Spring 2023

MS Environmental Biology Capstone Project

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Recommended Citation
Hennis, Ceiteag, "MS Environmental Biology Capstone Project" (2023). *Regis University Student Publications (comprehensive collection)*. 1092.
https://epublications.regis.edu/theses/1092

MS ENVIRONMENTAL BIOLOGY
CAPSTONE PROJECT

by

Ceiteag Helen Hennis

A Project Presented in Partial Fulfillment
of the Requirements for the Degree
Masters of Science
in Environmental Biology

REGIS UNIVERSITY
May, 2023

MS ENVIRONMENTAL BIOLOGY
CAPSTONE PROJECT

by

Ceiteag Helen Hennis

has been approved

May, 2023

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CHAPTER 1. LITERATURE REVIEW

Effects of altered flow regimes on the Colorado pikeminnow (*Ptychocheilus lucius*) and implications for its recovery

The construction of dams for the impoundment of reservoirs and hydroelectric power operations has well-known impacts on the natural biotic and abiotic dynamics of global riverine ecosystems. River regulation by dams can result in multiple stressors on aquatic organisms including altered downstream flow regimes, restricted migratory movement, sedimentation and siltation, channel simplification, and temperature alterations that are often cumulative in their effect on productivity, distribution, and habitat availability (Belarde, 2012; Bestgen et al., 2006; Bunn & Arthington, 2002; Minckley & Marsh, 2009; Schmutz & Moog, 2018). Downstream impacts of impoundments on hydrology noteworthily impact aquatic organisms and ecosystems (Schmutz & Moog, 2018). These negative impacts on the ecosystem are caused by the regulation and diminishing of seasonal flood pulses, where natural riverine ecosystems rely on extreme flood events for sediment and nutrient transport (Schmutz & Moog, 2018).

The Colorado River and its many tributaries originate from the snowpack of the Rocky Mountains and historically flowed to the Mexican Sea of Cortez (Minckley & Marsh, 2009; Summit, 2012). Historically, the Colorado River had seasonal high fluctuations in flows and sediment transport in spring and early summer, with monsoons increasing river discharge intermittently during the summer in the lower basin (Minckley & Marsh, 2009; Summit, 2012). Likewise, sediment load was high and discharged approximately 85 million tons of sediment basin wide (Pontius, 1997). Cyclical fluctuations of the river were characterized by major floods from melted snowpack to long periods of low flow (O'Connor et al., 1994; Summit, 2012). These seasonal fluctuations in flow and sediment greatly influenced floodplains, riparian areas, and vegetation along its banks (Minckley & Marsh, 2009; Pontius, 1997). The Colorado River features many specialized fish species that evolved along with the river's natural seasonal variations, once containing the world's largest number of endemic fish species (Minckley & Marsh, 2009; Summit, 2012). The vast size and diversity of habitats within the Colorado River provided ample resources to sustain these endemic fish species (Minckley & Marsh, 2009).

The Colorado River presently is heavily impacted by dams which pose diverse challenges to fisheries management (Belarde, 2012; Bestgen et al., 2006; Minckley & Marsh, 2009; Osmundson et al., 2002). Native Americans and European settlers influenced the Colorado River through water diversion, however, it was not until the 20th century that humans started creating an unnatural system out of the Colorado River (Minckley & Marsh, 2009). Between the 1930s-1980s, reservoirs were built via dam impoundment, changing the river from its free-flowing lotic status into a series of disjunct lentic habitats (Minckley & Marsh, 2009; Osmundson, 2011). These reservoirs store runoff from snowmelt in the spring for the generation of power and irrigation purposes, further disrupting the natural flow over time (Van Steeter & Pitlick, 1998). Dams continue to divert water from the Upper Colorado River to other drainages along the east slope of the Continental Divide in Colorado, resulting in decreased downstream habitat for fish species (Osmundson et al., 2002; Woodling, 1985). Because of dams, the Colorado River does not meet the Sea of Cortez most years as it is diverted for human use or evaporated from the surface of reservoirs (Minckley & Marsh, 2009). Growing demands for water from population centers in the Western U.S. and reductions in water availability due to climate change are likely to exacerbate these issues in the coming years (Haddeland et al., 2014).

The Colorado River basin is home to the endemic Colorado pikeminnow (*Ptychocheilus lucius*), a migratory, slow-growing fish species whose distribution and abundance have declined substantially in part due to the construction and operation of dams disrupting the natural variable flow of the system (Belarde, 2012; Bestgen et al., 2006; Bestgen et al., 2020; Franssen et al., 2007; Minckley & Marsh, 2009; Osmundson et al., 2002; Woodling, 1985). Colorado pikeminnow were once abundant throughout the Colorado River, especially prevalent within the Lower Colorado River basin (Minckley, 1991). The species is now found only in the Upper Colorado River basin (Upper basin) upstream of Lake Powell (Glen Canyon Dam), with a large persistent population found in the Green River subbasin and smaller stocked populations found in the Colorado River and San Juan River subbasins (Gilpin, 1992; Minckley & Marsh, 2009; Osmundson & White, 2017) (Figure 1). The Colorado pikeminnow is vulnerable to habitat degradation from water depletions and hydroelectric operations due to the species' changing habitat needs for its different life stages (Belarde, 2012; Osmundson et al., 2002). Habitat degradation also increases this endangered' species' susceptibility to environmental stochasticity and catastrophes (Osmundson, 2011). Because of their continued decline and federal and state endangered status, the Colorado pikeminnow is one of the four species that are the focus of species-recovery efforts (Upper Colorado River Endangered Fish Recovery Program).

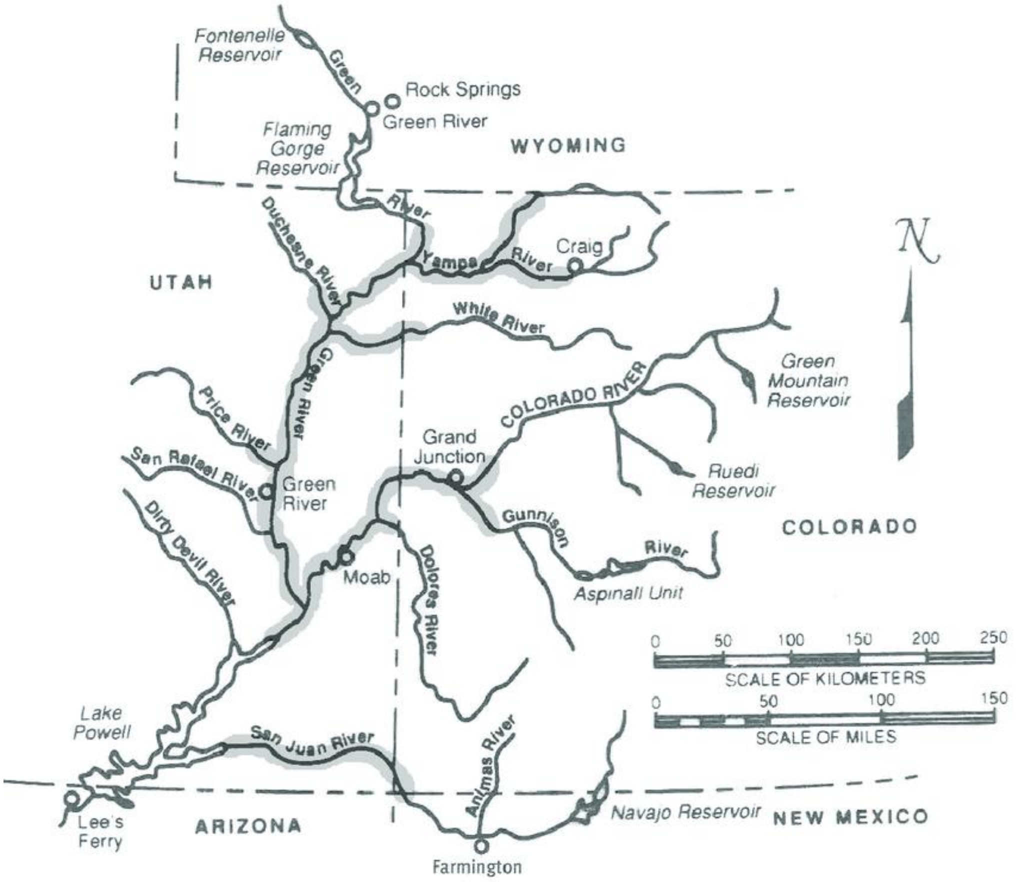

Figure 1. The present-day distribution of Colorado pikeminnow in the Upper basin (Valdez & Muth, 2005). Shaded areas represent the areas where the species is currently limited. Major reservoirs limiting their distribution include Lake Powell, Navajo Reservoir, and Flaming Gorge Reservoir.

The Colorado pikeminnow has been studied for more than 40 years and there is an abundance of information available on the causes of its decline. Osmundson & White (2017) found that recovery efforts, including river regulation, over the past 30+ years have not sufficiently addressed threats to the recruitment of the species. This review will (1) focus on the effects of altered flow and subsequent temperature regimes caused by dam operations on the Colorado pikeminnow throughout the Colorado River basin and (2) identify potential obstacles to recovery caused by climate change including increased water usage. Flow regime is an important factor that influences Colorado pikeminnow persistence and the ichthyofaunal assemblage of which it is a part, and disturbances to this regime affect both the species and its ecosystem (Osmundson et al., 2002). The implications of this literature review may also apply to other endangered “big river” fish species endemic to the Colorado River Basin, such as the Humpback chub (*Gila cypha),* Bonytail chub (*Gila elegans*), and Razorback sucker (*Xyrauchen texanus*), as these species also are managed by joint recovery effort (Upper Colorado River Endangered Species Recovery Program).

In general, dam releases are often drawn from the bottom of reservoirs (the hypolimnetic layer) releasing cold water downstream and can negatively affect early life stages of Colorado pikeminnow (Dibble et al., 2021; Grand et al., 2006; Osmundson, 2011). High within-day flow fluctuations are expected to have negative effects on backwater nursery temperature, decreasing the suitability of these habitats (Grand et al., 2006). Hypolimnetic releases also have a negative effect on early life stages by affecting spawning efforts and survival of juvenile Colorado pikeminnow (Haynes et al., 1984; Marsh, 1985; Minckley & Marsh, 2009). The optimal water temperature for pikeminnow spawning is between 68-72ºF in early to mid-summer (Haynes et al., 1982; Minckley & Marsh, 2009). Cold water releases may eliminate spawning sites when low temperatures prohibit fertilization from even occurring (Woodling, 1985). With an optimal temperature for egg development and hatching (68°F), changes in water temperatures from cold water releases can further alter development success (Marsh, 1985). This is especially important for this highly migratory species since they exhibit precise site fidelity to spawning sites (Minckley & Marsh, 2009). In addition to spawning constraints, hypolimnetic releases from dams impact the growth rate of larval and juvenile Colorado pikeminnow (Kaeding & Osmundson, 1988). Limited warmwater habitat in the Upper basin is exacerbated by cold water releases, which have been found to result in more recent trends of slow growth rates in this species (Kaeding & Osmundson, 1988). This is significant as slower growth is expected to result in increased susceptibility of juvenile fish to predation and decreased reproductive potential throughout their lifespan (Minckley & Marsh, 2009). Taken together, the effects of cold-water releases on early life stages of pikeminnow inhibit their growth and survival and is a major hindrance to the recovery of the species (Grand et al., 2006; Osmundson, 2011).

Hypolimnetic releases also have a negative effect on the availability of adult Colorado pikeminnow habitat (Dibble et al., 2021; Osmundson, 2011). Colorado pikeminnows have a life history strategy wherein adults migrate upstream to find greater prey densities with the tradeoff of lower-than-optimal water temperatures (Osmundson, 2011). In sections of the Upper basin downstream of dams, upstream reservoir storage has reduced the frequency and magnitude of flows that produce important warm off-channel habitats used for seasonal thermal refugia in adults (McAda, 2003; Osmundson, 2011; Van Steeter & Pitlick, 1998). Years without these upstream thermal refugia have contributed to temperature-mediated range reduction of Colorado pikeminnow, restricting them to warmer downstream areas where forage fish abundance is lowest (Osmundson, 2011; Osmundson et al., 2002). As an example, the Gunnison River historically provided more ideal temperatures and forage for pikeminnow before the construction of the Aspinall Unit dams (Osmundson, 2011). Furthermore, hypolimnetic releases from large dams hinder recolonization efforts upstream of barriers and displace Colorado pikeminnow through the cooling of summer water temperatures (Osmundson, 2011). Hinderance of recolonization efforts and range reduction due to cold water releases are factors that lead to the further decline of this species.

River flow regulation affects sedimentation rates, turbidity, and the extent of riparian areas, all important aquatic habitat features. Due to the operation of major dams in the Upper basin, the median peak flow upstream of dams and spring seasonal discharges have declined causing fine sediment to accumulate on the riverbed and channel substrate (Osmundson et al., 2002; Osmundson & White, 2017). This has narrowed the mainstem and backwater habitat channel areas, resulting in a decline in habitat for all life stages of Colorado pikeminnow (Pitlick & Cress, 2000; Van Steeter & Pitlick, 1998). Occurrence of peak flows sufficient to mobilize and redistribute cobble and flush fine sediments has decreased within the range of Colorado pikeminnow, impacting substrate availability for egg deposition and incubation during spawning events (Osmundson et al., 2002). In addition, altered flows have been shown to decrease turbidity, which is an important factor in reducing predation on young Colorado pikeminnows (Farrington et al., 2015). Lastly, studies have found that flattening of the annual hydrograph has been associated with vegetation encroachment in the river channel of the Colorado River, further reducing habitat suitability for adults (Sankey et al., 2015). Therefore, natural flow regime restoration is necessary for restoring sediment transport and maintaining intact populations of Colorado pikeminnow (Osmundson et al., 2002).

Many studies have considered the effects of river regulation on the Colorado pikeminnow’s food sources (Franssen & Durst, 2014; Franssen et al., 2007; Osmundson et al., 2002). Flows high enough to mobilize accumulated fine sediment on the riverbed have occurred at a lower frequency over the past 50 years, resulting in extended periods of lowered benthic biomass and reduced capacity of the system to support adult Colorado pikeminnow’s prey species (Osmundson et al., 2002). Likewise, peak flows and reservoir discharge negatively affect the production and availability of prey species (Franssen & Durst, 2014; Franssen et al., 2007). The presence of non-native species in the Upper Basin further complicates this issue (Franssen et al., 2007). Artificial flow regimes have been shown to cause decreased survival of native prey fishes of Colorado pikeminnow and these populations are further hindered by competition with non-native fishes for prey fish (Franssen et al., 2007). To combat this issue, flow management of spring dam discharges in the San Juan River basin towards a high spring discharge can be used to increase prey availability for Colorado pikeminnow (Franssen & Durst, 2014). Because discharge from dams regulates the abundance of Colorado pikeminnow's prey, this can be an important management tool to increase prey availability (Franssen et al., 2007).

Altered hydrology also influences spawning and spawning migration success of the Colorado pikeminnow, which evolved under large spring-flow conditions (Franssen et al., 2007; Haynes et al., 1984). Protecting spawning areas for reproductive success is important for the management of this species (Bestgen & Hill, 2016; Clark Barkalow et al., 2021). Interruptions to this natural spring flow pulse by dams are expected to negatively impact the reproduction of this species and the suitability of spawning habitat (Bestgen & Hill, 2016; Bestgen et al., 1998). Many studies have found that when flows are too low, emergence of larvae may be inhibited and larvae may not be carried downstream to suitable nursery habitat (Bestgen & Hill, 2016; Bestgen et al., 1998). The effect on spawning is of utmost importance since a high frequency of weak recruitment years reduces the long-term viability of the species (Osmundson & White, 2017). Thus, accurate and precise knowledge of spawning timing is important for management of dam releases to promote spawning in Colorado pikeminnow (Clark Barkalow et al., 2021).

Another identified cause of the decline in Colorado pikeminnow is the lack of nursery habitat available for juveniles (Bestgen et al., 2020). Warm backwater areas off the main river channel that are shallow and have low flow velocities are important nursery habitats for the growth of young life stages of pikeminnow (Bestgen & Hill, 2016; Bestgen & Williams, 1994; Haynes & Muth, 1982; Minckley & Marsh, 2009; Schmidt & Brim Box, 2004). Unnatural flow regimes have lowered summer base flows of the Upper basin, which has decreased backwater nursery habitats (Woodling, 1985). Studies on flows released from the Flaming Gorge Dam (FGD) in the Green River tributary of the Colorado River basin have shown that the magnitude of flows, timing of reservoir release, and mean daily water temperatures are major contributors to suitable habitat creation for larval survival (Bestgen et al., 2020). For example, high releases from the FGD during time of larval drift increase the proportion of larval pikeminnow displaced into adverse river environments (Schmidt & Brim Box, 2004). Management of base flows from the FGD for juvenile survival to the adult stage is one emphasis of the Recovery Program and current studies have been implemented to evaluate experimental base flows on success of juveniles (Bestgen et al., 2020). Nursery habitat protection is important for conservation and recovery efforts of this species due to the importance of early life stages for future population abundance (Bestgen et al., 2020).

Dam-induced physical alterations of flow often have a multiplicative interactive effect on Colorado pikeminnow in the presence of non-native predatory fish species (Belarde, 2012), which are generally less affected by altered flow fluctuations (Bestgen et al., 2020). Increases in non-native fishes have been associated with physical alterations of the Colorado River basin through reservoir impoundment and stabilization of flow regimes (Bestgen & Hills, 2016; Minckley & Marsh, 2009). Reservoir management that decreases spring discharge and increases summer flow stability facilitates nonnative fish populations (Propst & Gido, 2004). The decline in base flow in the Green River by 40% from the 1980s has resulted in establishment of abundant red shiner (*Cyprinella lutrensis*), a potential competitor and predator of juvenile Colorado pikeminnow (Bestgen & Hill, 2016). The presence of non-native red shiner has a significant negative impact on juvenile pikeminnow survival and adds compounding stress in experiments with high flow fluctuations (Belarde, 2012).

The arid Southwest is likely to see more development and increased water demand of the Colorado River system for agriculture and human consumption in large population centers in the Western US and Mexico, threatening its ecological integrity (Dibble et al., 2021; Minckley & Marsh, 2009; Pennock et al., 2022). Renegotiations for water allocation have already started occurring amongst stakeholders and will have impacts on native fish assemblages, including the Colorado pikeminnow (Dibble et al., 2021). Voluntary release of fish flows, those mimicking natural flow regimes, by dam operators may diminish over time due to increased water demands (Osmundson & White, 2017). The Recovery Program is dependent on recovery being achieved while also allowing for water development within the Colorado River basin, posing a difficult challenge for managers (Osmundson & White, 2017; Pennock et al., 2022). Storage decisions in the future should consider their impacts on native fish species (Dibble et al., 2021). Prioritization of storage in select reservoirs over others will positively affect native fish species, including the Colorado pikeminnow, and mitigate the spread of non-native species (Dibble et al., 2021). Furthermore, protection of rivers within the Colorado River system with natural flow regimes for conservation will be beneficial for the recovery of Colorado pikeminnow and other endangered species (Pennock et al., 2022).

Climate change also threatens flow regimes and water temperatures in the Colorado River basin (Garofalo, 2019). Studies have shown a warming trend in the Upper basin (Osmundson, 2011), and projected declines in river discharge from 10-20% by 2050 (McCabe & Wolock, 2007). Low base flows seen in the Green River between 2000-2012 have been attributed to widespread drought in the Upper basin (Bestgen & Hill, 2016). An example from the Lower

Colorado River basin found that recent drought trends and a declining Lake Powell reservoir have resulted in the formation of waterfalls, potentially creating barriers to upstream movement of stocked Colorado pikeminnow in the San Juan River (Cathcart et al., 2018). Warming temperatures may result in range expansion of Colorado pikeminnow in the Upper basin, however, this may be offset by climate change's negative effects of reduced flows on their habitat (Osmundson, 2011). Therefore, there are potential positive and negative repercussions of climate change on this species.

The findings presented in this literature review indicate the need for changes in flows throughout the Upper basin toward a natural flow paradigm. Restoring the Upper basin's aquatic community to a more natural state is important for the recovery of Colorado pikeminnow. Although reservoir releases are currently managed to mimic natural flow regime in the Colorado River basin, spring peak flows are still decreasing and summer flows are much higher than historical records, affecting the recovery of the species and proliferation of non-natives (Franssen et al., 2007). More research is needed to understand how adaptive management can maintain natural flow patterns and how this will affect Colorado pikeminnow, especially in the presence of nonnative fishes and climate change. Moreover, it is expected that as human population increases, water usage will increase, decreasing the ability of dam operators to mimic natural flows in the Colorado River basin (Osmundson & White, 2017). Therefore, other routes of restoration may need to be prioritized to restore temperature regimes, habitat suitability, and prey availability for the Colorado pikeminnow. Lastly, as many of the studies in this review cover other endangered species native to the Colorado River, similar issues of altered flow regimes should be addressed for these species as well.

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CHAPTER 2. GRANT PROPOSAL

Creating and testing the efficacy of a habitat scorecard for juvenile Colorado pikeminnow (*Ptychocheilus lucius*)

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November 30, 2022

Section 1: Abstract

Assessing wildlife habitat quality is essential for evaluating wildlife restoration activities by wildlife managers. Personnel with Colorado Parks and Wildlife’s Wetland Wildlife Conservation Program utilize habitat scorecards to document the need and success of wetland restoration projects for wetland species. Habitat scorecards have been created and used for Colorado River endemic fish species, such as the bonytail chub and bluehead sucker. There is a need to create habitat scorecards for a similarly threatened endemic species, the Colorado pikeminnow (Ptychocheilus lucius), a Tier 1 fish species of concern and “flagship species” for the recovery of endangered species. I plan to create a habitat scorecard to expand on those developed by Colorado Parks and Wildlife (CPW) for juvenile Colorado pikeminnow and assess the ability of the scorecard to predict the use of habitats in the San Juan River. I will identify key habitat variables and the relative value of habitat conditions found in their range to create the scorecard. I will test the accuracy of the scorecard in sites along the San Juan River where Colorado pikeminnow has been reintroduced. This scorecard will be helpful in the assessment of restoration practices by providing a uniform measure of restoration success.

Section 2: Introduction

Objective:

I propose to create a habitat scorecard to expand on those developed by Colorado Parks and Wildlife (CPW) for juvenile Colorado pikeminnow (*Ptychocheilus lucius*). I will also assess how well the scorecard predicts the relative use of juvenile Colorado pikeminnow in the San Juan River.

Literature Review:

Assessing wildlife habitat quality is essential for evaluating wildlife restoration activities by wildlife managers (Behney, 2020). In Colorado, DNR personnel with the Wetland Wildlife Conservation Program use a simple scorecard to document both the need and success of wetland restoration projects for habitats used by many fish species, such as bonytail chub, bluehead sucker, Rio Grande sucker, and Rio Grande chub (Colorado Wetland Program Plan). These scorecards were created by the Colorado Natural Heritage Program for use on many priority wetland-dependent species based on a tier system, with Tier 1 being the highest priority (CPW, 2015). These scorecards consist of multiple-choice questions focusing on key habitat variables unique to each species (Figure 2). Each of the questions is weighted by their importance in predicting habitat quality. The objective of the scorecards is to predict habitat quality for each species while also being usable by personnel with varying levels of expertise (Behney, 2020). The total weight of each question is calculated based on an extensive literature review and expert input (Behney, 2020).

The future goals of the Colorado Wetland Program Plan are to continue developing wildlife priority species scorecards and tests for standardization of these habitat assessments (Marshall & Lemly, 2020). Habitat scorecards have been created and utilized for two Colorado River endemic fish species, the bonytail chub (Figure 2) and bluehead sucker, both Tier 1 fish species (CPW, 2015). There is a need to create habitat scorecards for a similarly threatened endemic species, the Colorado pikeminnow (*Ptychocheilus lucius*), another Tier 1 fish species (CPW, 2015). The Colorado pikeminnow is federally endangered, previously ranging throughout the Colorado River basin, and is threatened by streamflow regulation, habitat modification, nonnative fish species, and pollutants (Minckley & Marsh, 2009; USFWS, 2002; Woodling, 1985). Although the State Wildlife Action Plan has designated this species as having an urgency of conservation action and in a declining trend (CPW, 2015), no habitat scorecard has been created. Much is known about the habitat requirements of the Colorado pikeminnow due to over four decades of research on this species and its importance as a regional “flagship species” for the recovery of endangered species, making it a suitable candidate for the development of a habitat scorecard (Minckley & Deacon, 1991; Minckley & Marsh, 2009).

This study will focus on habitat variables and habitat conditions concerning juvenile and young-of-year Colorado pikeminnow. This is because early-life mortality rates are significant in Colorado pikeminnow, and each year class’s survival and recruitment are reflected in the entire population over time (Kaeding & Osmundson, 1998; USFWS, 2002). A habitat scorecard for juveniles is practicable because early life stages have specific optimal environments for growth and survival, i.e., warm backwater nurseries and river channels (McAda & Ryel, 1999; Muth et al., 2000). They also prefer silt-and-sand bottoms with little to no current and have specific temperature tolerances and prey items (Bulkley et al., 1982; Holden & Wick, 1982; Minckley & Marsh, 2009; Woodling, 1985). Lastly, the threat of non-native predatory fish species, such as red shiner (*Cyprinella lutrensis*), on juveniles is substantial and threatens their survival (Bestgen & Byers, 2006; Minckley & Marsh, 2009). Since a range of optimal to suboptimal conditions are known for juvenile Colorado pikeminnow, a habitat scorecard may be used to determine the likelihood of key life stage benchmarks such as overwintering survival (McAda & Ryel, 1999; USFWS, 2002). In addition, young Colorado pikeminnow remains in nursery areas for 2-4 years before moving upstream, making a habitat scorecard for juveniles useful for the entire life stage (Osmundson et al., 1998).

The San Juan River, a major tributary of the Colorado River basin, will be the focus of the habitat sampling in this study. Efforts to reestablish Colorado pikeminnow through stocking hatchery-reared juveniles have occurred yearly in the San Juan River since 1996 (Durst & Franssen, 2014; Ryden & Alm, 1996; USFWS, 2002). The decline of Colorado pikeminnow in the San Juan River has been attributed to flow modifications due to the Navajo and Glen Canyon dams, fish barriers, thermal stressors, channel simplification, and the introduction of non-native species (Farrington et al., 2015). The current population in the San Juan River consists primarily of juvenile, stocked individuals with rare adults (Durst & Franssen, 2014). Since stocked individuals rarely live beyond three years in the San Juan River (Durst & Franssen, 2014), habitat scorecard assessment may identify potential issues with the availability of suitable habitat throughout this river. Habitat assessments in this area may also aid in prioritizing management actions to restore adequate habitat and decrease predation in this species (USFWS, 2002). Information gathered from this study will benefit the San Juan River Basin Recovery Implementation Program (SJRIP, 1995).

Anticipated Value:

Creating a comprehensive habitat scorecard and evaluating its efficacy for juvenile Colorado pikeminnow will be beneficial for assessing restoration practices by creating a uniform measure of restoration success and future restoration plans.

Questions (Q) and Hypotheses (H):

Q1: What key habitat variables will be needed to assess juvenile Colorado pikeminnow habitat?

H1. The comprehensive habitat scorecard will include information on stream features, substrate, prey availability, habitat connectivity, hydrology, presence of non-native predatory fish, and water temperature.

Q2. What conditions of each key habitat variable will be most valuable for juvenile Colorado pikeminnow habitat restoration?

H2. A comprehensive literature review of Colorado pikeminnow habitat requirements will elucidate the relative value of habitat conditions found in each habitat variable.

Section 3: Methods

Study Sites:

Sampling will be conducted throughout portions of the Lower and Middle San Juan River currently inhabited by Colorado pikeminnow (Figure 1) (USFWS, 2002). The study area was selected to ensure that the population of Colorado pikeminnow sampled is not restricted by habitat fragmentation. The study area extends downstream from Shiprock, New Mexico (river miles 147.9) to the Lake Powell inflow in the Glen Canyon National Recreation Area of Utah. Habitat and fish sampling will be conducted in suitable backwater areas off the main river channel. These sites will be accessed using a 16-foot inflatable raft that will transport researchers and collection gear.

Creating the Scorecard:

To create the Colorado pikeminnow habitat scorecard, an extensive literature review will be completed to understand the preferred habitat conditions of young-of-year and juvenile Colorado pikeminnow. Habitat variables that will be researched will be stream features, such as the availability and depth of flooded backwaters, bottom substrate, aquatic insect and crustacean availability, connectivity of habitats to different life cycles, hydrology and dam presence, presence of non-native predatory fish, and water temperature. This review will also investigate the conditions for each habitat variable within their range. Each key habitat variable on the scorecard will be given approximately three conditions identified from best to worst. The relative weight of each possible condition will be given a score based on how it represents habitat quality. The habitat’s conditions will equal a total of one hundred possible points.

Fish & Habitat Sampling:

To test the ability of the assessment to predict the density of juvenile Colorado pikeminnow, the habitat scorecard will be used to evaluate ten random sample sites along the Lower and Middle San Juan River. This sampling will occur in the fall season to assess backwater habitat quality while juvenile Colorado pikeminnow increase their forage range. Each sample site's habitat will receive a score out of 100, which will be used to compare the relative habitat suitability of each site. After habitat assessments are completed, seine hauls will be conducted to get a relative abundance of young-of-year and juvenile Colorado pikeminnow at each site. Seining surveys have been proven to be the best sampling protocol for collecting juveniles in the San Juan River (Farrington et al., 2015). Seining effort in each sampling area will be equal to compare relative abundances between sites. Each fish collected will be measured and weighed to determine the condition and age of the juveniles.

Data Analysis:

To evaluate the relationship between the intensity of Colorado pikeminnow use of sites and habitat assessment score, a linear mixed-effect model will be done in R (R Core Team 2021) using the package lme4 (Bates et al., 2015) to model fish abundance against habitat quality scores. This analysis will determine the habitat scorecard's effectiveness in predicting the relative use of juveniles. The site will be used as a random effect in all models. For analyses, changes in AICc values and model weights will be used to compare models.

Negative Consequences:

Negative consequences will be minimal during this study. Through a scientific collecting permit, I would obtain permission to catch and release any captured Colorado pikeminnow from Colorado Parks & Wildlife. Because researchers will be seining, fish sampling may cause unintended death to juvenile Colorado pikeminnow. In general, seining may also contribute to the bycatch of unintended species. Safety precautions will be taken to eliminate bycatch and death to Colorado pikeminnow. Habitat sampling will represent minimal impacts on the land.

Project Schedule:

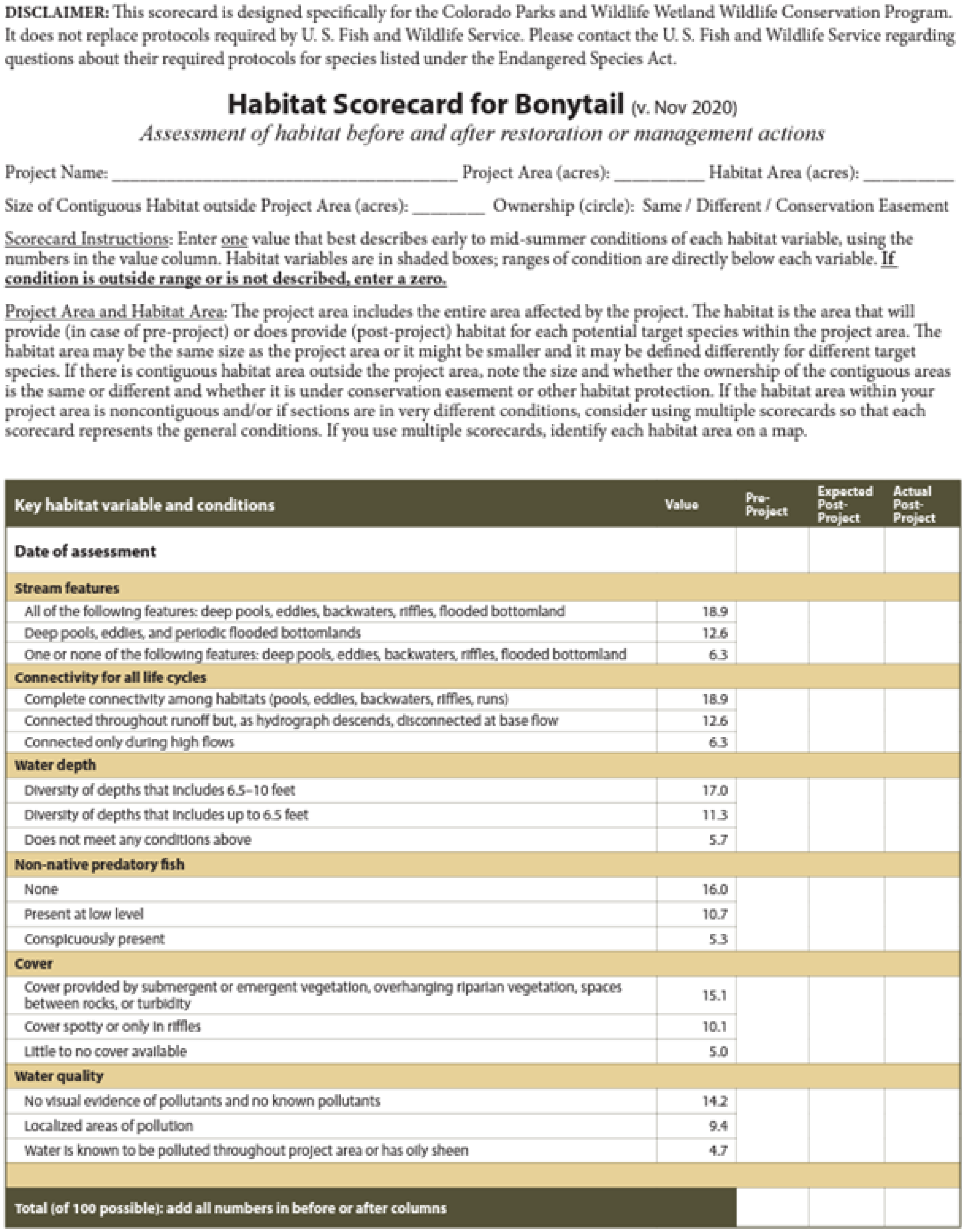
Dates	Activities	Deliverables
May-August 2023	Extensive literature review and creation of Habitat Scorecard	Habitat Scorecard
August 2023	Preparation of sampling equipment and housing, training of field technicians	Readiness for the sampling period, GPS coordinates of sampling areas
September 2023	Habitat and Fish Sampling in the San Juan River	Raw data from surveys
December-January 2023	Complete data analysis	Analyses for report
January-April 2023	Draft, edit, and complete the report	Final report

Section 4: Budget

	Justification	Cost, unit	Quantity	Total Cost
Field Survey Technician Stipend (2)	For two technicians to assist the researcher	$12.56/hour	100	$1,256
Gas	1 round trip from Denver to Utah and 5 round trips from the hotel to sampling sites	$3.46/gal	50	$173
Housing	Housing for field crew for one week	$150	7	$1050
Seine	Fish sampling gear	$120	1	$120
Measuring Board	Fish sampling gear	$35	1	$35
Scale	Fish sampling gear	$100	1	$100
Garmin GPSMAP 64X Handheld GPS	GPS locations for sampling sites	$300	1	$300
Inflatable raft	Access to sampling sites	$1500	1	$1500
Total Resource Expenditures				$4534

Appendix

Figure 1. Distribution of wild Colorado pikeminnow throughout the Colorado River Basin (retrieved from USFWS, 2002). Bolded areas represent the current distribution of the species.



DISCLAIMER: This scorecard is designed specifically for the Colorado Parks and Wildlife Wetland Wildlife Conservation Program. It does not replace protocols required by U. S. Fish and Wildlife Service. Please contact the U. S. Fish and Wildlife Service regarding questions about their required protocols for species listed under the Endangered Species Act.

Habitat Scorecard for Bonytail (v. Nov 2020)

Assessment of habitat before and after restoration or management actions

Project Name: ______________________________ Project Area (acres): _________ Habitat Area (acres): _________

Size of Contiguous Habitat outside Project Area (acres): _______ Ownership (circle): Same / Different / Conservation Easement

Scorecard Instructions: Enter one value that best describes early to mid-summer conditions of each habitat variable, using the numbers in the value column. Habitat variables are in shaded boxes; ranges of condition are directly below each variable. **If condition is outside range or is not described, enter a zero.**

Project Area and Habitat Area: The project area includes the entire area affected by the project. The habitat is the area that will provide (in case of pre-project) or does provide (post-project) habitat for each potential target species within the project area. The habitat area may be the same size as the project area or it might be smaller and it may be defined differently for different target species. If there is contiguous habitat area outside the project area, note the size and whether the ownership of the contiguous areas is the same or different and whether it is under conservation easement or other habitat protection. If the habitat area within your project area is noncontiguous and/or if sections are in very different conditions, consider using multiple scorecards so that each scorecard represents the general conditions. If you use multiple scorecards, identify each habitat area on a map.

Key habitat variable and conditions	Value	Pre-Project	Expected Post-Project	Actual Post-Project
Date of assessment				
Stream features				
All of the following features: deep pools, eddies, backwaters, riffles, flooded bottomland	18.9			
Deep pools, eddies, and periodic flooded bottomlands	12.6			
One or none of the following features: deep pools, eddies, backwaters, riffles, flooded bottomland	6.3			
Connectivity for all life cycles				
Complete connectivity among habitats (pools, eddies, backwaters, riffles, runs)	18.9			
Connected throughout runoff but, as hydrograph descends, disconnected at base flow	12.6			
Connected only during high flows	6.3			
Water depth				
Diversity of depths that includes 6.5–10 feet	17.0			
Diversity of depths that includes up to 6.5 feet	11.3			
Does not meet any conditions above	5.7			
Non-native predatory fish				
None	16.0			
Present at low level	10.7			
Conspicuously present	5.3			
Cover				
Cover provided by submergent or emergent vegetation, overhanging riparian vegetation, spaces between rocks, or turbidity	15.1			
Cover spotty or only in riffles	10.1			
Little to no cover available	5.0			
Water quality				
No visual evidence of pollutants and no known pollutants	14.2			
Localized areas of pollution	9.4			
Water is known to be polluted throughout project area or has oily sheen	4.7			
Total (of 100 possible): add all numbers in before or after columns				

Figure 2. Example habitat scorecard for bonytail chub (*Gila elegans*) created by Colorado Parks & Wildlife. This figure shows the key habitat variables in bold, with three possible conditions and their relative values.

Section 5: Qualifications of Researcher

Ceiteag Hennis

chennis@regis.edu

EDUCATION

Master of Science, Environmental Biology
April 2023
Regis University, Denver, CO

Bachelor of Science, Marine Biology
December 2019
University of South Florida, Tampa, FL

ACADEMIC/RESEARCH EXPERIENCE

Capstone Analysis Chapter Spring 2023

Relationship of aquatic fauna and water quality to groundwater prevalence in a network of short-grass prairie streams

In collaboration with US Forest Service's National Stream & Aquatic Ecology Center, analyzed a dataset collected at stream sites within the Pawnee National Grassland in Weld County, CO. Determined relationship of aquatic biota diversity characteristics and community assemblage with groundwater signature. Presented findings at Regis University Biology Research Symposium.

Coal Creek Bioassessment, collaborative graduate project Spring 2023

Marshall fire effects on the biological integrity of Coal Creek, Louisville, CO

Analyzed and summarized fish and aquatic macroinvertebrate data to determine if there was a notable decrease in biological integrity due to the Marshall Fire. Analyzed and summarized stream physical habitat data to determine the effect on the riparian area and effect on the physical habitat downstream from fire boundary. Presented findings to City of Louisville Open Space Advisory Board.

Independent Analysis, graduate ecological modeling project Spring 2022

Influence of ecological and biometric data on mercury concentrations within fish communities in a large sub-arctic lake

Independently analyzed a dataset of ecological and biometric measurements and tissue mercury concentration from freshwater fish sampled in a Northern Canadian Lake. Comparison of generalized linear models to determine the best predictors of methylmercury within tissues of freshwater fish and interpreted their effect. Presented work at Regis University Biology Research Symposium.

Grassland Management Study, collaborative graduate project Fall 2021-Spring 2022

Community effects of woody encroachment on mixed-grass prairies along the Front Range, Colorado

Vegetation sampling and identification of grassland forbs, grasses, and shrubs. Analyzed the effect of Gambel oak on soil and plant communities in two managed grasslands along Colorado's Front Range. Dendrochronology, tree density sampling data, and spatial analysis were used to determine the encroachment status of Gambel oak. Provided a detailed management plan and recommendations for rangeland and fire management of Gambel oak to Denver Mountain Parks and Highlands Ranch Community Association, Highlands Ranch, CO.

Hillsborough County Tegu Removal Project, intern Fall 2018-Spring 2019

Spatial extent of Argentinian black and white tegu invasion and cost of eradication

Assisted with camera station and baited live trap monitoring of study area in Hillsborough County, FL. Utilization of ATVs and handheld GPS units. Assisted with photo identification for capture-recapture analysis. Wildlands Conservation in collaboration with Florida Fish & Wildlife Conservation Commission.

Tropical Marine Ecology and Conservation Field Work, undergraduate student Summer 2018

Effects of marine protection and sediment stress effects on coral reef ecosystems

Surveyed reef fish through underwater stationary point count surveys. Recorded benthic cover of coral, algae, and other benthic organisms using the line intercept method. Processed sedimentation samples collected from reef sites. Used Coral Point Count (CPCe) software to determine coral cover on reef sites from photographs. Used preliminary data to determine the effectiveness of marine protected areas (MPA) on different aspects of coral reef ecosystems in St. Lucia. Designed lessons on watershed conservation and taught classes to St. Lucian primary students. University of South Florida in collaboration with Soufrière Marine Management Association.

WORK/INTERNSHIP EXPERIENCE

Fisheries Research Extern

National Stream & Aquatic Ecology Center, US Forest Service | Fort Collins, CO Jan. 2023-May 2023

Assisted with fish movement study on the Cache La Poudre River, CO. Compiled pit-tag detections from antenna arrays for analysis. Compared stream stage and dam discharge data to movement of fish to determine hydrological conditions that allow non-native eastern brook trout to traverse a waterfall barrier. Developed brook trout growth model and created data visualizations in R.

Fisheries Research Technician

Fox Sturgeon Lab, University of Georgia | Port St. Joe, FL May 2022-August 2022

Sampled Gulf sturgeon with gill and trammel nets for life history and juvenile habitat use research in the Apalachicola River, FL. Took measurements, genetic tissue samples, fin ray aging structures, and pit-tagged individuals. Maintained acoustic receiver arrays and used acoustic telemetry to identify tagged individuals in target areas. Operated and trailered small boats in riverine and coastal environments. Gear maintenance, including mending nets and boat/trailer repairs.

Diver

Under the Sea Aquarium Services | Denver, CO June 2021-December 2021

Performed weekly diving and cleaning of freshwater tanks. Assisted lead aquarist with water quality and animal husbandry of freshwater fish.

Environmental Specialist I

Environmental Health, Florida Department of Health | Lecanto, FL January 2020-May 2021

Coordinator for Drinking Water Toxics program. Investigated and surveyed groundwater contamination in support of the Department of Environmental Protection. Wrote permits, reviewed, and inspected onsite sewage treatment systems as a Certified Environmental Health Professional.

Field Intern
Wildlands Conservation | Tampa, September 2018-December 2019

Assisted with field and office work associated with research projects and surveys. Conducted vegetation and wildlife monitoring on conservation banks and easements throughout Florida, including callback surveys for Florida scrub jays, nest surveys for sandhill cranes, and coverboard surveys for Florida sand skinks. Assisted with data collection for tegu monitoring and removal research. Spatial analysis of Florida sand skink habitat on conservation banks in Central Florida.

Dean's Scholarship Student Aid
Dept. of Geosciences, Austin Peay State University | Clarksville, TN August 2015-May 2017

Performed administrative duties and student assistance in office. Assisted geosciences faculty with producing classroom materials, grading assignments, and proctoring exams.

VOLUNTEER EXPERIENCE

Colorado Parks and Wildlife
Fort Collins, Colorado
Volunteer, Electrofishing November 2022

Denver West Trout Unlimited
Jefferson County, Colorado
Volunteer, Macroinvertebrate & Angling Surveys September 2022

Florida Fish & Wildlife Conservation Commission
St. Petersburg, Florida
Marine Mammal Pathobiology Lab Volunteer May 2019-December 2019

Clearwater Marine Aquarium
Clearwater, Florida
Marine Mammal Rescue Team Volunteer January 2018-December 2019

PRESENTATIONS

Relationship of aquatic biota and groundwater influence in a network of short-grass prairie streams in the Pawnee National Grassland, CO. Poster. Regis University Research Symposium. April 17, 2023.

Berta, M., **Hennis, C**. Marshall fire effects on the biological integrity of Coal Creek, Louisville, CO. Oral. Presentation to City of Louisville Open Space Advisory Board. April 12, 2023.

Hennis, C., Huck, C., Meek, K., & Swanson, D. Community effects of woody encroachment on mixed-grass prairies along the Front Range, Colorado. Oral. Presentation to land managers of Denver Mountain Parks and Highlands Ranch Community Association. April 25, 2022.

Influence of ecological and biometric data on mercury concentrations within fish communities in large sub-arctic lakes, using generalized linear models. Poster. Regis University Research Symposium. April 18, 2022.

Bergman, D., **Hennis, C.**, Shapiro, K., & Strecker, M. Highlands Ranch Open Space Conservation Area Management Plan. Oral. Presentation to land managers of Highlands Ranch Community Association. November 29, 2021.

Study abroad experience in marine biology at the Tropical Research and Education Center in San Pedro, Belize. Poster. Austin Peay State University High Impact Practice Showcase. Spring 2016.

REPORTS

Hennis, C., Huck, C., Meek, K., & Swanson, D. 2022, May. Plant community and soil nutrient associations with Gambel oak and age of Gambel oak stands in Backcountry Wilderness Area, Douglas County, Colorado. Scientific Report to Backcountry Wilderness Area, Highlands Ranch Community Association.

SKILLS & CERTIFICATIONS

Certifications

- NAUI Open Water Scuba; professional diving
- CITI Program: Wildlife Research, Working with the IACUC
- Florida Boater's License; safe handling, maintenance, and trailering of 18 ft+ boats

Computer Skills

- R (programming language), Program MARK, SPSS, MS Excel, CPCe software, and PRIMER-e for statistical analysis and data visualizations
- Use of HOBOware software and WaTSS (Colorado Parks and Wildlife aquatic research software) for hydrology and water quality summaries
- ArcPro, ArcMap, Survey123, Google Earth Pro, Map Plus, and handheld GPS units
- ZooMonitor

Field Skills

- ID experience in freshwater, marine, and inshore fishes, aquatic macroinvertebrates, Caribbean coral species, Western birds, and plants
- Fisheries sampling methods including electrofishing, seines, trammel nets, gill nets, and snorkel surveys
- Determination of hydric soil indicators and soil classification for environmental permitting and wetland delineation
- Field camera station setup and maintenance
- Operation of ATV/4WD vehicles
- Animal behavioral data collection

Lab Skills

- Use of dissecting/compound microscopes and preparation of microscope slides
- Preservation of specimens
- Preparation and dating of tree cores
- Chemical treatment and medication of aquatic fish diseases

Writing Skills

- Literature review
- Scientific and professional writing
- NEPA process and documentation
- Grant proposals

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CHAPTER 3. JOURNAL MANUSCRIPT

Relationship of aquatic fauna occurrence and water quality parameters to groundwater prevalence in a network of short-grass prairie streams

Abstract

Small dryland streams are an integral piece of the Great Plains ecosystem and have received less attention than other freshwater ecosystems. The Pawnee National Grassland (PNG) in Colorado comprises a network of watersheds typical of the Great Plains and its aquatic habitats are supported by groundwater discharge. Because flood events from precipitation are infrequent and occur over short durations, a better understanding of the influence of groundwater on the quality of perennial habitats and the presence of aquatic biota is needed to ensure the PNG's continued support of unique aquatic biota. From data collected by USFS researchers, I assessed how groundwater prevalence influences water quality relevant to the preferred conditions of aquatic biota and addressed how the prevalence of groundwater in surface water habitats influences the diversity and assemblage of aquatic biota. By analyzing temperature, salinity, specific conductance, and total dissolved solids measurements by groundwater influence classification, I found that higher groundwater influence was associated with better water quality. Also, by analyzing data on the difference in aquatic biota diversity characteristics by groundwater influence classification, I found groundwater influence was not significantly associated with any diversity measures other than abundance of aquatic macroinvertebrates. However, overall trends showed higher fish species richness, higher invertebrate abundance, lower invertebrate richness, and lower invertebrate evenness in sites with strong groundwater influence. This study fills in gaps in the knowledge of groundwater's influence on native aquatic

species in the PNG and provides insights into the susceptibility of these habitats to agriculture groundwater pumping and drought.

Introduction

Small dryland streams, an integral piece of the Great Plains ecosystem, have received less attention than other freshwater ecosystems (Wohl et al., 2009; Dodds et al., 2004; Matthews, 1988). Agriculture and urbanization have significantly impacted Great Plains streams through water diversions and the creation of reservoirs, which have resulted in increased intermittency, overexploitation of aquifers, channelization, and riparian modification (Dodds et al., 2004; Falke et al., 2011; Falke & Gido, 2006). Amongst the harsh physical characteristics typical of prairie streams, the extreme hydrologic variance of the Great Plains is especially distinctive (Dodds et al., 2004). High streamflow caused by intense flooding and intermittent drying due to low runoff is characteristic of grassland hydrology and substantially affects the abundance of aquatic organisms (Diaz et al., 2008; Dodds et al., 2004; Matthews, 1988). There is a lack of knowledge of the aquatic communities in these streams because of the high frequency and low predictability of flooding events (Poff & Ward, 1989). Understanding the ecology and habitat suitability of Great Plains streams is essential for conservation efforts for the many threatened and endangered aquatic species only found there (Dodds et al., 2004; Falke et al., 2012).

Aquatic species in the Great Plains, especially native fishes, are adapted to frequent flooding and drying events (Falke et al., 2011; Dodds et al., 2004). These species are usually small and short-lived, reaching sexual maturity early to recolonize sites quickly (Fausch & Bestgen, 1997). Most fish species are restricted to spring-fed refuge pools during drying events and dispersal opportunities occur only after flooding events that create connectivity between these pools (USDA, 2014). Because of this, many prairie fish species have patchy distributions that are challenging to manage and conserve (Fischer & Pauker, 2008). Likewise, the influence of anthropogenic disturbance, including groundwater development and reduction of water quality (Rahel & Thel, 2004b), on prairie aquatic systems is a challenge for determining the causes of species decline and loss (Falke et al., 2011; McCartney, 2002). As a result of habitat loss, 20 of the 37 native fish species in the Platte, Arkansas, and Republican River basins of Colorado's eastern plains have become extirpated, endangered, threatened, or a species of concern (Falke et al., 2011). One area of interest in the South Platte basin is the Pawnee National Grassland of northeastern Colorado, and features a few of these imperiled native species.

Pawnee National Grassland (PNG) in Weld County CO, comprises a network of watersheds that exhibit hydrology characterized by extreme flooding followed by drying periods (USDA, 2014; Wohl et al., 2009). The grassland has short sections of perennial surface water connected irregularly by intermittent streams that support populations of plains fishes, frogs, turtles, salamanders, and aquatic macroinvertebrates (USDA, 2014; Wohl et al., 2009). Of the thousands of miles of streams on the PNG, less than 2 miles of these are perennial (USDA, 2014). A high interannual variation in water volume in these pools leads to a high variation in water level, water quality, and suitable habitat for aquatic biota (Entwistle & Nieves-Rivera, 2014; USDA, 2014). Water quality conditions in the PNG's streams range from suitable for aquatic organisms to seasonally unsuitable, where some refuge habitats dry out due to weather patterns and drought (USDA, 2014; Falke et al., 2011; Fausch and Bestgen, 1997).

Due to the stochasticity of rainfall events typical to the Great Plains, perennial aquatic habitats in the PNG are maintained throughout the year by groundwater exposed to the surface of the stream course in pools or through spring runoff (USDA, 2014; Wohl et al., 2009; Winter, 2007). The ability of aquifers to support groundwater habitats influences the amount and distribution of perennial habitats for aquatic biota (USDA, 2014). In stream sections not supported by groundwater, droughts may lead to the desiccation of dispersing aquatic species (Fausch & Bestgen, 1997). Unfortunately, a significant threat to these perennial habitats is the pumping of groundwater for agricultural irrigation, as there are many livestock watering facilities located throughout the PNG (USDA, 2014). The resulting habitat loss affects the ability of aquatic organisms to recolonize reaches and, in some cases, complete their life history (Falke et al., 2011; Rahel & Thel, 2004b). Because flood events from precipitation are infrequent and occur over a short duration, a better understanding of the influence of groundwater on the quality of perennial habitats and the presence of aquatic biota is needed to ensure the PNG continues to support its unique aquatic biota.

This study aims to determine the relationship between aquatic biota presence and groundwater influence in a network of short-grass prairie streams in the Pawnee National Grassland, CO. The specific goals of the study are to (1) assess how groundwater prevalence influences water quality relevant to the preferred conditions of aquatic biota address, and (2) address how the prevalence of groundwater in surface water habitats influences the diversity and assemblage of aquatic biota. I hypothesize that high groundwater influence has a positive effect on water quality and predict that this will result in better water quality conditions for aquatic biota, especially fish. Similarly, I hypothesize that persistent pools associated with high groundwater influence are associated with better quality habitat for aquatic species than low or no influence of groundwater and predict that this will support a higher abundance, diversity, and number of sensitive species/species of concern. Lastly, I also predict that the community composition of aquatic macroinvertebrates will differ with groundwater influence. This study fills in gaps in the knowledge of groundwater's influence on native aquatic species and provides insights into the susceptibility of these habitats to agriculture groundwater pumping and drought.

Methods

Study Area

U.S. Forest Service (USFS) personnel collected data in surface water habitats located in the East and West units of the Pawnee National Grassland (PNG) in Weld County, CO as part of a groundwater investigation between 2012 and 2016 in response to oil & gas exploration (USDA, 2014). Spring runoff, seasonal precipitation, and groundwater exposed to the surface of the stream course maintain surface flow in these aquatic habitats (USDA, 2014). Average annual precipitation on the East unit is 13-15 in/year and on the West unit is 11-13 in/year (Rasmussen et al., 1971). The USFS collected groundwater isotope data and water quality at 139 targeted sites along Oasis Spring Pond, Geary Creek, Owl Creek, Little Crow Creek, Little Owl Creek, Eastman Creek, Willow Creek, Coal Creek, Wildhorse Creek, South Pawnee Creek, and Kibben Creek. USFS collected aquatic macroinvertebrates at a subset of these sites under Groundwater-Dependent Ecosystems (GDE) inventories. The USFS collected fish generally in six of the streams. The USFS's National Stream & Aquatic Ecology Center in Fort Collins, CO maintains and manages all data.

Field Collection

The USFS collected water samples from known groundwater sources and surface water habitats in July and August of 2016 to determine the influence of groundwater sources on surface water habitats. Sites sampled include known perennial water sites, sites with uncertain water sources, and groundwater sources at wells and windmills within ¼ mile of surface water sites. USFS sampled wells to establish the signature isotopic composition of groundwater near surface water sampling sites. USFS sampled sites at the downstream pour point of each habitat patch and collected samples from downstream to upstream. For windmills and wells, USFS collected samples from water flowing from the pump. At each site, USFS collected water samples using a 30mL borosilicate glass vial. USFS personnel shipped samples to the University of Wyoming's stable isotope facility to analyze Oxygen-18 and deuterium signatures. The USFS sampled many water quality measures at each site; however, this study utilizes measurements of water temperature, specific conductance, total dissolved solids (TDS), and salinity.

The USFS collected aquatic macroinvertebrate community data as part of a greater sampling effort under the guidance of the Groundwater Dependent Ecosystem: Level II Inventory Guide (USDA Forest Service, 2012) in June 2017. USFS personnel sampled aquatic macroinvertebrates using one-minute timed collections at each site. Aquatic macroinvertebrates were collected through stratified sampling with time spent sampling each aquatic habitat type at a site proportional to the size of the aquatic habitat type. USFS personnel collected organisms using a 250 µm D-frame net to dislodge insects from the structure along the shoreline and emptied the net contents into a 500 µm sieve and preserved them in 95% ethyl alcohol. In the lab, USFS personnel used a random gridded tray to pick a 300 sub-sample count of aquatic macroinvertebrates from each site. USFS personnel then sent specimens to Timberline Aquatics, Inc. in Fort Collins, CO for further identification of macroinvertebrates to the lowest possible taxonomic level.

In a separate effort, the USFS collected fish occurrence data as part of a long-term dataset of fish occurrences in streams on the PNG that spans back to 1988. USFS personnel collected fish data used in this study from sites in May and June of 2014 from a select number of sites along Coal Creek, Geary Creek, Owl Creek, South Pawnee Creek, Wildhorse Creek, and Willow

Creek. USFS personnel collected fish from seine hauls in each surface water site and identified all captured fish and marked them as present.

Data Analysis

Based on the Oxygen-18 (δ18O) signature, deuterium (δ^2H) signature, and deuterium excess calculated for each site, I categorized the association of groundwater at each site into three groups: (1) strong influence, (2) moderate influence, and (3) weak influence. I based this process of defining groundwater input on criteria determined by Joe Gurrieri, hydrogeologist, at the USFS National Groundwater Program in Lakewood, CO (Table 1). This criterion was calculated from comparisons of O18 and deuterium signatures between the samples and the Global Meteoric Water Line (GMWL; Dansgaard, 1964) and Local Meteoric Water Line (LMWL) (Harvey, 2005).

Table 1. Criteria for strong, moderate, weak, and no association with groundwater signature used for data analysis.

	δ18O Signature	**δ^2H Signature**	**d-excess**
Strong	-12.4 to -8.6	-91 to -68	-1 to -10
Moderate	-7.9 to -5.3	-70 to -52	-5 to -11
Weak	-5.4 to -3.1	-55 to -30	-11 to -20
None	**> -3.1**	**> -29**	**< -21**

I completed all analyses in R (R Core Team, 2020). To assess the relationship between groundwater influence and water quality conditions, I fit a linear regression with groundwater influence as the predictor and water quality parameters as the response variable. I used the δ18O signature as the measure of groundwater influence, with lower values indicating a stronger groundwater signature (Table 1). The water quality measures I used in these analyses were specific conductance, total dissolved solids (TDS), water temperature (°C), and salinity measures. I log-transformed conductance, TDS, and salinity to reduce the skewness of the original values.

To assess how the prevalence of groundwater in surface water habitats influences the diversity of aquatic macroinvertebrates, abundance, richness, evenness, and proportion of EPT taxa were compared between the three groundwater influence groups. Since subsamples of aquatic macroinvertebrate specimens were used for sites with large counts, I corrected for the abundance of aquatic macroinvertebrates given the proportion of grid cells counted in the lab. I used this correction to estimate the abundance of specimens originally collected at each site. To assess the difference in invertebrate abundance between the three groundwater groups, I fit a Poisson regression using the corrected abundance estimates. I also fit a Poisson regression to determine the difference in aquatic macroinvertebrate richness between the three groundwater groups. For both abundance and richness, I used Tukey all-pair comparisons to compare the differences between the three groups using the *multcomp* package in R (Hothorn et al., 2008). Pielou's evenness was calculated for each site using the *vegan* package in R (Oksanen et al., 2022). I fit a one-way ANOVA with groundwater influence as the predictor variable and aquatic macroinvertebrate evenness as the response variable to assess if evenness differed between the groundwater categories. I performed a post-hoc Tukey's HSD test to specifically quantify these differences after accounting for multiple comparisons. Lastly, to assess the difference in Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa, I fit a binomial generalized linear model with groundwater influence as the predictor variable and the proportion of EPT taxa as the independent variable.

To determine the gradients in aquatic macroinvertebrate community composition among the three categories, I ordinated macroinvertebrate data to establish gradients of community diversity. I calculated relative abundances for each macroinvertebrate taxon, and then calculated Bray- Curtis dissimilarities for the non-metric multidimensional scaling (NMDS) ordination. I then carried out NMDS using the metaNMDS function in the vegan package of R (Oksanen et al., 2020) and I retained two dimensions.

Lastly, I calculated fish species richness for each site based on the presence of fish at each site. After I classified the groundwater influence of the sites, I determined that the USFS did not collect fish at any site that had a strong groundwater influence. I performed t-tests comparing fish species richness between both moderate and weak groundwater sites. I documented the number of sites where Plains Topminnow and Northern Plains Killifish occurred to determine the proportion of sites where these two species are found. I also performed t-tests to assess the difference in the proportion of sites containing these two species between moderate and weak groundwater sites.

Results

Water Quality

In the linear regression of water temperature (Celsius) and δ18O groundwater signature, there was a slight positive relationship between these two variables (Figure 1a, p-value: 0.004, R^2= 0.06, f-stat: 8.462 on 1 and 136 DF). This relationship shows that a one-unit δ18O increase is associated with a 21% increase in °C (95% CI: 7-35%). Because higher δ18O values indicate weaker groundwater signatures, weaker groundwater influence is associated with higher temperatures. The three coldest water temperatures were collected at sites with exceptionally strong groundwater influence, such as Oasis Spring Pond and sample sites 1 & 2 at Willow Creek.

Linear regressions also revealed similar results for conductance, salinity, and total dissolved solids. There was a significant positive relationship between specific conductance (m/S) and δ18O groundwater signature (Figure 1c, p-value: <0.0001, R^2=0.19, f-stat: 32.45 on 1 and 137 DF). This relationship shows that a one-unit δ18O increase is associated with an 8% increase in specific conductance (95% CI: 5-11%), indicating that higher specific conductance values are associated with weaker groundwater influence. For example, the 17 highest measurements of conductance are associated with sites that have very low to almost no groundwater influence, especially within Pawnee Creek. There was a significant positive relationship between total dissolved solids (TDS) and δ18O groundwater signature (Figure 1d, p-value: <0.0001, R^2=0.18, f-stat: 30.3 on 1 and 137 DF). This relationship shows that a one-unit δ18O increase is associated with a 9% increase in specific conductance (95% CI: 6-12%), indicating that higher TDS values are associated with weaker groundwater influence. Like specific conductance, TDS showed a strong trend in very high measurements of TDS associated with sites with the weakest groundwater influence. The 18 highest measures of TDS are associated with sites with very low to almost no groundwater influence. Lastly, like specific conductance and TDS, there was a significant positive relationship between salinity (ppt) and δ18O groundwater signature (Figure 1b, p: <0.0001, R^2=0.18, f-stat: 30.06 on 1 and 137 DF). This relationship shows that a one-unit δ18O increase leads to an 8% increase in salinity (95% CI: 5-11%), indicating that high salinity values are associated with weak groundwater signature. Similarly, the first 16 highest salinity measurements were from sites with very low to no groundwater influence, especially South Pawnee Creek.

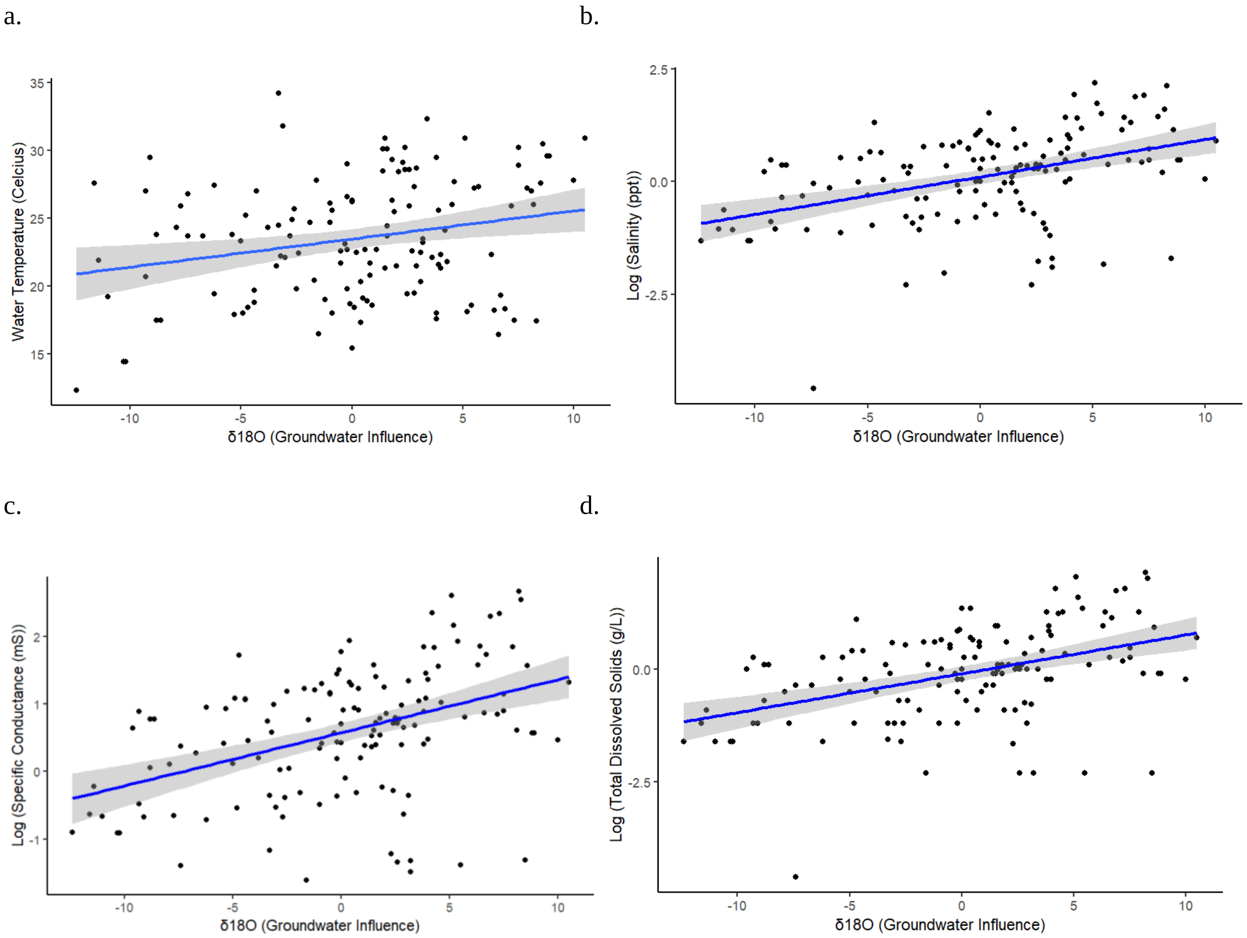

Figure 1. a. Linear regression showing a slightly positive relationship between water temperature (°C) and δ18O groundwater signature. b. Linear regression showing a slightly positive relationship between log-transformed salinity (ppt) and δ18O groundwater signature. c. Linear regression showing a slightly positive relationship between log-transformed specific conductance (m/S) and δ18O groundwater signature. d. Linear regression showing a slightly positive relationship between log-transformed total dissolved solids (TDS) and δ18O groundwater signature. In each graph, points represent each water sample, and the blue line represents the linear relationship between the data.

Fish Diversity

Fish species richness was very low in all the sites sampled, with three sites having zero species in 2014. Owl Creek, a weak groundwater site, had the highest species richness of any site sampled, with Iowa Darter (*Etheostoma exile*), Northern Plains Killifish (*Fundulus kansae*), Black Bullhead (*Ameiurus melas*), and Green Sunfish (*Lepomis cyanellus).* Median species richness for moderate groundwater influence sites was 2 (95% CI: 0.62-4.65), and weak groundwater influence was 1 (Figure 2, 95% CI: 0.07-2.20). In general, moderate groundwater sites had higher species richness, however, there was no significant difference between the groundwater influence groups (p=0.53, t=0.71, df=3).

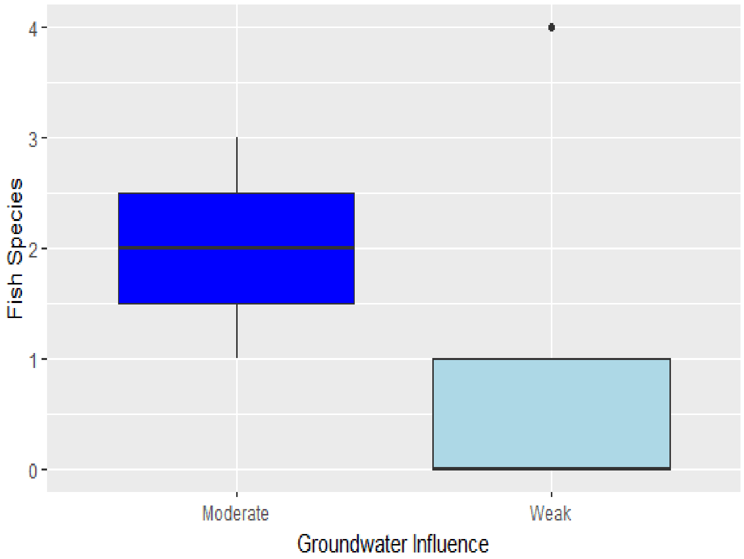

Figure 2. Boxplot shows no significant difference in fish species richness at moderate and weak groundwater sites.

The presence of species of concern, such as Plains Topminnow (*Fundulus sciadicus*) and Northern Plains Killifish (*Fundulus kansae*), was low. Plains Topminnow was only present in Willow Creek, and Plains Killifish was only present in Owl Creek. The proportion of moderate and weak groundwater sites with Plains Topminnow was 0.5 and 0.0, respectively (Figure 3a). There was no significant difference in the proportion of sites with Plains Topminnow between moderate and weak groundwater sites (p=0.5, t=1, df=1). The proportion of moderate and weak groundwater sites with Northern Plains Killifish was 0 and 0.25, respectively (Figure 3b). There was also no significant difference in the proportion of sites with Northern Plains Killifish between moderate and weak groundwater sites (p=0.391, df=3, t=-1).

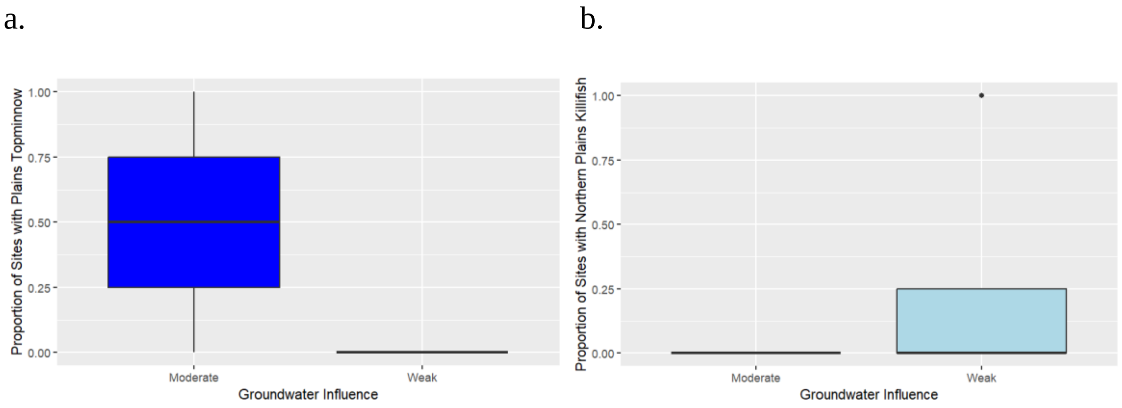

Figure 3. Boxplots showing (a) Plains Topminnow only occurring in moderate groundwater sites and (b) Northern Plains Killifish only occurring in weak groundwater sites.

Aquatic Macroinvertebrate Community Diversity

Strong groundwater sites had the highest median abundance at 345 aquatic macroinvertebrates per sample (95% CI: 271.22-437.45). Moderate groundwater influence had a median aquatic macroinvertebrate abundance of 103 (95% CI: 91.62-114.56). Weak groundwater influence sites had a significantly higher abundance than moderate sites, with a median abundance of 233 macroinvertebrates per sample (95% CI: 184.09-294.63, $p<0.001$). Aquatic macroinvertebrate abundance was significantly higher in the strong groundwater sites than in both moderate and weak groundwater sites ($p<0.001$; Figure 4).

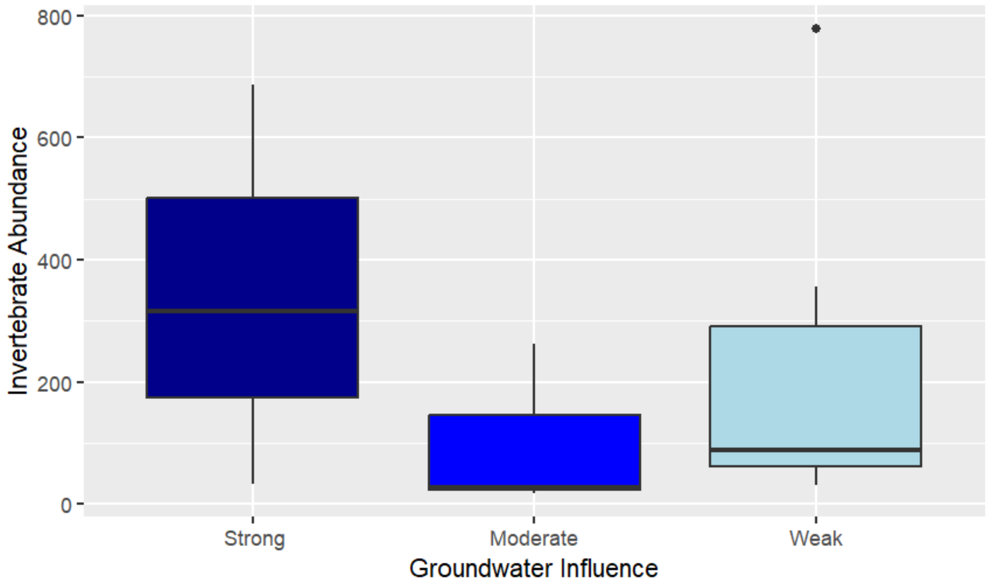

Figure 4. Boxplot showing a significant difference in invertebrate abundance counts between the three groundwater groups.

In general, sites with weak groundwater influence had the highest invertebrate richness (Figure 5a). Median richness in the sites with a strong groundwater influence was 13 taxa (95% CI: 5.7-28.68). Median richness in sites with a moderate groundwater influence was 11 taxa (95% CI: 7.66-15.19). Lastly, median richness in sites with a weak groundwater influence was 15 taxa (95% CI: 7.25-31.96). There was no significant difference in invertebrate richness between the three groundwater influence groups (p=0.758). Similarly to richness, aquatic macroinvertebrate evenness was highest in weak groundwater sites (Figure 5b). Median evenness in strong groundwater sites was 0.59 (95% CI: 0-1.0), moderate groundwater sites was 0.71 (95% CI: 0.4-1.0), and weak groundwater sites was 0.69 (95% CI: 0.03-1.0). There was also no significant difference in evenness between the three groundwater influence groups (p=0.7611, R^2=0.06, F-stat=0.28 on 2 and 9 DF).

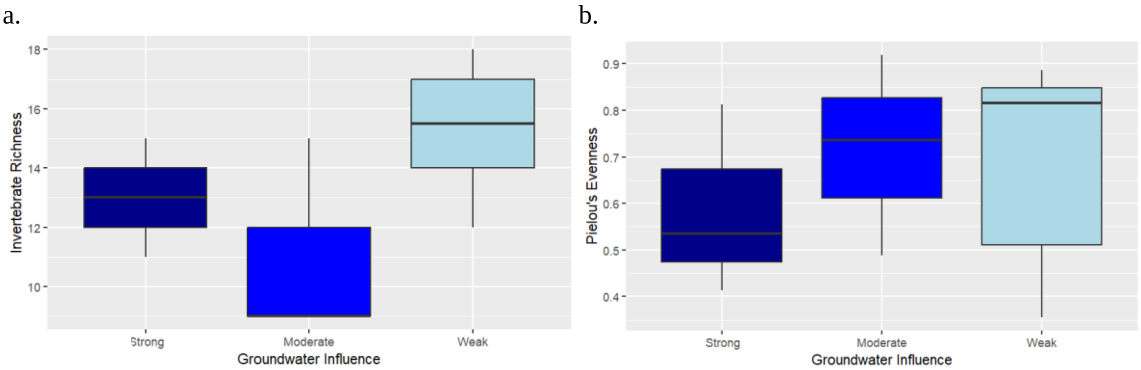

Figure 5. a. Boxplot showing no significant difference in aquatic macroinvertebrate richness between the three groundwater groups. b. Boxplot showing no significant difference in aquatic macroinvertebrate community evenness between the three groundwater groups.

Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa proportion for each site was very low (Figure 6). Weak groundwater sites had a median EPT proportion of 0.014 (95% CI: 0-0.04). The median proportion of EPT taxa in moderate groundwater sites was 0.05 (95% CI: 0.04-0.06). The median proportion of EPT taxa in moderate groundwater sites was higher than in strong groundwater sites, with 0 EPT taxa at all three sites sampled. Despite being low, the median proportion of EPT taxa at moderate groundwater sites was significantly higher than both strong and weak groundwater sites (p<0.001; Figure 6).

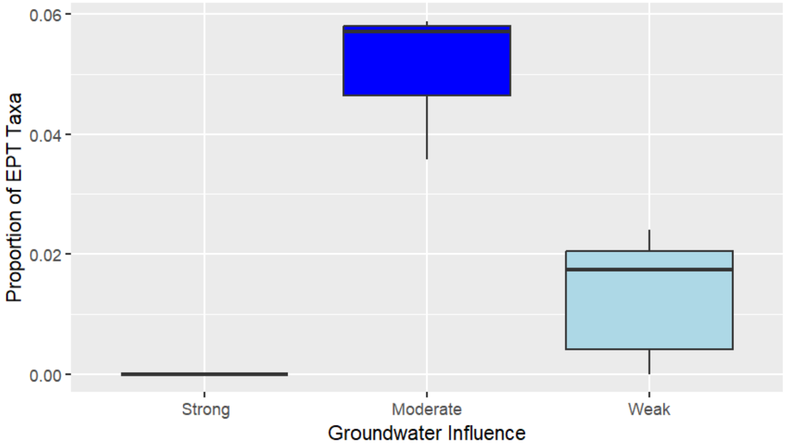

Figure 6. Boxplot showing a significantly higher proportion of EPT taxa in moderate groundwater sites than in strong and weak groundwater sites.

Aquatic Macroinvertebrate Community

The aquatic macroinvertebrate communities showed some notable groupings according to groundwater influence as a result of non-metric multidimensional scaling (NMDS), with 67% of the variance explained by axis 1 and 11% of the variance explained by axis 2 (Figure 7). The final configuration showed a stress of 0.9. NMDS scores on axis 1 or 2 did not differ as a function of groundwater influence (p=0.61 and p=0.89, respectively). However, high groundwater sites represent a more refined aquatic invertebrate community composition, or the least community variation, than moderate and weak groundwater sites (Figure 7). Moderate groundwater sites had the greatest community variation. Taxa that make up a large proportion of the high groundwater sites are *Chironomus* sp (non-biting midges), *Hygrobates* sp (mites), *Phaenopsectra* sp (non-biting midges), *Acricotopus* sp (non-biting midges), *Tanypus sp* (non-biting midges), and *Hyalella azteca* (amphipod), Erpobdellidae (leeches), and Lymnaeidae (pond snails). Two sites, Willow SW17 and Little Crow SW9, have very different aquatic macroinvertebrate communities from the rest. Willow SW17, a moderate groundwater site, is dominated by *Pisidium* sp (freshwater clams), *Paratanytarsus* sp (non-biting midges), and *Dicrotendipes.* sp (non-biting midges). Little Crow SW9, a weak groundwater site, is dominated by *Berosus sp* (water beetles), *Argia* sp (damselflies), *Sympetrum* sp (dragonflies), and *Rhantus* sp (water beetles).

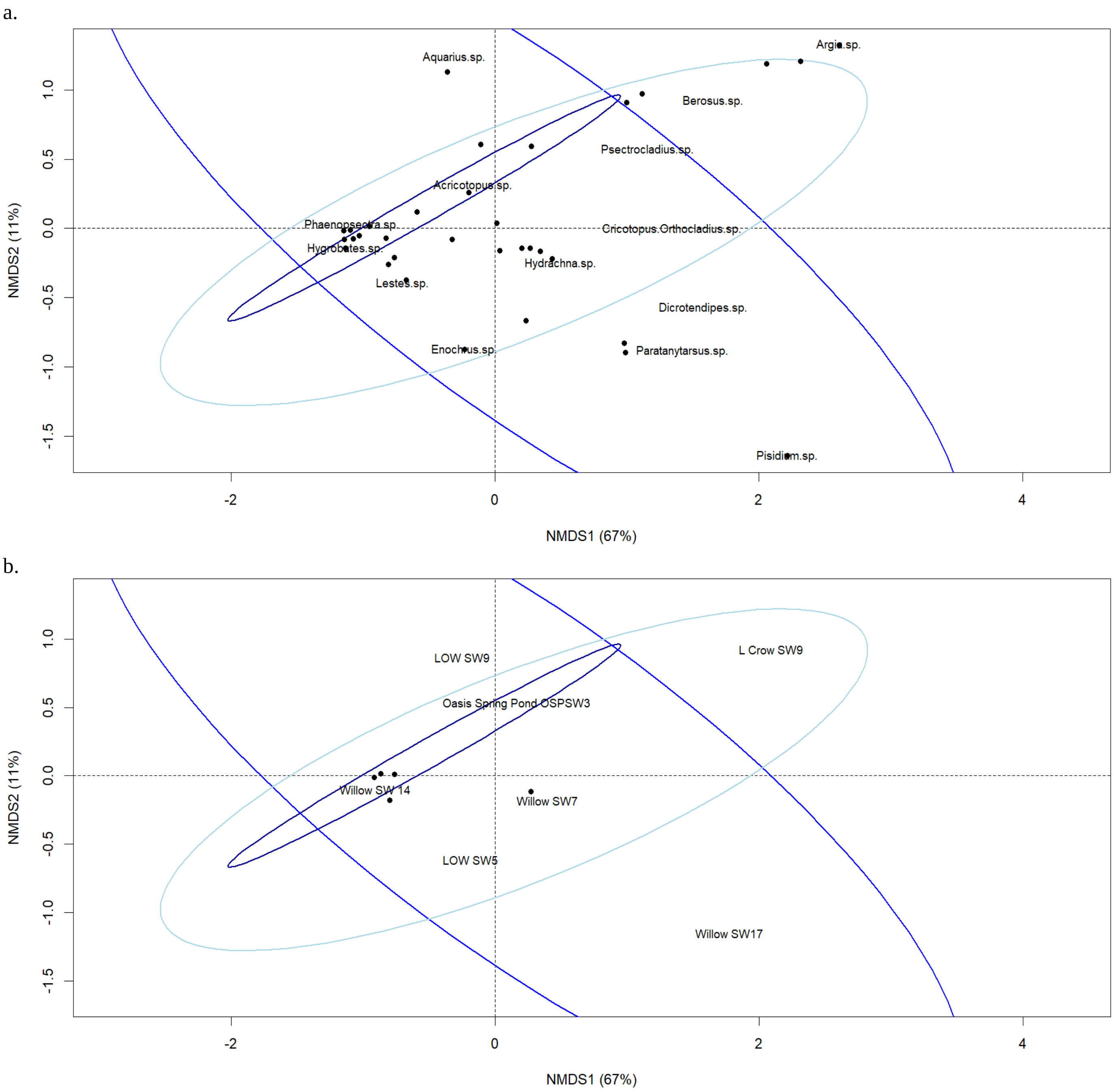

Figure 7. a. NMDS plot containing the sites sampled and their aquatic macroinvertebrate communities. Closed-labeled circles represent taxa. b. Copy of NMDS plot in figure a, with sites sampled represented by labeled, black circles. In both plots, dark blue ellipses represent the strong groundwater community, medium blue ellipses represent the moderate groundwater community, and light blue ellipses represent the weak groundwater community. Each site name is shortened by the major creek and the specific site sampled.

Discussion

In this study, I assessed the influence of groundwater influence in streams in the Pawnee National Grassland on aquatic biota presence and water quality. I asked whether groundwater influenced water quality measures that are relevant to the preferred conditions of stream fish. By analyzing data on temperature, salinity, specific conductance, and total dissolved solids between groundwater influence classification, I found that groundwater influence was significantly associated with water quality. Sites with higher groundwater influence were associated with better water quality measurements for fish. I also asked whether the prevalence of groundwater in surface water habitats is associated with the occurrence and assemblage of aquatic biota present. By analyzing data on the difference in aquatic biota diversity characteristics between sites with differing groundwater influence classifications, I found groundwater was not significantly associated with any diversity measures except for abundance of invertebrates and the proportion of EPT. However, overall trends showed higher fish species richness, higher invertebrate abundance, lower invertebrate richness, and lower invertebrate evenness in sites with strong groundwater influence. Lastly, I found that groundwater influence was not associated with unique invertebrate communities.

The significant relationship between groundwater signature and water chemistry supported the hypothesis that high groundwater sites would have better water quality measures for aquatic biota. Although Great Plains fish species are specialized for these habitats, some species are adapted to spring-fed pools and are intolerant of harsh physiological conditions, such as high temperatures and salinity (Higgins & Wilde, 2005; Dodds et al., 2004; Fausch & Bestgen, 1997). Areas with low water quality can limit dispersal and recolonization of fish species, such as the Plains Killifish and Plains Topminnow (Rahel & Thel, 2004a; Rahel & Thel, 2004b). Lower water temperatures in the summer months were associated with sites that have higher groundwater influence, indicating that groundwater input can moderate stream temperatures. This is especially important in summer months where high groundwater sites can provide refugia for fish species when water temperatures can reach extreme values across the PNG (Power et al., 1999; Fausch & Bestgen, 1997). I also found that lower specific conductance, salinity, and total dissolved solids (TDS) were all similarly associated with higher groundwater sites, which was expected since these measurements are correlated. High specific conductivity, salinity, and total dissolved solids create more stressful conditions for aquatic biota, result in decreased abundance (Bass, 1994), and can have a major role in structuring aquatic community assemblages (Higgins & Wilde, 2005). It should be noted that most sites were considered oligosaline compared to other Great Plains aquatic habitats (Wollheim & Lovvorn, 1995) and all salinity measures were well within the tolerance values of common prairie fish species, including the Plains Killifish (Ostrand & Wilde, 2001).

Because high groundwater sites are associated with better water quality and are predicted to have better habitat quality overall, I expected that high groundwater sites would have a higher diversity of fish and aquatic macroinvertebrates. This hypothesis was not supported fully by the results. Although nonsignificant, fish species richness was higher in moderate groundwater sites than in weak groundwater sites. Additionally, Plains Topminnow were only found in moderate groundwater sites. Alternatively, Plains Killifish were only present in weak groundwater sites, indicating, which was unexpected. These results are not significant, which may be explained by the small sample size and low diversity of fish in general throughout the PNG. This is not surprising because there is relatively little fish diversity in Great Plains streams, especially within the upper Platte River Basin (Fausch & Bestgen, 1997). Since these streams have low habitat complexity and a harsh physicochemical environment overall (Matthew, 1988), this may explain the lack of groundwater effect on the fish community. Although there appears to be limited groundwater effects on fish diversity, it should be noted that the three sites with zero fish present all had weak groundwater influence. These three stream systems, Coal Creek, Geary Creek, and Wildhorse all historically had fish present, and fish were collected in the PNG as recently as 2002, showing the potential effect of intense groundwater pumping on the available fish habitat in these streams (USDA, 2014). A limitation of the study is the lack of power of the statistical analyses because fish were only sampled in six locations in 2014 and many of these sites had zero fish present. In the future, more intensive fish sampling should be completed to better interpret the effect of groundwater on these fish communities.

Similarly, the hypothesis that high groundwater sites are associated with better water quality and provide better aquatic macroinvertebrate habitat quality overall was generally not supported by the aquatic macroinvertebrate results. Abundance was significantly higher in high groundwater, which was driven by Willow Creek site 14 with the highest abundance of macroinvertebrates out of any site. However, trends seen in other diversity measures between the three groundwater classes were not expected. For example, it has been shown that higher abundances of EPT taxa are associated with perennial habitats supported by groundwater (Burk & Kennedy, 2013). Although moderate groundwater sites had a significantly higher proportion of EPT taxa than both high and weak groundwater sites, EPT taxa were rare, indicating a potential effect of groundwater abstraction on aquatic macroinvertebrate communities in the PNG (White et al., 2021). This result contrasts with a nearby stream along the Colorado Front Range, Sand Creek, which had a high diversity of EPT taxa despite being a similarly small stream (Stoaks & Kondratieff, 2014). Dominant taxa amongst many sites were freshwater snails

(*Physa* sp. *and Gyraulus* sp.) and oligochaete worms (Naididae), which were also found in high abundances or have large distributions in the Great Plains (Stephen, 2017; Phillips et al., 2016). Non-significant trends may be explained by the fact that some sites along South Pawnee Creek and Little Owl Creek showed little groundwater influence despite being persistently wet and supporting a high diversity and abundance of aquatic fauna. This high variation in the sites coupled with the lack of power due to a small sample size (12) could explain the lack of significance. Additionally, isotopic signatures have been shown to have a vertical variation with sampling depth and potential for lake stratification, which may lead to errors in the sampling technique used for this study (Joshi et al., 2018). Lastly, there may be other factors affecting aquatic macroinvertebrate communities not included in this study, such as the amount of suspended sediments, which have been shown to shape aquatic macroinvertebrate communities in the Great Plains (Phillips et al., 2016; Whiles & Dodds, 2002).

Although groundwater influence was not associated with unique macroinvertebrate communities, there were some notable communities. High groundwater sites had a much narrower ellipse (Figure 7), indicating a much more defined aquatic macroinvertebrate community than moderate and weak groundwater sites. High groundwater aquatic macroinvertebrate communities were associated with many genera of non-biting midge taxa, mites, *Hyalella azteca,* (an abundant amphipod species), leeches, and pond snails. None of these taxa contain species of conservation concern in the state of Colorado (CPW, 2015). Alternatively, Little Crow 9, a weak groundwater site, is associated with *Argia* sp and *Sympetrum* sp. These are two genera that contain species of greatest conservation need in Colorado, the Paiute Dancer (*Argia alberta)* and the Red-veined meadowfly (*Sympetrum madidum*) (CPW, 2015). However, most specimens within this study were not identified to species, so it is unknown if these species were present within the genera found at these sites. More specific identification of aquatic macroinvertebrates is warranted due to the threat of increased oil and gas leasing, groundwater extraction, and agricultural runoff in the PNG (USDA, 2014).

Although the second hypothesis that high groundwater sites would be associated with higher aquatic diversity was not supported, it is important to note that these sites would not sustain aquatic communities without groundwater discharge (USDA, 2014). Other than stochastic precipitation events, groundwater exposed to the surface supplies the surface water throughout the PNG (USDA, 2014). Because high groundwater sites were significantly correlated with better water quality measures, it is evident that groundwater influence has a large impact on the suitability of these habitats for aquatic biota. There is a potential that the trends expected at these sites may not be seen at the modest scale of this study. Future research on aquatic communities in the PNG is warranted based on their unique attributes and importance as refugia for aquatic species in a portion of the Great Plains threatened by groundwater pumping.

Acknowledgments

I would like to thank Matthew Fairchild with the USFS's National Stream & Aquatic Ecology Center for his guidance, allowing me to be a part of this study, and for supplying the data for the analyses, in addition to Joe Gurrieri with USFS's Groundwater Program for his guidance in determining groundwater influence. Thanks to all of USFS's personnel with the Arapahoe and Roosevelt National Forests & Pawnee National Grassland who were involved with the studies conducted at the Pawnee National Grassland. Additionally, I would like to thank Dr. Tyler Imfeld for analysis assistance and manuscript revisions, as well as my academic advisor, Dr. Mike Ghedotti, and my graduate cohort for their support and edits throughout the writing of this manuscript.

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CHAPTER 4

The Upper Colorado River Basin’s Nonnative and Invasive Aquatic Species Control Strategy

Introduction

The prevalence of nonnative piscivorous fish species in the Upper Colorado River Basin (UCRB) has increased in recent history through the introduction and management of sportfish, especially in manmade reservoirs along the Colorado River. There are serious concerns about the negative impact of nonnative aquatic species on the recovery of four federally endangered species in the UCRB, including the Razorback Sucker (*Xyrauchen texanus*), Bonytail Chub (*Gila elegans*), Colorado Pikeminnow (*Ptychocheilus lucius*), and Humpback Chub (*Gila cypha*) (Martinez et al., 2014). Predation on these four species by nonnative fishes is the most important factor contributing to their decline (Johnson et al., 2008; Clarkson et al., 2005). Because of this, one goal of the Upper Colorado River Basin and San Juan River Basin Endangered Fish Recovery Programs is to eradicate invasive aquatic species within the UCRB (Martinez et al., 2014). However, prior efforts to control nonnative fishes have been limited because some angler and government agency departments oppose removing popular nonnative sportfish species and would rather allocate funds to promote nonnative recreational fisheries (Martinez et al., 2014; Clarkson et al., 2005). More recently, all stakeholders have supported a more focused removal of nonnative fishes because of the continued development of the UCRB’s prevention and control strategy (Martinez et al., 2014). To minimize conflict among stakeholders during decision-making, I recommend that initial large-scale removal efforts should be focused on the critical habitat areas of the four endangered fish species in the UCRB. I also recommend that removal efforts be focused on those fish deemed non-compatible fish species to the recovery and preservation of endangered and native aquatic species as determined by the U.S. Fish and Wildlife Service (USFWS; USFWS, 2009). Lastly, the removal method used should be appropriate to the specific aquatic habitat and species being managed.

Environmental issue/context

In the UCRB, there are over 40 established nonnative fish species, most being introduced as sportfish or as bait, compared to only 14 native fish (Johnson et al., 2008; Clarkson et al., 2005; Valdez & Muth, 2005). Nonnative fish species interact negatively with native fishes by competing for resources, preying upon juvenile fish, hybridizing with closely related native species, degrading native fish habitat, and transmitting diseases (Coggins et al., 2011; Gozlan et al., 2010). Native Colorado River species are naïve to novel fish predators because they have co-evolved with just one native predatory species (Colorado Pikeminnow) and are unable to avoid introduced predatory fish species (Clarkson et al., 2005). Recovery of the four most imperiled species in the UCRB requires reductions in the abundance and distribution of nonnatives (Martinez et al., 2014; Clarkson et al., 2005). Since the late 1990s, fisheries management programs have sought to remove nonnative fishes in the UCRB to promote native fish recovery, and these efforts have successfully increased the abundance of the four endangered native fish species (Ward & Morton-Starner, 2015; Coggins et al., 2011; Marks et al., 2010; Mellis et al., 2010). Fisheries management in the UCRB has employed several different methods for nonnative fish removal including electrofishing along hundreds of miles of the San Juan River, piscicide use in floodplain ponds along the Colorado and Gunnison rivers in Colorado, trapping throughout the UCRB, and adopting regulations in Utah’s Green River that allow anglers to kill any Smallmouth Bass (*Micropterus dolomieu*) or Burbot (*Lota lota*) they catch (Martinez et al., 2014; Gardunio et al., 2011).

Although nonnative species may harm the environment, economy, and human health (Martinez et al., 2014), the effort to remove them has led to major conflicts among different stakeholder groups in the UCRB. Certain removal efforts, including mechanical removal and mandatory harvest regulations, are debated among agencies and generally opposed by recreational anglers because of the uncertainty of their effectiveness (Coggins et al., 2011; Clarkson et al., 2005). Additionally, prior efforts to initiate any control of nonnative fish populations have been limited in scope because anglers and some agency departments oppose removing popular sportfish species in critical habitat (Martinez et al., 2014; Clarkson et al., 2005). The mission statements of fisheries agencies require that recreational angling and conservation priorities be jointly managed, and this has led regulations to be weak or control efforts to be mismanaged due to intra-agency conflicts on how to spend limited funding (Carey et al., 2012; Landom, 2010; Clarkson et al., 2005).

Stakeholders

Upper Colorado River Basin Recovery Implementation Collaborative

Government agencies of the UCRB Recovery Implementation Collaborative, including USFWS and native species management programs of the States of Colorado, New Mexico, Utah, and Wyoming, have agreed that nonnative and imperiled native species cannot co-exist in the same habitat and that nonnative species will need to be removed for natives to recover (Martinez et al., 2014; Clarkson et al., 2005). This group values endemic fish biodiversity and is responsible for protecting these endangered species and managing their recovery. However, the UCRB's agencies are concerned about the chronic impacts of increased electrofishing on the survival and hatching of the embryos of Colorado Pikeminnow and other native cyprinids as a by-product of increased nonnative fish removal (Martin & Wright, 2010; Bohl et al., 2009).

State and Federal Agency Sportfish Management Programs

Many sportfish management programs, including recreational fisheries management programs within Colorado Parks and Wildlife and Utah Division of Wildlife, still stock and promote nonnative sport fish in the UCRB (Kolar et al., 2010), including the Northern Pike (*Esox lucius*), which has become very problematic in some tributaries of the Colorado River (Johnson et al., 2008). These agencies value support from recreational anglers and in many cases promote fish stocking of nonnative species to maintain robust populations of these fish (Rahel, 2004). State and federal agencies also value sportfish programs that generate fishing license sales and federal subsidies, as well as the deeply rooted tradition of sportfishing (Landom, 2010; Clarkson et al., 2005).

Recreational Anglers

Recreational anglers support the stocking of sportfish and value recreational fishing opportunities. Because state agencies maintain established populations of nonnatives, anglers who may have captured these species for many years in the same body of water expect these fisheries to perpetually provide fish (Martinez et al., 2014; Landom, 2010). Additionally, illegal and accidental introduction of sportfish by anglers is a global fisheries management issue, and such introductions occurred in the UCRB when burbot was introduced into the Green River drainage of the Colorado River Basin (Gardunio et al., 2011). Because anglers catch nonnative sportfish for both sport and food, most recreational fishers do not support the removal of these species (Michel et al., 2020; Gardunio et al., 2011) and may be opposed to mandatory harvest measures and must-kill regulations.

Recommendations

To reduce conflicts, a compromise to protect native species while also protecting sportfish interests is appropriate. Water bodies in the UCRB should be designated for either conservation of native fishes or nonnative sport fishing (Clarkson et al., 2005). In man-made reservoirs in the UCRB where nonnative fish are particularly numerous, and many native species are ill-adapted, it is neither feasible nor reasonable to completely eradicate nonnatives (Pennock et al., 2021; Johnson et al., 2008; Clarkson et al., 2005). Reservoirs should be designated for sportfish management, and removal efforts should be focused on other water bodies. The primary focus should be to remove nonnatives from the four endangered fish species' critical habitat areas in the UCRB and to create physical barriers to decrease future invasion of nonnatives in these areas. Small warm water streams in the UCRB that smaller-bodied nonnatives occupy should also be prioritized for removal efforts due to their low value to recreational fishers and considerable value as habitat for native species. By prioritizing some areas for nonnative removal but others for maintenance of nonnative populations, the number of potential conflicts among stakeholders will be minimized (Laub et al., 2018; Clarkson et al., 2005). Lastly, unique river systems, such as the Yampa River, which has the most natural flow regime of any river of its size in the UCRB, should be managed to support natives by an aggressive nonnative removal program (Johnson et al., 2008).

In addition to prioritizing some areas for removal,l it is important to use an appropriate removal method that accounts for each area's size, presence of critical habitat, and composition of non-natives. For example, although the chemical removal of nonnatives may be controversial to conservation groups and recreational anglers, this method is appropriate for low-order streams and side-channel habitats off major rivers dominated by nonnative species because it is the most efficient method (Clarkson et al., 2005). The use of the piscicide rotenone has successfully eradicated nonnative species (Franssen et al., 2014). After piscicide eradication, native species can then be reintroduced to the site. However, piscicide application is not a viable option in all areas due to public concern and the presence of protected species (Franssen et al., 2014). In these cases, long-term mechanical fish removal through netting or electrofishing is required (Clarkson et al., 2012). Ultimately, the removal method should be decided on a case-by-case basis dependent on stream physiography, removal feasibility, the conservation status of the species, and the visibility of the public.

Lastly, removal efforts should be prioritized based on whether each nonnative species is compatible with the recovery and preservation of endangered species within critical habitat of the UCRB (USFWS, 2009). The USFWS has created a list of nonnative species that qualify as compatible or non-compatible based on their documented effects on native species. Removal should focus on non-compatible species. These species include Smallmouth Bass, Northern Pike, Walleye (*Sander vitreus*), and many catfish species, for which native Colorado River species have not evolved avoidance mechanisms (Ward et al., 2020; USFWS, 2009). For example, one introduced species, the Flathead Catfish (*Pylodictus olivaris*), consumes native fish at a rate that exceeds their annual productivity resulting in significant declines of native fish biomass, thereby warranting its removal from native-fish conservation areas (Hedden et al., 2016). As a compromise, many popular sportfish, including sterile hybrid nonnative predators and hatchery-reared trout that are deemed compatible can be maintained in waters designated for recreational fish management (Ward et al., 2018; Clarkson et al., 2005).

Conclusion

In conclusion, nonnative fish species are a major threat to the recovery of four endangered native fish species in the UCRB (Johnson et al., 2008; Clarkson et al., 2005). To protect and support the recovery of the UCRB's native fish species, nonnative fish management must be a priority, as stated by the Upper Colorado River Basin and San Juan River Basin Endangered Fish Recovery Programs (Martinez et al., 2014). Clarkson et al. (2005) emphasize eliminating conflict between nongame fishes and nonnative sport species by managing fisheries in separate watersheds. In addition, I recommend that the removal method of nonnatives should be decided on a case-by-case basis dependent on many factors presented here and that removal should focus on species incompatible with the recovery and conservation of native species.

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