G. R., Miller, R. R., and Sable, W. D. 1979. Species relationships among fishes of the genus Gila in the upper Colorado River drainage. Pages 613-623 *in* R. M. Linn, editor. Proceedings of the First Conference on Scientific Research in the National Parks. National Park Service, Transactions and Proceedings Series 5, Washington, DC.

Snyder, D. E., S. C. Seal, J. A. Charles, and C. L. Bjork. 2016. Guide to cyprinid fish larvae and early juveniles of the Upper Colorado River Basin with computer-interactive key. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 149 Final Report.

Spahr, N. E., L. E. Apodaca, J. R. Deacon, J. B. Bails, N. J. Bauch, C. M. Smith, and N. E. Driver. 2000. Water quality in the Upper Colorado River Basin, Colorado, 1996-1998. U.S. Geological Survey, Report 1214, Denver, CO.

Speas, D. W., J. A. Hawkins, P. D. MacKinnon, K. R. Bestgen, and C. D. Walford. 2014. Entrainment of native fish in Maybell Ditch, Northwestern Colorado, 2011-2012. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Final Report.

Speas, D. W., J. Stahil, P. MacKinnon, and K. McAbee. 2016. Stationary PIT detection system in the Green River Canal, Green River, UT. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number C-28a Annual Report.

Staffeldt, R. R., M. S. Partlow, B. R. Anderson, and M. J. Breen. 2017. Nonnative fish control in the middle Green River. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 123b Annual Report.

Stamp, M., M. Golden, and R. C. Addley. 2005. Evaluation of the need for fish passage at the Arizona Public Service and Fruitland Irrigation diversion structures. U.S. Bureau of Reclamation, Salt Lake City, UT.

Suttkus, R. D., and Clemmer, G. H. 1979. Fishes of the Colorado River in Grand Canyon National Park. Pages 599-604 *in* R. M. Linn, editor. Proceedings of the First Conference on Scientific Research in the National Parks. National Park Service, Transactions and Proceedings Series 5, Washington, DC.

Tarrant, P., T. Sawyer, R. Mestek, and S. Neuer. 2009. Feasibility study for early warning systems for algae-induced tastes and odors. American Water Works Association, Denver, CO. Final Report.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012. An overview of CMIP5 and the experimental design. Bulletin of the American Meteorological Society 93(4):485-498.

Thompson, J. M., E. P. Bergersen, C. A. Carlson, and L. R. Kaeding. 1991. Role of size, condition, and lipid content in the overwinter survival of age–0 Colorado squawfish. Transactions of the American Fisheries Society 120(3):346-353.

Trammell, M. A., E. P. Bergersen, and P. J. Martinez. 1993. Evaluation of an introduction of Colorado squawfish in a main stem impoundment on the White River, Colorado. The Southwestern Naturalist 38(4):362-369.

Trammell, M. A., and T. E. Chart. 1999a. Aspinall studies: Evaluation of nursery habitat availability and Colorado pikeminnow young of year habitat use, in the Colorado River, Utah, 1992-1996. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado.

Trammell, M. A., and T. E. Chart. 1999b. Flaming Gorge studies: Colorado pikeminnow young-of-year habitat use, Green River, Utah, 1992-1996. Upper Colorado River Endangered Fish Recovery Program, Denver, Colorado. Project Number FG-33.

Tyus, H. M. 1991. Ecology and management of Colorado squawfish. Pages 379-402 *in* J. E. Deacon, and W. L. Minckley, editors. Battle Against Extinction: Native Fish Management in the American West. The University of Arizona Press, Tucson, AZ.

Tyus, H. M. 1990. Potamodromy and reproduction of Colorado squawfish in the Green River Basin, Colorado and Utah. Transactions of the American Fisheries Society 119:1035-1047.

Tyus, H. M. 1986. Life strategies in the evolution of the Colorado squawfish (*Ptychocheilus lucius*). Great Basin Naturalist 46(4):656-661.

Tyus, H. M., and G. B. Haines. 1991. Distribution, habitat use, and growth of age-0 Colorado squawfish in the Green River Basin, Colorado and Utah. Transactions of the American Fisheries Society 120(1):79-89.

Tyus, H. M., and C. W. McAda. 1984. Migration, movements and habitat preferences of Colorado squawfish, *Ptychocheilus lucius*, in the Green, White and Yampa Rivers, Colorado and Utah. The Southwestern Naturalist 29(3):289-299.

Tyus, H. M., and W. L. Minckley. 1988. Migrating Mormon crickets, *Anabrus simplex* (Orthoptera: Tettigoniidae), as food for stream fishes. The Great Basin Naturalist 48(1):25-30.

Tyus, H. M., and N. J. Nikirk. 1990. Abundance, growth, and diet of channel catfish, *Ictalurus punctatus*, in the Green and Yampa rivers, Colorado and Utah. The Southwestern Naturalist 35(2):188-198.

Tyus, H. M., and J. F. Saunders. 2000. Nonnative fish control and endangered fish recovery: lessons from the Colorado River. Fisheries 25(9):17-24.

U.S. Bureau of Reclamation. 2018. Colorado River accounting and water use report: Arizona, California, and Nevada: calendar year 2017. U.S. Bureau of Reclamation, Boulder City, NV.

U.S. Bureau of Reclamation. 2017a. Quality of Water Colorado River Basin: Progress Report No. 25. U.S. Department of the Interior, Salt Lake City, UT.

U.S. Bureau of Reclamation. 2017b. Annual report of operations for Flaming Gorge Dam water year 2016. U.S. Bureau of Reclamation, Salt Lake City, UT.

U.S. Bureau of Reclamation. 2016a. SECURE Water Act Section 9503(c) -- Reclamation climate change and water. Department of the Interior, Denver, CO.

U.S. Bureau of Reclamation. 2016b. West-Wide Climate Risk Assessments: Hydroclimate Projections. Technical Memorandum No. 86-68210-2016-01.

U.S. Bureau of Reclamation. 2012a. Colorado River basin water supply and demand study. U.S. Bureau of Reclamation, Boulder City, NV.

U.S. Bureau of Reclamation. 2012b. Record of decision for the Aspinall Unit operations final environmental impact statement. U.S. Bureau of Reclamation, Salt Lake City, UT.

U.S. Bureau of Reclamation. 2007. Animas River fish passage and canal entrainment evaluation and recommendations. U.S. Bureau of Reclamation, Grand Junction, CO.

U.S. Bureau of Reclamation. 2006a. Fish protection at water diversions: a guide for planning and designing fish exclusion facilities. U.S. Bureau of Reclamation, Denver, CO. Water Resources Technical Publication.

U.S. Bureau of Reclamation. 2006b. Record of Decision: Operation of Flaming Gorge Dam Final Environmental Impact Statement.

U.S. Department of the Interior. 2016. Glen Canyon Dam long-term experimental and management plan final environmental impact statement. U.S. Department of the Interior, Washington, D.C.

U.S. Fish and Wildlife Service. 2020. Colorado pikeminnow (*Ptychocheilus lucius*) 5-Year status review: summary and evaluation. Upper Colorado River Endangered Fish Recovery Program, Lakewood, CO.

U.S. Fish and Wildlife Service. 2018a. Final biological opinion for San Juan River Navajo irrigation and rehabilitation improvement project--Fruitland-Cambridge and Hogback-Cudei Irrigation Units--and Colorado River salinity program habitat replacement. U.S. Fish and Wildlife Service, Albuquerque, NM.

U.S. Fish and Wildlife Service. 2018b. Revised Navajo Dam operating procedures for the 1999 San Juan River flow recommendations. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Draft Report.

U.S. Fish and Wildlife Service. 2018c. Species status assessment for the humpback chub (*Gila cypha*). U.S. Fish and Wildlife Service, Denver, CO.

U.S. Fish and Wildlife Service. 2016. USFWS species status assessment framework: an integrated analytical framework for conservation. Version 3.4 dated August 2016.

U.S. Fish and Wildlife Service. 2015. Final biological opinion for the Four Corners Power Plant and Navajo Mine energy project. U.S. Fish and Wildlife Service, Albuquerque, NM.

U.S. Fish and Wildlife Service. 2011. Colorado pikeminnow (*Ptychocheilus lucius*) 5-Year review: summary and evaluation. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

U.S. Fish and Wildlife Service. 2009. Final biological opinion for the Navajo-Gallup water supply project, U.S. Bureau of Reclamation, Durango, Colorado.

U.S. Fish and Wildlife Service. 2002. Colorado Pikeminnow (*Ptychocheilus lucius*) recovery goals: amendment and supplement to the Colorado squawfish recovery plan. Denver, CO.

U.S. Fish and Wildlife Service. 1999. Final programmatic biological opinion for Bureau of Reclamation's operations and depletions, other depletions, and funding and implementation of Recovery Program actions in the upper Colorado River above the confluence with the Gunnison River.

U.S. Fish and Wildlife Service. 1994. Endangered and threatened wildlife and plants; determination of critical habitat for the Colorado River endangered fishes: Razorback sucker, Colorado squawfish, humpback chub, and bonytail chub.

U.S. Fish and Wildlife Service. 1987. Interagency standardized monitoring program handbook. U.S. Fish and Wildlife Service, Grand Junction, CO.

Udall, B., and J. Overpeck. 2017. The twenty-first century Colorado River hot drought and implications for the future. Water Resources Research 53(3):2404-2418.

Uilenberg, B. R. 2005. Capital projects coordination. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number C-21 Annual Report.

Upper Colorado River Endangered Fish Recovery Program. in prep. A review of the Upper Colorado River Endangered Fish Recovery Program's recovery actions and endangered species response in the Colorado River: review of the 15-Mile Reach Programmatic Biological Opinion. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Draft Report.

Upper Colorado River Endangered Fish Recovery Program. 2016. November 28, 2016 management committee webinar summary.

Valdez, R. A. 2018. Data assimilation for the Colorado pikeminnow population viability analysis. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

Valdez, R. A., T. A. Francis, D. Elverud, and D. W. Ryden. 2017. Colorado pikeminnow PVA scenarios for the upper Colorado River subbasin. Upper Colorado River Endangered Fish Recovery Program, Denver, CO.

Valdez, R. A., P. Mangan, M. McInerny, and R. P. Smith. 1982. Tributary report: fishery investigations of the Gunnison and Dolores Rivers. U.S. Fish and Wildlife Service, Grand Junction, Colorado. Part 2: Field investigations, report #4.

Valdez, R. A., P. Mangan, R. P. Smith, and B. Nilson. 1982. Upper Colorado River investigation (Rifle, Colorado to Lake Powell, Utah). U.S. Fish and Wildlife Service, Salt Lake City, UT.

Valdez, R. A. and R. T. Muth. 2005. Ecology and conservation of native fish in the upper Colorado River basin. Pages 157-204 *in* J. N. Rinne, R. M. Hughes, and B. Calamusso, editors. Historical changes in large river fish assemblages of the Americas. American Fisheries Society, Symposium 45, Bethesda, Maryland.

Valdez, R. A., D. W. Speas, and D. M. Kubly. 2013. Benefits and risks of temperature modification at Glen Canyon Dam to aquatic resources of the Colorado River in Grand Canyon. U.S. Bureau of Reclamation, Upper Colorado Region, Salt Lake City, UT.

Van Haverbeke, D. R., D. M. Stone, M. J. Dodrill, K. L. Young, and M. J. Pillow. 2017. Population expansion of humpback chub in western Grand Canyon and hypothesized mechanisms. The Southwestern Naturalist 62(4):285-292.

van Steeter, M. M., and J. Pitlick. 1998. Geomorphology and endangered fish habitats of the upper Colorado River: 1. Historic changes in streamflow, sediment load, and channel morphology. Water Resources Research 34(2):287-302.

Vanicek, C. D. 1967. Ecological studies of native Green River fishes below Flaming Gorge Dam, 1964-1966. Doctoral dissertation. Utah State University, Logan, Utah.

Vanicek, C. D., and R. H. Kramer. 1969. Life history of the Colorado squawfish, *Ptychocheilus lucius*, and the Colorado chub, *Gila robusta*, in the Green River in Dinosaur National Monument, 1964–1966. Transactions of the American Fisheries Society 98(2):193-208.

Vanicek, C. D., R. H. Kramer, and D. R. Franklin. 1970. Distribution of Green River fishes in Utah and Colorado following closure of Flaming Gorge Dam. The Southwestern Naturalist 14(3):297-315.

Vejrík, L., I. Matějíčková, J. Seďa, P. Blabolil, T. Jůza, M. Vašek, D. Ricard, J. Matěna, J. Frouzová, J. Kubečka, M. Říha, and M. Čech. 2016. Who is who: an anomalous predator-prey role exchange between Cyprinids and Perch. PLoS One 11(6):e0156430.

Walker, A. E., J. C. Schmidt, and P. E. Grams. 2019. Twentieth century geomorphic changes of the lower Green River in Canyonlands National Park, Utah: an investigation of timing, magnitude, and process. National Park Service, Moab, UT. Study Number CANY-00163 Final Report.

Ward, D. L., and C. R. Figiel. 2013. Behaviors of southwestern native fishes in response to introduced catfish predators. Journal of Fish and Wildlife Management 4(2):307-315.

Webber, P. A., K. R. Bestgen, and G. B. Haines. 2013. Tributary spawning by endangered Colorado River basin fishes in the White River. North American Journal of Fisheries Management 33(6):1166-1171.

Weedman, D. A. 2004a. Results of the Salt River, Gleason Flat to Highway 288, fisheries survey May 17-21, 2004. Arizona Game and Fish Department, Phoenix, AZ.

Weedman, D. A. 2004b. Results of the Verde River, Childs to Sheep Bridge, fisheries survey June 14-17, 2004. Arizona Game and Fish Department, Phoenix, AZ.

Weissinger, R. H., B. R. Blackwell, K. Keteles, A. Battaglin William, and P. M. Bradley. 2018. Bioactive contaminants of emerging concern in National Park waters of the northern Colorado Plateau, USA. Science of the Total Environment 636:910-918.

Wick, E. J., D. L. Stoneburner, and J. A. Hawkins. 1983. Observations on the ecology of Colorado squawfish (*Ptychocheilus lucius*) in the Yampa River, Colorado, 1982. Water Resources Field Support Laboratory, National Park Service, Fort Collins, CO.

Woodhouse, C. A., G. T. Pederson, K. Morino, S. A. McAfee, and G. J. McCabe. 2016. Increasing influence of air temperature on upper Colorado River streamflow. Geophysical Research Letters 43(5):2174-2181.

Wydoski, R. S., and J. Hamill. 1991. Evolution of a cooperative recovery program for endangered fishes in the upper Colorado River basin. *in* W. L. Minckley, and J. E. Deacon, editors. Battle Against Extinction: Native Fish Management in the American West. University of Arizona Press, Flagstaff, Arizona.

Zeigler, M. P., and M. E. Ruhl. 2017. Small-bodied fishes monitoring in the San Juan River: 2016. San Juan River Basin Recovery Implementation Program, Albuquerque, NM.

Zeigler, M. P., A. L. Barkalow, J. M. Wick, M. E. Ruhl, and S. L. Durst. 2019. San Juan River Colorado pikeminnow adaptive management stocking plan. San Juan River Basin Recovery Implementation Program, Albuquerque, NM. Draft Report.

Zeigler, M. P., J. M. Wick, and M. E. Ruhl. 2018. Small-bodied fishes monitoring in the San Juan River: 2017. San Juan River Basin Recovery Implementation Program, Albuquerque, NM.

Zelasko, K. A., K. R. Bestgen, J. A. Hawkins, and G. C. White. 2016. Evaluation of a long-term predator removal program: abundance and population dynamics of invasive northern pike in the Yampa River, Colorado. Transactions of the American Fisheries Society 145(6):1153-1170.

Zelasko, K. A., K. R. Bestgen, J. A. Hawkins, and G. C. White. 2015. Abundance and population dynamics of invasive northern pike *Esox lucius*, Yampa River, Colorado, 2004-2010. Upper Colorado River Endangered Fish Recovery Program, Denver, CO. Project Number 161b Final Report.

APPENDICES

Appendix I. Nonnative fishes in the Colorado River Basin (adapted from Valdez and Muth 2005 and Minckley and Marsh 2009).

Species	Scientific Name
Atherinopsidae (silversides)	
Inland silverside	*Menidia beryllina*
Catostomidae (suckers)	
Utah sucker	*Catostomus ardens*
longnose sucker	*C. catostomus*
white sucker	*C. commersonii*
Rio Grande sucker	*C. plebeius*
buffalo	*Ictiobus spp.*
Centrarchidae (sunfish)	
rock bass	*Ambloplites rupestris*
warmouth	*Chaenobryttus gulosus*
green sunfish	*Lepomis cyanellus*
bluegill	*L. macrochirus*
redear sunfish	*L. microlophus*
smallmouth bass	*Micropterus dolomieu*
largemouth bass	*M. salmoides*
white crappie	*Pomoxis annularis*
black crappie	*P. nigromaculatus*
Characidae	
pacu	*Colossoma sp.*
Cichlidae (cichlids)	
blue tilapia	*Oreochromis aureus*
Mozambique moothbrooders	*O. mossabicus*
redbelly tilapia	*Tilapia zilli*
Clupeidae (herrings)	
gizzard shad	*Dorosoma cepedianum*
threadfin shad	*D. petenense*
Cyprinidae (minnows)	
goldfish	*Carassius auratus*
grass carp	*Ctenopharyngodon idella*
red shiner	*Cyprinella lutrensis*
common carp	*Cyprinus carpio*
Utah chub	*Gila atraria*
brassy minnow	*Hybognathus hankinsoni*
plains minnow	*H. placitus*
leatherside chub	*Lepidomeda sp.*
golden shiner	*Notemigonus crysoleucas*
sand shiner	*Notropis stramineus*
fathead minnow	*Pimephales promelas*
bullhead minnow	*P. vigilax*
longnose dace	*Rhinichthys cataractae*
redside shiner	*Richardsonius balteatus*
creek chub	*Semotilus atromaculatus*
Cyprinodontidae (killifish and pupfish)	
plains topminnow	*Fundulus sciadicus*
plains killifish	*F. zebrinus*
rainwater killifish	*Lucania parva*
Esocidae (pikes)	

Species	Scientific Name
northern pike	*Esox lucius*
Gadidae (cods)	
burbot	*Lota lota*
Gasterosteidae (sticklebacks)	
brook stickleback	*Culaea inconstans*
Ictaluridae (catfish)	
black bullhead	*Ameiurus melas*
yellow bullhead	*A. natalis*
brown bullhead	*A. nebulosus*
flathead catfish	*Pylodictis olivaris*
channel catfish	*Ictalurus punctatus*
Loricariidae	
vermiculated sailfin catfish	*Pterygoplichthys disjunctivus*
Moronidae (temperate basses)	
white bass	*Morone chrysops*
yellow bass	*M. mississippiensis*
striped bass	*M. saxatilis*
Percidae (perches)	
Iowa darter	*Etheostoma exile*
johnny darter	*E. nigrum*
yellow perch	*Perca flavescens*
walleye	*Sander vitreus*
Poeciliidae (livebearers)	
western mosquitofish	*Gambusia affinis*
sailfin molly	*Poecilia latipinna*
Salmonidae (trout and salmon)	
Yellowstone cutthroat trout	*Oncorhynchus clarkii*
greenback cutthroat trout	*O. c. stomias*
coho salmon	*O. kisutch*
rainbow trout	*O. mykiss*
kokanee	*O. nerka*
brown trout	*Salmo trutta*
brook trout	*Salvelinus fontinalis*
lake trout	*S. namaycush*

Appendix II. List of water bodies upstream of Colorado pikeminnow habitat containing the three most problematic nonnative fish species (adapted from Martinez et al. 2014).

Pond, Reservoir, or Water	State	Northern Pike	Smallmouth Bass	Walleye
Big Sandwash	UT		X	X
Bullock	UT			X
Catamount Lk.	CO	X		
Chapman	CO	X		
Connected Lk.	CO	X		
Crawford	CO	X		
Elkhead Res.	CO	X	X	
Flaming Gorge Res.	UT/WY		X	
Green Mtn Res.	CO	X		
Gypsum Ponds	CO		X	
Harvey Gap	CO	X	X	
Highline Lake	CO		X	
Juniata	CO		X	X
Kenney	CO	X		
Lake Powell	UT	X	X	X
Mack Mesa	CO	X		
McPhee	CO		X	X
Red Fleet	UT			X
Ridgway	CO		X	
Rifle Gap	CO	X	X	X
Rio Blanco	CO	X		
Stagecoach	CO	X	X	X
Starvation	UT		X	X
Vallecito	CO		X	
Williams Fork Res.	CO	X		
Wolford	CO	X		

Appendix III. Conversion of Mercury (Hg) concentrations in water to whole body burden in Colorado pikeminnow (mg/kg wet weight [ww]). Table adapted from USFWS (2015).

Total Hg in water (ug/L) BAF* = 53,000 (EPA 1997)	Colorado pikeminnow whole body Hg burden (mg/kg ww)	Total Hg in water (ug/L) BAF* = 53,000 (EPA 1997)	Colorado pikeminnow whole body Hg burden (mg/kg ww)	Total Hg in water (ug/L) BAF* = 53,000 (EPA 1997)	Colorado pikeminnow whole body Hg burden (mg/kg ww)	Total Hg in water (ug/L) BAF* = 53,000 (EPA 1997)	Colorado pikeminnow whole body Hg burden (mg/kg ww)
1.9E-12	1E-10	0.0283	1.5	0.07358	3.9	0.11887	6.3
1.9E-11	1E-09	0.03019	1.6	0.07547	4	0.12075	6.4
1.9E-10	1E-08	0.03208	1.7	0.07736	4.1	0.12264	6.5
1.9E-09	1E-07	0.03396	1.8	0.07925	4.2	0.12453	6.6
1.9E-08	1E-06	0.03585	1.9	0.08113	4.3	0.12642	6.7
1.9E-07	0.00001	0.03774	2	0.08302	4.4	0.1283	6.8
1.9E-06	0.0001	0.03962	2.1	0.08491	4.5	0.13019	6.9
0.00002	0.001	0.04151	2.2	0.08679	4.6	0.13208	7
0.00019	0.01	0.0434	2.3	0.08868	4.7	0.13396	7.1
0.00094	0.05	0.04528	2.4	0.09057	4.8	0.13585	7.2
0.00189	0.1	0.04717	2.5	0.09245	4.9	0.13774	7.3
0.00377	0.2	0.04906	2.6	0.09434	5	0.13962	7.4
0.00566	0.3	0.05094	2.7	0.09623	5.1	0.1415	7.5
0.00755	0.4	0.05283	2.8	0.09811	5.2	0.1434	7.6
0.00943	0.5	0.05472	2.9	0.1	5.3	0.1453	7.7
0.01132	0.6	0.0566	3	0.10189	5.4	0.1472	7.8
0.01321	0.7	0.05849	3.1	0.10377	5.5	0.1491	7.9
0.01509	0.8	0.06038	3.2	0.10566	5.6	0.1509	8
0.01698	0.9	0.06226	3.3	0.10755	5.7	0.1528	8.1
0.01887	1	0.06415	3.4	0.10943	5.8	0.1547	8.2
0.02075	1.1	0.06604	3.5	0.11132	5.9	0.1566	8.3
0.02264	1.2	0.06792	3.6	0.11321	6	0.1585	8.4
0.02453	1.3	0.06981	3.7	0.11509	6.1	0.1604	8.5
0.02642	1.4	0.0717	3.8	0.11698	6.2	0.1623	8.6

* Bioaccumulation Factor (BAF)

Appendix IV. Total dissolved mercury (Hg) in lower Colorado River mainstem water samples (USGS data provided 26 July 2018).

Sample date - gage 9423000 - Colorado River below Davis Dam, AZ/NV	Total Hg in water (ug/L)	Sample date - gage 9427520 - Colorado River below Parker Dam, AZ/CA	Total Hg in water (ug/L)	Sample date - gage 9429490 - Colorado River above Imperial Dam, AZ/CA	Total Hg in water (ug/L)
8/14/2014	< 0.005	2/22/2010	< 0.010	2/24/2010	< 0.010
11/20/2014	< 0.005	5/24/2010	< 0.010	5/20/2010	< 0.010
2/10/2015	< 0.005	8/19/2010	< 0.010	8/17/2010	< 0.010
6/9/2015	< 0.005	11/23/2010	< 0.005	11/29/2010	< 0.005
8/31/2016	< 0.005	2/15/2011	< 0.010	2/17/2011	< 0.005
12/28/2016	< 0.005	5/10/2011	< 0.005	5/12/2011	< 0.005
3/16/2017	< 0.005	8/23/2011	< 0.005	8/25/2011	< 0.005
5/31/2017	< 0.005	11/15/2011	< 0.005	11/22/2011	< 0.005
		2/14/2012	< 0.005	2/16/2012	< 0.005
		5/24/2012	< 0.005	5/7/2012	< 0.005
		8/23/2012	< 0.005	8/22/2012	< 0.005
		11/28/2012	< 0.005	11/29/2012	< 0.005
		2/20/2013	< 0.005	2/13/2013	< 0.005
		5/16/2013	< 0.005	5/29/2013	< 0.005
		8/12/2013	< 0.005	8/14/2013	< 0.005
		11/26/2013	< 0.005	11/21/2013	< 0.005
		2/26/2014	< 0.005	2/25/2014	< 0.005
		5/16/2014	< 0.005	5/14/2014	< 0.005
		8/27/2015	< 0.005	9/3/2015	< 0.005
		12/14/2015	< 0.005	12/17/2015	< 0.005
		2/17/2016	< 0.005	3/30/2016	< 0.005
		5/16/2016	< 0.005	6/22/2016	< 0.005

Appendix V. Flow recommendation targets for the Green River (Muth et al. 2000)

Location	Flow and Temperature Characteristics	Hydrologic Conditions and 2000 Flow and Temperature Recommendations				
		Wet (0–10% Exceedance)	Moderately Wet (10–30% Exceedance)	Average (30–70% Exceedance)	Moderately Dry (70–90% Exceedance)	Dry (90–100% Exceedance)
Reach 1 Flaming Gorge Dam to Yampa River	Peak Flow Magnitude	≥8,600 cfs (244 cubic meters per second [m^3/s])	≥4,600 cfs (130 m^3/s)	≥4,600 cfs (130 m^3/s)	≥4,600 cfs (130 m^3/s)	≥4,600 cfs (130 m^3/s)
	Peak Flow Duration	Dependent upon the amount of unregulated inflows into the Green River and the flows needed to achieve the recommended flows in Reaches 2 and 3.	Dependent upon the amount of unregulated inflows into the Green River and the flows needed to achieve the recommended flows in Reaches 2 and 3.	Dependent upon the amount of unregulated inflows into the Green River and the flows needed to achieve the recommended flows in Reaches 2 and 3.	Dependent upon the amount of unregulated inflows into the Green River and the flows needed to achieve the recommended flows in Reaches 2 and 3.	Dependent upon the amount of unregulated inflows into the Green River and the flows needed to achieve the recommended flows in Reaches 2 and 3.
	Base Flow Magnitude	1,800–2,700 cfs (50–60 m^3/s)	1,500–2,600 cfs (42–72 m^3/s)	800–2,200 cfs (23–62 m^3/s)	800–1,300 cfs (23–37 m^3/s)	800–1,000 cfs (23–28 m^3/s)
	Water Temperature Target	≥18 °C for 2-5 weeks in the beginning of the base flow period	≥18 °C for 2-5 weeks in the beginning of the base flow period	≥18 °C for 2-5 weeks in the beginning of the base flow period	≥18 °C for 2-5 weeks in the beginning of the base flow period	≥18 °C for 2-5 weeks in the beginning of the base flow period
Reach 2 Yampa River to White River	Peak Flow Magnitude	≥26,400 cfs (748 m^3/s)	≥20,300 cfs (575 m^3/s)	≥18,600 cfs (527 m^3/s) in 1 of 2 average years; ≥8,300 cfs (235 m^3/s) in other average years	≥8,300 cfs (235 m^3/s)	≥8,300 cfs (235 m^3/s)
	Peak Flow Duration	Flows greater than 22,700 cfs (643 m^3/s) should be maintained ≥ 2 weeks, and flows 18,600 cfs (527 m^3/s) for 4 weeks or more.	Flows greater than 18,600 cfs (527 m^3/s) should be maintained for ≥ 2 weeks.	Flows greater than 18,600 cfs (527 m^3/s) should be maintained for at least 2 weeks in at least 1 of 4 average years.	Flows greater than 8,300 cfs (235 m^3/s) should be maintained for at least 1 week.	Flows greater than 8,300 cfs (235 m^3/s) should be maintained for 2 days or more except in extremely dry years (98% exceedance).

Location	Flow and Temperature Characteristics	Hydrologic Conditions and 2000 Flow and Temperature Recommendations				
		Wet (0–10% Exceedance)	Moderately Wet (10–30% Exceedance)	Average (30–70% Exceedance)	Moderately Dry (70–90% Exceedance)	Dry (90–100% Exceedance)
Reach 2 Yampa River to White River	Base Flow Magnitude	2,800–3,000 cfs (79–85 m^3/s)	2,400–2,800 cfs (69–79 m^3/s)	1,500–2,400 cfs (43–67 m^3/s)	1,100–1,500 cfs (31–43 m^3/s)	900–1,100 cfs (26–31 m^3/s)
	Water Temperature Target	Green River should be no more than about 5°C colder than Yampa River at their confluence during summer base flow period.	Green River should be no more than about 5°C colder than Yampa River at their confluence during summer base flow period.	Green River should be no more than about 5°C colder than Yampa River at their confluence during summer base flow period.	Green River should be no more than about 5°C colder than Yampa River at their confluence during summer base flow period.	Green River should be no more than about 5°C colder than Yampa River at their confluence during summer base flow period.
Reach 3 White River to Colorado River	Peak Flow Magnitude	≥39,000 cfs (1,104 m^3/s)	≥24,000 cfs (680 m^3/s)	≥22,000 cfs9 (623 m^3/s) in 1 of 2 average years	≥8,300 cfs (235 m^3/s)	≥8,300 cfs (235 m^3/s)
	Peak Flow Duration	Flows >24,000 cfs (680 m^3/s) should be maintained for 2 weeks or more, and flows >22,000 cfs (623 m^3/s) for 4 weeks or more.	Flows >22,000 cfs (623 m^3/s) should be maintained for 2 weeks or more.	Flows >22,000 cfs (623 m^3/s) should be maintained for 2 weeks or more in at least 1 of 4 average years.	Flows >8,300 cfs (235 m^3/s) should be maintained for at least 1 week.	Flows >8,300 cfs (235 m^3/s) should be maintained for 2 days or more except in extremely dry years (98% exceedance).
	Base Flow Magnitude	3,200–4,700 cfs (92–133 m^3/s)	2,700–4,700 cfs (76–133 m^3/s)	1,800–4,200 cfs (52–119 m^3/s)	1,500–3,400 cfs (42–95 m^3/s)	1,300–2,600 cfs (32–72 m^3/s)

Appendix V. Green River flow recommendations (Muth et al. 2000) spring flow hydrologic classification achievements (2006–2016). Table from Reclamation 2017b.

Year	May 1st April-July Unregulated Inflow Forecast (1000 AF)	Spring Hydrologic Classification
2006	1,100	Average (Above Median)
2007	500	Moderately Dry
2008	820	Average (Below Median)
2009	890	Average (Below Median)
2010	515	Moderately Dry
2011	1,660	Moderately Wet
2012	630	Moderately Dry
2013	480	Moderately Dry
2014	1,320	Average (Above Median)
2015	570	Moderately Dry
2016	770	Moderately Dry

Green River flow objective achievements 2006–2016. Table adapted from Reclamation (2017c)

Spring peak flow objective	Hydrologic classification	Desired frequency of achievement	Achievement rate to date (cumulative frequency)
Reach 2: Peak ≥ 22,700 cfs for at least 2 weeks	Wet	10%	9%
Reach 2: Peak ≥ 18,600 cfs for at least 4 weeks	Wet	10%	9%
Reach 2: Peak ≥ 18,600 cfs for at least 2 weeks	Average (wet)	40%	18%
Reach 3: Peak ≥ 24,000 cfs for at least 2 weeks	Wet	10%	9%
Reach 3: Peak ≥ 22,000 cfs for at least 4 weeks	Wet	10%	9%
Reach 3: Peak ≥ 22,000 cfs for at least 2 weeks	Average (wet)	40%	9%

Appendix VI. Proposed changes to summer (base) flow Green River Flow recommendations by Bestgen and Hill (2016a) to support Colorado pikeminnow recruitment dynamics.

Hydrologic classification	Reach 2, Middle Green River flows		Reach 3, Lower Green River flows	
	2000 (Muth et al.)	Proposed	2000 (Muth et al.)	Proposed
Dry (10% of years, 0 to 10% exceedance)	26—31 m^3/s (900—1,100 cfs)	48—51 m^3/s (1,700—1,800 cfs)	37—74 m^3/s (1,300—2,600 cfs)	48—57 m^3/s (1,700—2,000 cfs)
Moderately dry (20% of years)	31—43 m^3/s (1,100—1,500 cfs)	51—57 m^3/s (1,800—2,000 cfs)	42—96 m^3/s (1,500—3,400 cfs)	57—65 m^3/s (2,000—2,300 cfs)
Average (40% of years)	43—68 m^3/s (1,500—2,400 cfs)	57—74 m^3/s (2,000—2,600 cfs)	51—119 m^3/s (1,800—4,200 cfs)	65—79 m^3/s (2,300—2,800 cfs)
Moderately wet (20% of years)	68—79 m^3/s (2,400—2,800 cfs)	62—79 m^3/s (2,200—2,800 cfs)	77—133 m^3/s (2,700—4,700 cfs)	74—91 m^3/s (2,600—3,200 cfs)
Wet (10% of years, 90 to 100% exceedance)	79—85 m^3/s (2,800—3,000 cfs)	68—85 m^3/s (2,400—3,000 cfs)	91—133 m^3/s (3,200—4,700 cfs)	79—108 m^3/s (2,800—3,800 cfs)

Appendix VII. Upper Colorado River recommended mean monthly flows (cfs) for the 15–Mile Reach

Rate*	25 percent	25 percent	30 percent	20 percent
Exceedance	25 percent	50 percent	80 percent	100 percent
January	1,630	1,630	1,630	1,240
February	1,630	1,630	1,630	1,240
March	1,630	1,630	1,630	1,240
April	3,210	2,440	2,260	1,860
May	10,720	9,380	7,710	7,260
June	15,660	14,250	11,350	6,850
July	7,060	5,370	3,150	1,480
August	1,630	1,630	1,240	810
September	1,630	1,630	1,240	810
October	1,630	1,630	1,240	810
November	1,630	1,630	1,630	1,240
December	1,630	1,630	1,630	1,240

* Rate is the percent of years recommended for identified flows based on winter snowpack levels. For example, in the wettest 25 percent of years, flows in June should average at least 15,660 cfs; stated another way, this recommendation should be met in 5 of every 20 years. During low–water years, June flows should average no less than 6,850 cfs, and such a minimum should occur at a rate of no more than 4 in 20 years (20 percent). Table from Osmundson et al. 1995.