THESIS

DEVELOPING ROCK RAMP FISHWAY CRITERIA FOR FISHES OF REGIONAL CONSERVATION CONCERN

Submitted by

Kira Paik

Department of Fish, Wildlife, and Conservation Biology

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2024

Master's Committee:

Advisor: Christopher A. Myrick

Yoichiro Kanno
Ellen Wohl

ABSTRACT

DEVELOPING ROCK RAMP FISHWAY CRITERIA FOR FISHES OF REGIONAL CONSERVATION CONCERN

Rivers and streams in the United States have been greatly fragmented by the construction of instream structures such as dams, diversions, and culverts to meet the growing needs of human populations. Many of these structures inhibit upstream movement by fish species, negatively affecting abundance as well as overall survival. Conservation efforts are looking at restoring connectivity through the installation of fish passage structures or fishways. To improve effectiveness and functionality of these fish passage structures, the swimming abilities of the target species should be considered when creating the design. Rock ramp fishways are becoming increasingly utilized because they can allow passage of a large assortment of species with variable swimming abilities and are highly customizable. Creating cast concrete fishways in this style can also help to reduce the cost of construction of passage structures. We evaluated the passage success of five fish species of conservation concern using an experimental rock ramp fishway at slopes of 2-10%, in 2% increments. This study focused on species of national or regional conservation concern including Topeka Shiner *Notropis topeka*, Suckermouth Minnow *Phenacobius mirabilis*, Rio Grande Chub *Gila pandora*, Rio Grande Sucker *Catostomus plebeius*, and Mottled Sculpin *Cottus bairdii*.

Our results showed that decreased slope and distances would lead to higher passage success for the five species. For the entire length of the fishway (6.1 m), all species had very high passage probabilities (> 0.9) at the lowest slopes 2 and 4%, and for all species except the Topeka Shiner, the 6% slope also had high passage probabilities (> 0.8). At 8% and 10% slopes, passage success for these species decreased drastically (< 0.31) and would not be recommended for longer fishways (> 2.03 m between resting areas). Based on these results, managers designing fishways for these species should be

able to pick ideal combinations of slope and length to successfully allow passage of an acceptable proportion of the fish to attain management goals.

ACKNOWLEDGEMENTS

This research was funded by the U.S. Fish & Wildlife Service (agreement number FC17AC00758) and conducted at the Colorado State University Foothills Fisheries Laboratory. Thanks to the Thomas A. and Anne L. Shepherd Diversity Scholarship for allowing me to focus on graduate school and research. For their help with obtaining my study species as well as sharing their wealth of knowledge, I would also like to thank Colorado Parks & Wildlife, the J.W. Mumma Native Aquatic Species Restoration Facility (NASRF), and Neosho National Fish Hatchery who helped make this research possible. All work was completed under the approval of the Colorado State University Institutional Animal Care and Use Committee (protocol number 2734).

I would like to thank Chase Garvey, the best lab mate I could have asked for, for his friendship and help at the lab no matter the hour. Thanks to Jacob Eggers for his love and support, putting up with all of the crazy hours at the lab, helping me at the lab and in the field, and finding ways to lessen my stress and make me laugh. Thanks to Ike Thibedeau and Collin Farrell, who also helped make the graduate experience more enjoyable. Thanks to Tyler Swarr and Cole Brittain who provided useful insights from their graduate experiences working in the lab on similar projects. I am grateful to our team of technicians Logan Rowley, James Tarzon, Troy Stirling, Bella Bert, Chris Georgalos, and Sam Sherry as well as our volunteers who helped make our research go more smoothly and brought enthusiasm and merriment to the lab.

Special thanks to Dr. Larissa Bailey who kindly answered all questions I threw at her about Program MARK and modeling. I would also like to thank Jenn Logan, Boyd Wright III, Kendall Bakich, and Tory Eyre for the help collecting my study species in the field and for additional expertise on these species. Thanks to Ted Smith, Tom Mix, Jim Garcia, Roderick May, and Grant Langmaid for sharing their fish culturing knowledge as well as the fish they raised. I would like to thank my committee members, Dr. Yoichiro Kanno and Dr. Ellen Wohl for the support, guidance, and expertise they provided

to my graduate experience. Thanks to “Boiler Ben” of CSU Facilities Management who helped keep the lab running and water going to our fish.

Lastly, many thanks to my advisor Dr. Christopher Myrick for this opportunity, his friendship, mentorship, and support since the first class I took with him back in 2016. He always believed in me and what I could accomplish, for which I am greatly appreciative. Thanks for spending many late nights troubleshooting problems at the lab, providing guidance and solutions to the many challenges we faced, pushing me to be my best, and generally just having a cheerful attitude in the face of chaos.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DEVELOPING ROCK RAMP FISHWAY CRITERIA FOR FISHES OF REGIONAL CONSERVATION CONCERN

INTRODUCTION

Background

As human populations grow, so does the demand for resources. With continued expansion, we also see increased fragmentation of rivers by the instream structures required to support the growing need for drinking water, irrigation, and transport infrastructure. These instream structures can prevent the movement of many fish species by restricting or altogether preventing upstream and, in some cases, downstream movements. The United States National Inventory of Dams has records of >91,000 dams across the United States (US Army Corps of Engineers 2020), leaving only 2% of the rivers and streams unfragmented (Pringle 2003). Other infrastructure including road crossing structures such as culverts can also prevent movement of fish species (Bouska and Paukert 2010; Blank et al. 2011; Fuller et al. 2015). Temperate areas are the most fragmented globally by current dams, with fish in the order Cypriniformes experiencing particularly low habitat connectivity (Barbarossa et al. 2020). The inability to disperse and migrate across these barriers can have strong negative effects on species and their ability to complete their life histories and survive in our changing climate.

The fragmentation and impoundment of rivers can cause changes in fish assemblages including the reduction in populations of native species and the increased occurrence of nonnative species (Quist et al. 2005; Perkin and Gido 2011). It can cause declines in survival due to loss of access to resources such as food, thermal refugia, or spawning grounds (Perkin and Gido 2011). Negative effects may also extend beyond the aquatic system into the entire ecosystem, resulting in the loss of food sources, changes in water quality, changes in sediment transport, and loss of nutrient input (Pringle 2003; Barbarossa et al. 2020). This decrease in survival and abundance can lead to the listing of species as threatened or endangered at both state and federal levels.

Restoring River Connectivity Using Fish Passage Structures

Maintaining and restoring habitat connectivity is an increasingly important tool for mitigating the continued effects of climate change. Establishing connectivity for more than the larger-bodied, cold water species such as salmonids is essential, especially as they might not be the most vulnerable species due to their ability to more easily navigate obstacles and reach thermal refuges than small-bodied fish that share the same habitat (Birnie-Gauvin et al. 2019; LeMoine et al. 2020). Climate change is causing increasing temperatures, more frequent periods of drought, changes in flows regimes, stream drying, decreased dissolved oxygen, and shifts in ranges of temperate fish towards higher latitudes (Ficke et al. 2007; Falke et al. 2010; Comte et al. 2013; Hopper et al. 2020). Without connectivity, it becomes harder or impossible for fish to reach refugia during these disturbances and can ultimately lead to the reduction or extirpation of fish populations (Perkin and Gido 2012).

Removal of structures that disrupt stream connectivity can be costly and infeasible due to their unquestioned benefits to humans. One method to restore connectivity without removing structures or impeding their functionality is the construction of fish passage structures, or fishways. Large scale management for fish passage of migratory species began by the early 1900s, and fishways (sometimes referred to as fish ladders) and trap-and-haul operations are still the primary methods for restoring fish movement around otherwise impassable barriers (Grasty et al. 2021). A variety of types of fishways including pool-and-weir, vertical slot, Denil, rock ramp, and nature-like designs that have varied attraction and passage success are now being used to help restore connectivity for fish species (Bunt et al. 2012).

Originally, fishways were designed for the passage of large anadromous species, primarily salmonids (Katopodis and Williams 2012), but as growing numbers of small-bodied fish species are recognized as threatened or imperiled, fishway designs are changing to improve passage of a variety of species with different swimming abilities (Ficke 2015; Swarr 2018; Richer et al. 2020). Designs of fishways are frequently limited by space, cost, and flow where efforts to balance these can be challenging to also achieve ideal conditions for successful passage of target species (Birnie-Gauvin et al. 2019). The passage success of fishways is often lower than intended due to design flaws such as poor attraction efficiency and poor passage efficiency, and in many cases, the functionality is never evaluated after installation (Calles and Greenberg 2009). The type of fishway is another important consideration, as fishways that are effective in passing some species may limit the passage of others. For example, fishways designed for salmonids were found to have very low passage of Australian native fish species, with < 1% of the most abundant species able to successfully ascend (Mallen-Cooper and Brand 2007). Our research project was designed to collect data on fishway slope and length that should help maximize passage efficiency of rock ramp fishways for a select group of small-bodied fishes.

Determining the swimming ability of different species is vital to designing passage structures that will enable fish to circumvent barriers. Varying morphologies, size, swimming modes, and swimming behaviors of target species will affect passage success and should be considered in the design of fishways (Katopodis et al. 2001). Some studies use swim chambers to determine the maximum velocities and endurance of fish in order to extrapolate how far and how fast they can swim (Adams et al. 2000; Katopodis et al. 2001). However, the maximum swimming velocities of fish measured in swim chambers does not necessarily reflect the passable distances at equivalent velocities under field conditions. A recent study of Longnose Dace *Rhinichthys cataractae* found that this species was able to successfully navigate higher velocities and longer distances than what was previously estimated by performance in a swim chamber as they allow for more natural swimming behaviors (Dockery et al. 2017). Another study found that Smallmouth Bass *Micropterus dolomieu* could ascend an open raceway against water velocities twice that of the predicted maximum based on swimming trials in respirometers (Peake 2004). The use of a full-scale experimental rock-ramp fishway allowed us to realistically replicate passage structures that will be encountered by fish under field conditions while still providing control over variables such as fishway slope, water velocity, water temperature, and substrate type, which are all important aspects of rock ramp fishway design (Swarr et al. 2023).

Rock ramp fishways have a more natural appearance and cater to a wide range of species with varying swimming abilities, often by providing a wider range of hydraulic conditions that the fish can use. Studying the passage performance of fish species of interest prior to constructing and installing high cost fishways is prudent and effective. For example, a cast concrete rock ramp fishway designed using swimming abilities of Brassy Minnow *Hybognathus hankinsoni*, Longnose Dace *Rhinichthys cataractae*, Longnose Sucker *Catostomus catostomus*, and Brown Trout *Salmo trutta* installed on the Cache La Poudre River at the Fossil Creek Irrigation Diversion was evaluated for effectiveness of allowing passage by Richer et al. (2020). They found that all four target species did have at least one individual successfully pass through the structure, but saw lower passage success in the weaker-swimming species, Brassy Minnow (Richer et al. 2020). Slight changes in the slope of rock ramp fishways of this type can drastically change the passage success depending on the species (Swarr 2018). The cast concrete approach lends itself to being preformed or built in a modular format, and could potentially reduce the cost of fishway installation.

We evaluated the effect of rock ramp fishway slopes of 2-10% on the passage success of five species of conservation concern. The target species tested in this experiment were the Topeka Shiner *Notropis topeka*, Suckermouth Minnow *Phenacobius mirabilis*, Rio Grande Chub *Gila pandora*, Rio Grande Sucker *Catostomus plebeius*, and Mottled Sculpin *Cottus bairdii*. These species are mostly species of great conservation concern for managers in their native ranges.

MATERIALS AND METHODS

Study Species

Topeka Shiner

The Topeka Shiner was federally listed as an endangered species in 1998 under the Endangered Species Act (ESA) because of declining numbers caused by reduced habitat quality from destruction, modification, and fragmentation (US Office of the Federal Register 1998). This species prefers slower water velocities and relatively cooler prairie streams, but due to habitat loss and degradation, are now restricted to 10% of their original range (Campbell et al. 2016). Some studies have already taken place to measure swimming abilities of this species and their ability to navigate culverts, but this study looked specifically at their ability to navigate a rock ramp fishway that can be used to provide passage over instream barriers of moderate height (Adams et al. 2000; Bouska and Paukert 2010; Blank et al. 2011).

Suckermouth Minnow

Suckermouth Minnow are listed as a state endangered species in Colorado and a Species of Greatest Conservation Need in both Colorado and Wyoming as they have become rare, and populations continue to decline due to habitat alteration and fragmentation (Quist et al. 2005; Perkin and Gido 2012). In Colorado, it is native to the Arkansas and South Platte River drainages, but it also has a broader distribution on the Great Plains in the Missouri and Mississippi basins. This species' swimming ability in a closed swimming flume was measured by Ficke (2015) but performance in a rock ramp fishway has not been tested prior to this research.

Rio Grande Sucker

In Colorado, Rio Grande Sucker were listed as state-endangered in 1993 and are a Tier 1 Species of Greatest Conservation Need. They are also a focus of conservation efforts in New Mexico. This species has declined drastically in its native range of the Rio Grande drainage in both Colorado and New Mexico likely as a result of habitat fragmentation and the introduction of nonnative species (Rees and Miller 2005). There are no studies to date on this species' swimming performance or passage requirements, though they have been the subject of field-based passage projects (C. Brittain, USFWS, pers. Comm.).

Rio Grande Chub

The Rio Grande Chub is listed a species of special concern in Colorado as well as a Tier 1 Species of Greatest Conservation Need in Colorado, State Threatened in Texas, and is also a focus of conservation efforts in New Mexico. This species was historically found in the Rio Grande Basin, Pecos River Basin, and the San Luis Closed Basin, though it is now also found in the Gunnison River and San Juan River Drainages due to historical and accidental stocking (Rio Grande Chub and Rio Grande Sucker

Conservation Team 2021). They prefer cool temperature (max of 20.5°C) and are found in low gradient streams, often in deeper pools (Bestgen et al. 2003b). Like the Rio Grande Sucker, there is no information on their swimming performance or passage requirements, so the project findings could help influence recovery plans for the Rio Grande Chub as well.

Mottled Sculpin

Mottled Sculpin are not currently a species of conservation concern but are found in areas where passage structures are being installed for trout and other migratory species, so having information about their abilities can provide additional insight on the use of these structures by this species. The swimming ability of this species has been tested in a Blazka-type swim chamber, but not a rock ramp fishway prior to this study (Aedo et al. 2009). After the individuals of this species were collected for this study, broader genetic testing of Colorado sculpin populations suggested that these fish may actually be different species than the presumed *Cottus bairdii* (Young et al. 2022). However, for this study, we will consider them to be Mottled Sculpin until a more conclusive understanding on the genetics and distribution of the closely-related intermountain west sculpin species is gained.

Fish Collection and Holding

Fish were collected from wild populations when possible to better represent target populations. Suckermouth Minnow were collected from the South Platte River in eastern Colorado using a barge electrofishing setup mounted with a GPP (Generator Powered Pulsator, Smith-Root Inc.). Mottled Sculpin were collected from three locations (the White River near Buford, CO; Gore Creek near Vail, CO; and the Frying Pan River near Basalt, CO) using electrofishing including a Smith-Root Inc. LR-24 Electrofisher, and a bank shocking setup with a GPP. Due to low population levels and availability, the Rio Grande Chub, Rio Grande Sucker, and Topeka Shiners were obtained from hatcheries. The Rio Grande species were obtained from the J.W. Mumma Native Aquatic Species Restoration Facility (NASRF) in Alamosa, CO. Topeka Shiners were obtained from the Neosho National Fish Hatchery in Neosho, MO. All fish were transported back to the Colorado State University (CSU) Foothills Fisheries Laboratory (FFL), where they were held for testing.

Fish were held in 340-L circular tanks, separated by species. Tanks received continuous flow-through water that was air-saturated and thermally regulated to match the collection temperature, then adjusted to the desired testing temperatures (20°C for Topeka Shiner, Suckermouth Minnow, and Rio Grande Sucker, and 16°C for Mottled Sculpin and Rio Grande Chub). To compare more directly with previous studies (Swarr 2018; Brittain 2022), we tested at 20°C unless this temperature approached the upper thermal tolerance of the species; in those cases we decreased temperatures to 16°C to more closely match their native habitats and avoid negative effects of approaching their thermal limits. Water temperatures were regulated (± 1.0°C) using computer-controlled solenoid valves. Fish were kept on a photoperiod of 14L:10D light cycle. The fish were fed daily on a satiation diet of frozen bloodworms, frozen brine shrimp, and when possible, tropical flakes and trout pellets (Skretting, Tooele, Utah; Rangen, Buhl, Idaho), 1.5-3 mm in diameter.

PIT Tagging Procedure

Each fish was internally tagged with a passive integrated transponder (PIT) for tracking passage success in the experimental fishway and individual identification. Rio Grande Chubs (47-74 mm TL) and Topeka Shiners (57-70 mm TL) received 9-mm x 2.15-mm full duplex tags (Biomark, Boise, Idaho), while the Rio Grande Sucker (76-138 mm TL), Suckermouth Minnow (61-105 mm TL) and Mottled Sculpin (88-141 mm TL) received 12-mm x 2.15-mm full duplex tags (Biomark, Boise, Idaho). Tag size did not vary within a species to reduce the effect of potential differences in detection. Fish were tagged using the surgical procedure described by Swarr et al.(2022).

Fish were fasted for 48 hours prior to tagging. Fish were anesthetized with buffered tricaine methanesulfonate (25-75 mg/L). Once the fish lost equilibrium in the anesthetic bath, they were weighed (g) and measured (total length: TL, in mm) prior to tagging. PIT tags were surgically inserted into the abdominal cavity rather than injected to reduce the mortality due to the small body sizes of the five study species (Archdeacon et al. 2009). A scalpel was used to make a 2–mm incision anterior of the vent and offset from the midline, and then a PIT tag was gently inserted into the incision. After insertion, the fish were returned to the tank to recover and API® Stress Coat+™ was added. Fish were given at least one week or until the incision had fully healed before use in any passage experiments.

Fish Passage Structure

Trials were conducted in the 9.1 x 1.2 x 0.6 m recirculating flume previously constructed at the FFL as described by Swarr et al. (2023) and modified by Brittain (2022). A 6.1-m long rock-ramp fishway designed to resemble the cast-concrete type fishways used in Colorado (Richer et al. 2020) connects two resting pools of about 1.5 m in length. Two concrete cinder blocks were placed in the lower resting pool to provide cover. Various cover elements including concrete cinder blocks, PVC pipe shelters, and bricks were placed in the upper resting pool to provide cover to fish that successfully ascended the fishway. The slope of the flume was adjusted from 2 - 10%, and the surface of the fishway was fitted with large roughness elements (95-mm diameter molded polyethylene rocks) installed in a chevron pattern with spacing of 95 mm and small cobble (18-24 mm) on the rest of the surface determined by Brittain (2022) as maximizing passage rates despite higher velocities (Figure 1). The small cobble substrate was secured to the fishway floor with a strong adhesive between the larger roughness elements.

Water was delivered to the flume by a variable speed 15 hp (11.19 kW) Vertiflo model 832 vertical pump from a 22,700-l sump located outside the FFL. The pump output was adjusted to maintain an average water depth of 55 mm from 40 standardized locations throughout the rock ramp at each slope. Water flowed through the flume into a large aluminum sump tank before returning to the large outdoor sump though a 30.48-cm diameter return line. Water velocities were measured using a Flowtracker2® Handheld Acoustic Doppler Velocimeter (Xylem Inc.) at five points along eight transects spaced at 0.61–m intervals along the fishway. Water temperature was controlled using a TITAN® inline water heat/cool pump (model HP-2; AquaLogic Inc., San Diego, California) to match the temperatures of the holding systems and the testing temperatures.

Four PIT tag antennas installed under the floor of the fishway at 2.03-m intervals allowed detection of fish as they move through the fishway. Each antenna was connected to a IS1001-12V PIT tag reader (Biomark, Boise, Idaho). The first antenna monitored the fishway entrance to help quantify their motivation in entering the fishway (Silva et al. 2018). The fourth antenna was located at the top of the fishway (its exit) to account for the complete passage of fish through the fishway. Intermediate antennas helped increase precision of passage probability estimates and provide data on partial passage and fatigue distances that can further benefit fishway designs. The antennas were synchronized to reduce interference from each other due to their proximity to each other.

Experimental Approach

Passage in the rock ramp fishway was measured at slopes of 2 - 10% in 2% increments, beginning at 10% and ending at 2% for each species. The fish of the same species were randomly selected to be tested at a single slope, and each individual fish was tested up to three times at that slope to reduce the total number of fish needed for the study. Fish were moved from their holding tanks to the downstream pool of the experimental fishway in groups of ten fish per trial with a total of nine replicates. The nine replicates provide enough data for calculating passage probabilities, as determined by Swarr (2018) and preliminary Cormack-Jolly-Seber simulations in program MARK. They were given a maximum of 20 hours to ascend the structure, with 10 h of uninterrupted light followed by 10 h of uninterrupted dark. Trials began at 11:30 and ended at 07:30 the following morning. Total passage success was defined as a complete ascent of the rock ramp as determined by a detection at the fourth antenna or being located in the upstream refuge pool at the end of the trial. Due to environmental variability, temperatures did fluctuate some so water temperature was recorded every ten minutes throughout the trial using a Pendant® MX Temp logger (MX2201, Onset® HOBO®, Bourne, Maine) to provide an average water temperature for each trial.

At the end of each 20-h experimental run, fish were removed from the flume, fed, and given at least 48 h recovery period before being tested again. The fish were euthanized after their last trial (250 mg/L MS-222) based on Colorado Parks and Wildlife (CPW) or United States Fish and Wildlife Service (USFWS) policy. Specimens were preserved and donated to the CSU ichthyology collection and to CPW for research purposes.

Data Analysis

Passage Probabilities

Data were analyzed in Program MARK (White and Burnham 1999) with a Cormack-Jolly-Seber (CJS) model to determine the probability of passage as a function of slope and to estimate detection probability of the fish at each antenna (Burnham et al. 1987). This model has been used to estimate survival rates over time of many species using mark-recapture data with imperfect detection. For this study, the recapture data came from PIT tag detections by each antenna along the flume. Unlike many CJS models, the survival estimate quantifies the transition probability from the bottom to the top of the rock-ramp fishway, with the ability to accurately estimate the probability of successfully entering the fishway and navigating to each distance or antenna location (2.03, 4.07, and 6.01 m) rather than describing apparent survival or mortality over time (Swarr 2018).

Data were recorded in the format of an encounter history, beginning with placement in the flume, detection at the first, second, third, and fourth antenna, as well as if fish were found in the upper refuge area above the fourth antenna at the end of a trial. For example, this could provide encounter histories of 111111, if a fish was detected at all antennas and found in the upper refuge area at the end of the trial, or 110000 if the fish was placed in the flume and detected only at the first antenna during the length of the trial. These data were used to estimate the full or partial passage success at each slope.

Passage probabilities (φ) were modeled separately for each species based on assumed differences in swimming abilities as seen in other species (Ficke et al. 2011). For the analyses, to avoid confounding φ_4, detection in the upper refuge pool at the end of the trial was recorded, and the p_6 parameter was fixed to 1.0 (Figure 2). The φ_5 parameters were estimated separately from the other φ estimates, and were modeled to be constant across slopes for the passage success to the antennas due to the difference in nature of detection at and passage to the upper refuge area. A variety of models were fit to the data, and the best model was chosen using Akaike Information Criterion (AICc) values to provide the probability of passage success for each distance and slope for each species. A series of models were fit to the data in a stepwise procedure. First, we modeled all combinations of the main effects of slope and distance on the passage probability (φ) along with effects of slope and differences between antennas on the detection probabilities (p). Second, using the most supported models (ΔAICc < 2), we then investigated possible slope thresholds for passage success and linear effects models. Third, additional covariates were investigated to attempt to improve model fit of the most supported models (ΔAICc < 2) from the main effects models including fish total length (TL, mm), average water temperature during the trial (°C), prior experience in the fishway (yes=1,no=0), and which trial the fish was completing (1, 2, or 3) to demonstrate different effects of each trial such as a learning effect that could improve passage with additional experience in the fishway (Morin et al. 2020).

The estimated passage probabilities based on the top models were then used to help specify design recommendations for the development of future rock-ramp fishways to improve passage of our five species of interest. The cumulative passage to each distance (antenna) was calculated by multiplying the passage probabilities together. For example, probability of total passage of the rock ramp fishway would be $\varphi_{\text{total}} = \varphi_1 \times \varphi_2 \times \varphi_3 \times \varphi_4$.

To better understand how fish use the fishway, we also looked at the time that fish were moving through the rock ramp. Detections of fish were recorded with a time stamp that enabled us to look at when fish were using the fishway by calculating the total number of detections by time during the trials. The antenna readers were programmed to have a 10-s delay in recording detections for the same PIT tag to reduce the total number of detections if a fish held position over an antenna for an extended period. Data from the 2% slope were used to compare activity during the day and night, as fish were most likely to be able to fully ascend the fishway at this slope. Detections from antenna 4 were not included because detections at this antenna signified that the fish successfully ascended the fishway and exited the rock ramp section of the flume. Fish also frequently remained within range of this antenna for significant periods of time which would not accurately represent the time of active movement within the rock ramp section of the flume. We also looked at the time of the first successful ascent for each individual as determined by the time of their first detection on antenna 4 for each trial at each slope.

RESULTS

Effects of Slope

All five species exhibited a strong interest in ascending the fishway at all slopes as demonstrated by detections on the first antenna, with passage probability estimates for all slopes and species to the first antenna being close to 1.0 ($\varphi_1 \geq 0.945$). Detection probabilities were high for each antenna at every slope, with the lowest detection probability of $p = 0.918$ (Table 1). Decreasing the slope of the fishway was positively correlated with increasing fish passage success for Suckermouth Minnow, Rio Grande Sucker, Rio Grande Chub, Mottled Sculpin, and Topeka Shiner. We also saw higher passage probabilities for shorter distances. The lowest three slopes (2 - 6%) passed a majority of each species the entire length of the fishway, with marked decreases in passage success at the highest slopes (8 - 10%). There was some difference in passage success between species. At slopes where they were able to successfully ascend the fishway, we did see some individuals making multiple ascents of the fishway. We also saw that first successful ascents of the fishway often occurred in the first hour or two of the trial, with a secondary spike in activity when the lights turned off (Figure 3).

Topeka Shiner

The Topeka Shiner's passage success was affected by both slope and distance, with high levels of success at 2 and 4% slopes, and decreasing rates of success as both slope and distance increased at 6-10% (Figure 4). Only two individuals successfully ascended the entire fishway at 8% and no fish successfully ascended the fishway at 10%. The top model included an interactive effect of slope and distance with additive effects of experience and total length on passage success. Similarly supported models (ΔAICc < 2) all had interactive effects of slope and distance on passage success, but varied in the covariates with either experience, TL, temperature, or trial effects (Table 3). These models all had similar estimates for passage success.

Behaviorally, this species was observed using the angled margins of the trapezoidal fishway cross-section to ascend the flume. They sometimes held their longitudinal position by letting the water press them up against the small cobble substrate and sheltered behind small cobble and the larger roughness elements. Looking at their time of movement using detections during the 2% slope trials, this species moved more during the 10 hours of darkness with 78.7% of the 9,946 detections occurring during the night.

Suckermouth Minnow

The Suckermouth Minnow had very high passage success at the lower slopes (2 - 6%) with lower passage success at the higher slopes (Figure 5). At the two highest slopes, passage probability decreased rapidly with increasing distance along the rock ramp fishway. The best supported model included an additive slope and distance effect on passage success, with a threshold up to 4%, and had an estimated constant detection of $p = 0.992$ across all slopes and antennas. The covariates did not appear to improve the model fit enough to outweigh the cost of additional parameters, and the top main effects model still had the lowest AICc value (Table 4). Any models with covariates that were similarly supported had only one additional covariate, and are most likely acting as pretending variables. Therefore, I chose to use the estimates from the top main effects model for the passage estimates.

The Suckermouth Minnow at 2% slope did move more in the dark, with 83% of the 39,471 detections during the night. Individual fish of this species were also detected ascending and descending the fishway multiple times during the trial, especially at the lower slopes. The average number of complete ascents per individual during a trial at 2% was 11.13 (SD = 9.11) with a maximum of 45 transits by one individual in one trial.

Rio Grande Sucker

The Rio Grande Suckers had high passage success up to 6% slope, then passage success decreased at the highest two slopes. The top model for this species had an interactive slope and distance effect on passage success and additive trial and total length effects, with a threshold up to 4% (Table 5). This model also had detection varying by antenna, with a slightly lower estimate of detection for the lowest antenna. This was likely due to their behavior of staying over that antenna for longer periods of time that reduced the ability of the antenna to pick up other tags due to interference and tag collisions. The top model also had positive trial and total length effects, where later trials and larger fish had higher passage probabilities. The Rio Grande Sucker had high passage probabilities at 2%, 4%, and 6% slopes, at 0.942, 0.942, and 0.832, respectively (Figure 6). Despite these passage probabilities being less than 1.0, we did see every individual successfully ascend the entire fishway at 2% and 4%, suggesting they chose not to try to ascend the entire fishway during some of the trials. Again, at the higher slopes, we did see a large decrease in passage probability of ascending the entire fishway with passage probability estimates of 0.306 and 0.085 for 8% and 10%, respectively.

The Rio Grande Suckers moved more during the night than the day with 93.7% of the 11,813 detections occurring at night during the 2% slope trials. Behaviorally, this species was observed darting from one larger roughness element to the next, pausing behind them especially at higher slopes, as well as staying near the edges of the fishway during ascent attempts.

Rio Grande Chub

The Rio Grande Chub passage success was affected by slope and distance, with high passage success at 2-6% slopes and declining success at the 8 and 10% slopes. The top model included a linear effect of slope in addition to additive distance, trial, and TL effects on passage success (Table 6). The RGC had high estimates of passage success (approximately 1.0) at 2% and 4%. At 6% there was a small decrease in passage probability ($\varphi = 0.814$), though a majority of fish still successfully ascended the fishway (Figure 7). At slopes of 8% and 10% the RGC had much lower estimated passage probabilities ($\varphi < 0.122$).

Frequency of movement was very similar between day and night, with 46.6% of the 24,530 detections occurring during the day. There was an increase in detections during the first hour of darkness. This species was observed using both the slanted edges of the fishway as well as darting in and out from behind the larger roughness elements, and sometimes pausing in the velocity refuges created by the roughness elements.

Mottled Sculpin (Cottus spp.)

The Mottled Sculpin had high passage success at the 2-6% slopes ($\varphi = 0.955$), which then decreased as slope and distance increased (Figure 8). The top model included a threshold effect of slope at 2-6% with an interactive effect with distance as well as effects of TL and temperature on passage success (Table 7). There was variation in detection probabilities based on slope and antenna which is likely in part due to behavior. Individuals were seen holding position in the fishway on top of the antennas at the lower slopes which would cause a second fish swimming over the antenna at the same time to be undetected due to tag interference.

Mottled Sculpin also moved more during the night than the day, with 62.6% of 15,897 detections occurring at night. The sculpin held position along the bottom of the fishway, resting on the small cobble substrate. Individuals of this species also used the slanted edges of the fishway rather than the middle section, with one observed sitting nearly out of the water where it was still getting splashed, similar to the behavior of the Arkansas Darters *Etheostoma cragini* reported by Brittain (2022).

DISCUSSION

Our results demonstrated that the passage success of the five species tested in this study is maximized with either lower rock ramp fishway slopes (≤ 4 – 6%), or, when steeper fishways are used, with shorter distances. These results can be used to maximize passage success for these species in cast-concrete type rock ramp fishways with a small cobble substrate by choosing the best combinations of slope and distance. For all species, fishways of 6.1-m in length at slopes of 2% and 4% would pass a majority of fish ($\varphi \geq 0.903$) of the size ranges tested. For the Suckermouth Minnow, Mottled Sculpin, Rio Grande Sucker and Rio Grande Chub, 6.1-m fishways at 6% slope would still pass a large proportion of fish ($\varphi \geq 0.814$) and could still be considered as an acceptable design depending on the management requirements and the level of passage deemed appropriate. However, passage success could still be maximized for these species at higher slopes if the fishways include short distances between resting/recovery areas. For example, despite the total passage for Rio Grande Suckers at 8% slope being lower ($\varphi = 0.306$), passage to the second antenna was still very high ($\varphi = 0.941$), so a fishway that had 2.03-m long segments between resting pools would theoretically successfully pass most of the fish, provided that there was not a cumulative fatigue effect. A study on Sockeye Salmon *Oncorhynchus nerka*, Chinook Salmon *O. tshawytscha*, and Steelhead *O. mykiss* showed decreased passage success when they had to ascend eight fish passage structures compared to four (Keefer et al. 2021). It may also be essential to evaluate the post-passage effects on fish, as they may reduce health and survival despite passage success (Roscoe et al. 2011).

Topeka Shiner were the weakest swimmers based on passage estimates, which may reflect their distribution in low gradient Great Plains systems. At slopes above 4%, passage success declined dramatically, with total passage probabilities being 0.309 for 6% and < 0.021 for 8% and 10% slopes. However, they still had high passage probabilities to the second antenna at 6% and 8%, so fishway segments 2.03-m or less in length at these slopes could still be effective in restoring connectivity for this species when using 2- 4% slopes is not feasible. Another study tested the swimming abilities of this species using a swim chamber. They suggest that at velocities < 35 cm/s, Topeka Shiner can swim indefinitely, but velocities > 60 cm/s require burst swimming and need refuges for them to recover (Adams et al. 2000). Though these types of swimming tests can provide approximate estimates of how a fish will perform in a fishway, they are known to affect the behavior and performance of fish that may not accurately represent their abilities (Dockery et al. 2017). Average flows in the fishway for each slope were 49.6 cm/s (2%), 67.1 cm/s (4%), 72.4 cm/s (6%), 99.3 cm/s (8%), and 108.5 cm/s (10%) (Table 8). Based on these results, in the experimental rock ramp fishway at 2% with flows of 49.6 cm/s, Topeka Shiner should only have successful passage to 3.1 m, and the 4% flows should be unnavigable (Figure 9). However, the roughness elements and small cobble creating more complex flows, lower velocity boundary layers, and potential velocity refuges in the fishway that likely allowed the Topeka Shiners in this experiment to successfully ascend the greater distance of 6.1 m by taking advantage of the small refuge areas and low velocity side margins (Brittain 2022). Due to the high passage probability ($\varphi = 1.0$) at 2%, it is even possible they could successfully ascend longer distances than tested in this research, as suggested by the results described by Bouska and Paukert (2010). The substrate and larger roughness elements in the fishway likely enabled these fish to take refuge from higher flows when they needed and allowed them to navigate longer distances more successfully than predicted by the forced swimming experiment where they could not exhibit these natural swimming behaviors. Our results were similar to those of Bouska and Paukert (2010) and Blank et al. (2011) where Topeka Shiner had successful passage at slopes up to 2.12% through culverts and box culvert and low-water crossing designs at slopes up to 4.3%. Our results suggest that successful passage in a steeper culverts or crossings could be possible, but may require shorter distances between resting areas such as the typical baffled culvert design (Olsen and Tullis 2013).

Suckermouth Minnow, another Great Plains minnow species, were stronger swimmers relative to Topeka Shiners and had very high passage probability estimates at up to a 6% slope. Despite the passage probability estimate for 6% slope dropping below 1.0, only one individual fish did not successfully ascend the entire fishway during its three trials. This particular fish did make it to the second antenna (2.03 m). Based on this information, a 6.1-m long fishway at a slope of 6% or less should pass all, or nearly all, Suckermouth Minnow. However, at 8% slope we saw a drastic decrease in passage success. Shorter fishway lengths at this slope combined with resting areas could still allow sufficient passage depending on the management goals as passage probability was still high at $\varphi = 0.920$ to 2.03 m, and dropped to $\varphi = 0.490$ to 4.06 m. In a swim chamber, Suckermouth Minnow had maximum aerobic swimming speeds of 45 cm/s and maximum anaerobic swimming velocities of 87 cm/s (Ficke 2015). Based on the average water velocities of the 8% and 10% slopes exceeding these reported maximum anaerobic swimming velocities, it is not surprising that this species had lower passage success rates at these two slopes.

Rio Grande Suckers had passage probability estimates fairly similar to those calculated for the Suckermouth Minnow, with high probabilities at slopes of 2-6% and lower probabilities for the 8% and 10% slopes. While this species did not ever have probabilities of 1.0, all individuals were able to successfully ascend the lowest two slopes at least once. This could suggest that if in a system they had only one fishway to navigate, there would be high success for this species. However, if they were required to ascend multiple fishways to reach a desired habitat or resource, they may have reduced passage success at subsequent fishways similar to the salmonid species studied by Keefer et al. (2021) or the Bighead Carp (Hypophthalmichthys nobilis) studied by Newbold et al. (2016). Another study looking at three other desert Catostomid species reported maximum swimming velocities of 93.1 cm/s for Desert Sucker *Catostomus clarki*, 86.6 cm/s for Bluehead Sucker *C. discobolus*, and 55.9 cm/s for Sonora Sucker *C. insignis* for individuals ranging from 61.5-81.5 mm in TL (Ward et al. 2003). Based on the high passage success of Rio Grande Sucker up to 6% slope where average velocities were 72.4 cm/s, we might see similar performances from the Desert and Bluehead Sucker in the rock ramp fishway, but lower performance from the Sonora Sucker. However, using one species' performance to predict another's would likely not be super accurate, as there is a lot of variability in the swimming performances of Catostomid species and evaluating each species' swimming abilities in a rock ramp fishway would be required to make better predictions (Underwood et al. 2014).

Rio Grande Chub had very high passage probability estimates for 2% and 4% slopes. At a 6% slope, passage probability was still high ($\varphi = 0.813$), but did decrease a little from 4% ($\varphi = 0.988$). This could reflect their preference and adaptation to the lower gradient streams of the Rio Grande Basin (Bestgen et al. 2003a). Depending on management goals, if passing approximately 80% of individuals was deemed acceptable by natural resource managers, a 6.1-m fishway at 6% slope could still be effective. If managers want to maintain passage probabilities closer to 1.0, then either shorter distances at 6% slope with resting areas or lower slopes would be recommended. One such fishway has been designed for Placer Creek near Fort Garland, Colorado to pass Rio Grande Cutthroat *Oncorhynchus clarki virginalis* and other aquatic species like the Rio Grande Sucker and Rio Grande Chub. This design is a rock ramp through a 12.2-m long corrugated metal pipe at a 3.5% slope (C. Brittain, U.S. Fish and Wildlife Service, personal communication). Though this distance is double the length of experimental fishway used in this experiment, based on high success of passage of the Rio Grande species at 2-4% slope as well as frequent multiple ascents by individuals in this study, it could still allow for high passage success. One limiting factor of this study is that we only tested individuals from one age class for both Rio Grande species; larger adults of these species may have different swimming abilities and therefore different rates of passage success than what was found in this study. Size, both body mass and total length, has been found to have an effect on the swimming performance of fish, where larger fish were able to achieve higher absolute swimming speeds (Ojanguren and Brana 2003; Mateus et al. 2008; Srean et al. 2017). However, despite larger individuals having higher maximum swimming speeds, passage success may not reflect this trend and could exhibit lower passage success as seen by Brittain (2022). To be certain that adult fish would have similar or superior passage success, further research using older and larger individuals would be required.

Sculpin species are threatened by increasing temperatures and are predicted to see decreasing patch sizes in their native ranges with climate change (Adams et al. 2015). Multiple *Cottus* species exist where fish passage structures have been installed for other species such as salmonids that have the potential to restore connectivity. Unfortunately, not all types of fish passage structures are effective in allowing passage of all species. In a study on the Prickly Sculpin *Cottus asper* and Coastrange Sculpin

Cottus aleuticus, five step-type ladders (heights of > 15 cm) intended for salmonids did not restore connectivity for the sculpin and indeed served as barriers to movement and limited their distributions (Lemoine and Bodensteiner 2014). In this study we saw that cast concrete type rock ramp fishways are effective at allowing successful passage of Mottled Sculpin, so this type of fishway may be a better option for restoring connectivity for more species, including the small-bodied native species. Mottled Sculpin did very well at slopes 2-6%, with our model suggesting passage success does not change until the slope exceeds 6%. A study testing the swimming ability of Mottled Sculpin in Utah found that mean burst velocities were 109.3-131.3 cm/s (juveniles-larger individuals) with mean prolonged velocities of 46.5-58.3 cm/s, where prolonged velocities were more accurately described as critical holding velocities (Aedo et al. 2009). The prolonged swimming velocities would predict lower passage success based on the average velocities recorded in our experimental fishway, but the sculpin took advantage of the substrate and roughness elements that allowed them to take make use of small-scale velocity refuges and successfully navigate the higher velocities.

The similarity in sculpin passage success for slopes ≤ 6% could provide more freedom for engineers and managers installing passage structures in typical salmonid habitats to create designs that will maintain high rates of passage success for more species yet still allow for a variety of design options depending on the site-specific requirements. For example, if the potential physical footprint for a fishway was small or there were financial limitations, a steeper fishway of 6% slope could reduce costs and space requirements, yet still allow acceptable passage success of this species to the same extent as a fishway of lower slope. Sculpin were seen holding in place along the fishway, a behavior also reported by (Webb et al. 1996). It is possible that sculpin were only able to hold positions effectively up to velocities seen at 6% slope (72.4 cm/s) and could rest as needed between bursts of swimming, but were unable to hold position and therefore would be required to sprint the length of the fishway at the higher velocities (99.3 cm/s) seen at 8% resulting in the lower passage success. However, monitoring behavior and passage velocities during transit attempts during the entire trial was outside the scope of this study.

One thing to consider with the sculpin used in this study is that the fish collected were considered *Cottus bairdii*. However, based upon genetic analyses that were underway during the study, we likely have multiple species of *Cottus* (*C. punctalatus* and *C. annae*) in Colorado; because the sculpin for this study came from three different rivers we may have used a mixture of these cryptic species (Young et al. 2022). If we can assume that the morphological and physiological differences between these species are negligible, these results should be useful for all areas in Colorado and potentially other areas of the United States. Other *Cottus* species have been found to be similarly limited by barriers which does suggest their swimming abilities may be comparable (Lemoine and Bodensteiner 2014). Future research into differences in swimming abilities between the various *Cottus* species may be warranted as more information and understanding is gained on the identification and distribution of the genus. It is not yet clear whether results from one sculpin can be used to successfully predict the swimming performance of other species of similar size, morphology, and habitat type.

Another consideration on applications of this study is that wild and hatchery raised fish may have different swimming abilities. It has been well established in multiple species including Atlantic Salmon *Salmo salar* and Rainbow Trout *Oncorhynchus mykiss* that there can be a negative effect of hatchery-rearing on the fitness and swimming performance of fish (McDonald et al. 1998; Reinbold et al. 2009). We can also see more deformities and morphological differences in individuals amongst hatchery-reared fish potentially caused by differences between the hatchery and natural environments, some of which may cause decreased swimming efficiency (Belk et al. 2008; Vehanen and Huusko 2011). Swimming performance has been found to be lower in multiple species including Flannelmouth Sucker (*Catostomus latipinnis*), Bonytail (*Gila elegans*), and Razorback Sucker (*Xyrauchen texanus*) reared in standing water, compared to their exercised or wild counterparts (Ward and Hilwig 2004). However, if we consider the hatchery-reared fish to be inferior swimmers, fishway designs that allow them to successfully ascend a fishway should also allow their wild and stronger counterparts to do the same.

Additional research may be required to improve our understanding and ability to recommend passable rock ramp fishways. It may be worth considering increasing the number of PIT tag antennas in test fishways, if possible, to increase the resolution of what distances between the 2.03-m intervals are passable (Swarr et al. 2023). It would also be advantageous to conduct further research into the attraction efficiency of this type of fishway. Though nature-like fishways may have higher passage efficiency, compared to pool-and-weir, vertical-slot, and Denil fishways, (Bunt et al. 2012) found that they were much worse in terms of attraction efficiency. Another study showed passage success for a variety of species when enclosed in a small area at the base of the fishway, but had relatively little passage success or no passage success depending on the species when solely released into the pool below the rock ramp fishway (Richer et al. 2020). This reinforces the concept that passage success alone is not enough to determine the effectiveness of a fishway, as Silva et al. (2018) and others have noted.

Due to the increased roughness of the fishway surface from the addition of more substrate, when using this design in the field we may need to consider what velocities will allow the fishway to self-clean so there is not excessive sediment deposition or incorporate a cleaning or flushing schedule if necessary. Accurately estimating the sediment transport can be challenging due to the larger number of variables and complexity of flows that need to be taken into account. We would need to consider the flows available for the fishway, the velocities that the fish can successfully navigate, the effects of the substrate on turbulence and boundary shear stress within the fishway, and the grain size and cohesion of the sediment located in the system that we would need to be able to transport (Wiberg and Smith 1989; Baki et al. 2015). Particle sizes and bed shear stress are very important in calculating the sediment transport in open channels, with slope and hydraulic radius strongly influencing the bed shear stress (Ketabdar 2017). Grain sizes will vary with each system and its longitudinal location, typically with downstream fining of bedload (Costigan et al. 2014). However, the effect of flow and shear stress may vary, and in low-density larger substrate situations could underpredict the sediment transport capabilities (Papanicolaou et al. 2001). Measuring the turbulence and shear stress within the fishway would be useful for determining necessary flows to enable adequate sediment transport but was outside the scope of this study. This is an example of another design or operational consideration for a successful fishway installation, wherein including design or operational guidelines to periodically flush the sediment from within a cast concrete fishway would be necessary.

Restoring connectivity in the face of climate change will be essential, especially for the species in the more heavily affected areas like the Great Plains where we are seeing the decline and sometimes loss of native species due to depletion of groundwater, altered hydrographs, and habitat fragmentation (Falke et al. 2010). Despite being adapted to harsh conditions, many Great Plains fish are in decline as the hydrologic changes and habitat fragmentation exceed the limits of their plasticity (Perkin et al. 2015). The Rio Grande drainage basin is also subject to increasing habitat fragmentation and habitat degradation leading to declines in native species like the Rio Grande Sucker and Rio Grande Chub (Galindo et al. 2016). Connectivity is essential for conserving native species not only to allow them short term refuge, but also to enable the shifts in distribution to higher elevation that has been seen world-wide already (Comte et al. 2013). By restoring connectivity, it might help these affected areas and their biodiversity become more resilient with the changing climate.

Though restoring connectivity for native species is important, it is also necessary to consider the implications of such measures. In areas where we have invasive species that predate upon or outcompete the native species, maintaining fragmentation can also be a valuable management tool for conservation of native species (Perkin and Gido 2012; King and O’Hanley 2016). Isolation strategies have been successful in conservation of native trout species, but it is important to weigh the trade-offs in each management setting to determine the most beneficial solution for the ecosystem and its species as a whole (Fausch et al. 2009).

TABLES

Table 1. The size distribution and mean size ± standard deviation in total length (mm) and weight (g) of the five species tested in the rock ramp fishway.

Species	Total Length Distribution (mm)	Mean Total Length (mm)	Weight Distribution (g)	Mean Weight (g)
Topeka Shiner	55-77	70 ± 3.8	1.4-4.3	3.0 ± 0.5
Suckermouth Minnow	61-105	87.4 ± 9.2	2-10	5.6 ± 1.8
Rio Grande Sucker	76-138	106.7 ± 10.4	4-29	13.1 ± 4.0
Rio Grande Chub	47-74	57.3 ± 5.1	1-3.8	1.9 ± 0.5
Mottled Sculpin	88-141	112.9 ± 9.9	7.9-35.2	17.9 ± 5.0

Table 2. The estimated detection probabilities for each antenna (A1-A4) at each slope (2-10%) for each species.

Slope	Antenna	Topeka Shiner	Suckermouth Minnow	Mottled Sculpin	Rio Grande Sucker	Rio Grande Chub
2%	A1	1.000	0.992	0.985	1.000	1.000
	A2	0.986	0.992	0.980	1.000	1.000
	A3	1.000	0.992	0.974	1.000	0.988
	A4	1.000	0.992	1.000	0.993	1.000
4%	A1	1.000	0.992	0.982	1.000	1.000
	A2	0.986	0.992	0.976	1.000	1.000
	A3	1.000	0.992	0.968	1.000	0.988
	A4	1.000	0.992	1.000	0.993	1.000
6%	A1	1.000	0.992	0.953	1.000	1.000
	A2	0.986	0.992	0.936	1.000	1.000
	A3	1.000	0.992	0.918	1.000	0.988
	A4	1.000	0.992	1.000	0.993	1.000
8%	A1	1.000	0.992	1.000	1.000	1.000
	A2	0.986	0.992	1.000	1.000	1.000
	A3	1.000	0.992	1.000	1.000	0.988
	A4	1.000	0.992	1.000	0.993	1.000
10%	A1	1.000	0.992	1.000	1.000	1.000
	A2	0.986	0.992	1.000	1.000	1.000
	A3	1.000	0.992	1.000	1.000	0.988
	A4	1.000	0.992	1.000	0.993	1.000

Table 3. Cormack-Jolly-Seber models used to estimate the passage success (φ) and detection probability (p) for Topeka Shiner. The top ten models based on AICc are shown. Effects included slope, distance, antenna, fish total length (TL), trial, experience, and average temperature (Temp, °C).

Model	AICc	ΔAICc	AICc Weights	Model Likelihood	Num. Par	Deviance	-2log(L)
{φ(Slope*Distance+Experience+TL)p(Antenna)}	909.8282	0	0.15986	1	27	854.9096	854.9096
{φ(Slope*Distance+Experience)p(Antenna)}	910.3338	0.5056	0.12415	0.7766	26	857.4813	857.4813
{φ(Slope*Distance+TL)p(Antenna)}	910.4625	0.6343	0.11641	0.7282	26	857.61	857.61
{φ(Slope*Distance+Experience+TL+Temp)p(Antenna)}	911.4373	1.6091	0.0715	0.4473	28	854.4501	854.4501
{φ(Slope*Distance+Trial+TL)p(Antenna)}	911.6186	1.7904	0.06531	0.4085	27	856.7	856.7
{φ(Slope*Distance+Experience+Temp)p(Antenna)}	911.9174	2.0892	0.05624	0.3518	27	856.9988	856.9988
{φ(Slope*Distance+Trial)p(Antenna)}	912.05	2.2218	0.05264	0.3293	26	859.1975	859.1975
{φ(Slope*Distance+TL+Temp)p(Antenna)}	912.5036	2.6754	0.04195	0.2624	27	857.585	857.585
{φ(Slope*Distance+Experience+TL)p(.)}	912.5985	2.7703	0.04001	0.2503	24	863.8708	863.8708
{φ(Slope*Distance+Temp)p(Antenna)}	912.9189	3.0907	0.03409	0.2132	26	860.0664	860.0664

Table 4. Cormack-Jolly-Seber models used to estimate the passage success (φ) and detection probability (p) for Suckermouth Minnow. The top ten models based on AICc are shown. Effects included slope, distance, antenna, fish total length (TL), trial, experience, and average temperature (Temp, °C).

Model	AICc	ΔAICc	AICc Weights	Model Likelihood	Num. Par	Deviance	-2log(L)
{φ(threshold 2=4, Slope+Distance)p(.)}	958.9336	0	0.1975	1	9	940.8368	940.8368
{φ(threshold 2=4, Slope+Distance+Trial)p(.)}	960.393	1.4594	0.0952	0.482	10	940.2746	940.2746
{φ(threshold 2=4, Slope+Distance+Experience)p(.)}	960.6866	1.753	0.08221	0.4163	10	940.5681	940.5681
{φ(threshold 2=4, Slope+Distance+Temp)p(.)}	960.7647	1.8311	0.07906	0.4003	10	940.6462	940.6462
{φ(threshold 2=4, Slope+Distance+TL)p(.)}	960.7804	1.8468	0.07844	0.3972	10	940.662	940.662
{φ(threshold 2=4, Slope+Distance+N)p(.)}	960.9552	2.0216	0.07187	0.3639	10	940.8368	940.8368
{φ(threshold 2=4, Slope+Distance+Trial+Temp)p(.)}	962.2052	3.2716	0.03847	0.1948	11	940.063	940.063
{φ(threshold 2=4, Slope+Distance+Trial+TL)p(.)}	962.2291	3.2955	0.03801	0.1925	11	940.0869	940.0869
{φ(threshold 2=4, Slope+Distance+Trial+N)p(.)}	962.4168	3.4832	0.03461	0.1752	11	940.2746	940.2746
{φ(threshold 2=4, Slope+Distance+Experience+Temp)p(.)}	962.5261	3.5925	0.03277	0.1659	11	940.3839	940.3839

Table 5. Cormack-Jolly-Seber models used to estimate the passage success (φ) and detection probability (p) for Rio Grande Sucker. The top ten models based on AICc are shown. Effects included slope, distance, antenna, fish total length (TL), trial, experience, and average temperature (Temp, °C).

Model	AICc	ΔAICc	AICc Weights	Model Likelihood	Num. Par	Deviance	-2log(L)
{φ(threshold 2=4%, slope*distance +Trial+TL)p(antenna)}	1033.024	0	0.31583	1	23	986.4162	986.4162
{φ(threshold 2=4%, slope*distance +Trial+TL+Temp)p(antenna)}	1033.452	0.4281	0.25497	0.8073	24	984.7911	984.7911
{φ(slope*distance+Trial+TL)p(antenna)}	1035.624	2.6005	0.08605	0.2725	27	980.7903	980.7903
{φ(threshold 2=4%, slope*distance +Experience+TL)p(antenna)}	1035.996	2.9718	0.07147	0.2263	23	989.388	989.388
{φ(slope*distance+Trial+TL)p(.)}	1036.052	3.0281	0.06949	0.22	24	987.3911	987.3911
{φ(slope*distance+Trial+TL+Temp)p(antenna)}	1036.107	3.0832	0.0676	0.214	28	979.2107	979.2107
{φ(slope*distance+Trial+TL+Temp)p(.)}	1036.521	3.4967	0.05497	0.174	25	985.8042	985.8042
{φ(threshold 2=4%, slope*distance +Experience+TL+Temp)p(antenna)}	1037.852	4.8286	0.02824	0.0894	24	989.1917	989.1917
{φ(slope*distance+Experience+TL)p(antenna)}	1038.577	5.5527	0.01967	0.0623	27	983.7426	983.7426
{φ(slope*distance+Experience+TL)p(.)}	1039.005	5.9808	0.01588	0.0503	24	990.3437	990.3437

Table 6. Cormack-Jolly-Seber models used to estimate the passage success (φ) and detection probability (p) for Rio Grande Chub. The top ten models based on AICc are shown. Effects included slope, distance, antenna, fish total length (TL), trial, experience, and average temperature (Temp, °C).

Model	AICc	ΔAICc	AICc Weights	Model Likelihood	Num. Par	Deviance	-2log(L)
{φ(linear slope+distance+Trial+TL) p(antenna)}	835.4779	0	0.58621	1	12	811.3077	811.3077
{φ(linear slope+distance+Trial+TL+Temp) p(antenna)}	837.1972	1.7193	0.24815	0.4233	13	810.9985	810.9985
{φ(linear slope+distance+Experience+TL) p(antenna)}	838.7155	3.2376	0.11615	0.1981	12	814.5453	814.5453
{φ(linear slope+distance+Experience+TL+Temp) p(antenna)}	840.4239	4.946	0.04944	0.0843	13	814.2252	814.2252
{φ(linear slope+distance+Trial) p(antenna)}	856.3017	20.8238	0.00002	0	11	834.1577	834.1577
{φ(linear slope+distance+TL+Temp) p(antenna)}	856.5812	21.1033	0.00002	0	12	832.411	832.411
{φ(linear slope+distance+Trial+Temp) p(antenna)}	858.1585	22.6806	0.00001	0	12	833.9883	833.9883
{φ(linear slope+distance+TL) p(antenna)}	858.4743	22.9964	0.00001	0	11	836.3303	836.3303
{φ(linear slope+distance+Experience) p(antenna)}	859.7064	24.2285	0	0	11	837.5625	837.5625
{φ(linear slope+distance+Experience+Temp) p(antenna)}	861.4601	25.9822	0	0	12	837.2899	837.2899

Table 7. Cormack-Jolly-Seber models used to estimate the passage success (*φ*) and detection probability (*p*) for Mottled Sculpin. The top ten models based on AICc are shown. Effects included slope, distance, antenna, fish total length (TL), trial, experience, and average temperature (Temp, °C).

Model	AICc	ΔAICc	AICc Weights	Model Likelihood	Num. Par	Deviance	-2log(L)
{*φ*(slope*distance, 2=4=6%+TL+Temp) p(slope+antenna)}	1060.563	0	0.36618	1	23	1013.928	1013.928
{*φ*(slope*distance, 2=4=6%+TL) p(slope+antenna)}	1061.902	1.3385	0.18752	0.5121	22	1017.32	1017.32
{*φ*(slope*distance, 2=4=6%+Trial+TL+Temp) p(slope+antenna)}	1062.057	1.4935	0.17353	0.4739	24	1013.366	1013.366
{*φ*(slope*distance, 2=4=6%+Experience+TL+Temp) p(slope+antenna)}	1062.619	2.0556	0.13102	0.3578	24	1013.928	1013.928
{*φ*(slope*distance, 2=4=6%+Trial+TL) p(slope+antenna)}	1063.753	3.1895	0.07432	0.203	23	1017.117	1017.117
{*φ*(slope*distance, 2=4=6%+Experience+TL) p(slope+antenna)}	1063.955	3.3918	0.06717	0.1834	23	1017.32	1017.32
{*φ*(slope*distance, 2=4=6%+Temp) p(slope+antenna)}	1076.57	16.0068	0.00012	0.0003	22	1031.988	1031.988
{*φ*(slope*distance, 2=4=6%+Trial+Temp) p(slope+antenna)}	1078.014	17.451	0.00006	0.0002	23	1031.379	1031.379
{*φ*(slope*distance, 2=4=6%+Experience+Temp) p(slope+antenna)}	1078.623	18.0601	0.00004	0.0001	23	1031.988	1031.988
{*φ*(slope*distance, 2=4=6%) p(slope+antenna)}	1080.192	19.6284	0.00002	0.0001	21	1037.661	1037.661

Table 8. The range and mean water velocities ± standard deviation at the different rock ramp fishway slopes measured using an acoustic doppler velocimeter. Forty measurements were taken along eight evenly spaced transects along the length of the experimental fishway.

Slope	Velocity Distribution (cm/s)	Mean Water Column Velocity (cm/s)
2%	33.8-61.0	49.6 ± 7.1
4%	45.0-86.1	67.1 ± 10.0
6%	13.5-141.2	72.4 ± 21.9
8%	48.4-142.7	99.3 ± 20.0
10%	56.9-145.4	108.5 ± 19.3

FIGURES

Figure 1. The 95-mm roughness elements were spaced approximately one diameter apart in a chevron patter, with small cobble substrate adhered to the surface between the roughness elements and on the angled margins.

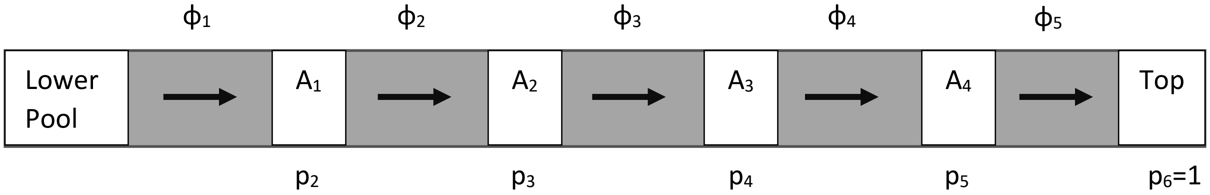

Figure 2. A depiction of the Cormack-Jolly-Seber model used to determine passage success up the experimental rock ramp (figure not to scale). A_x represents the PIT tag antennas located along the rock ramp. φ_i is the probability of passing from one rock ramp segment to the next (i.e., from above antenna 1 to above antenna 2). p_z is the probability of detection of fish at each antenna. $p_6=1$ because at the end of the trial fish at the top are always found so detection is perfect. φ_i and p_z are parameters estimated by program MARK based on detection of fish during trials.

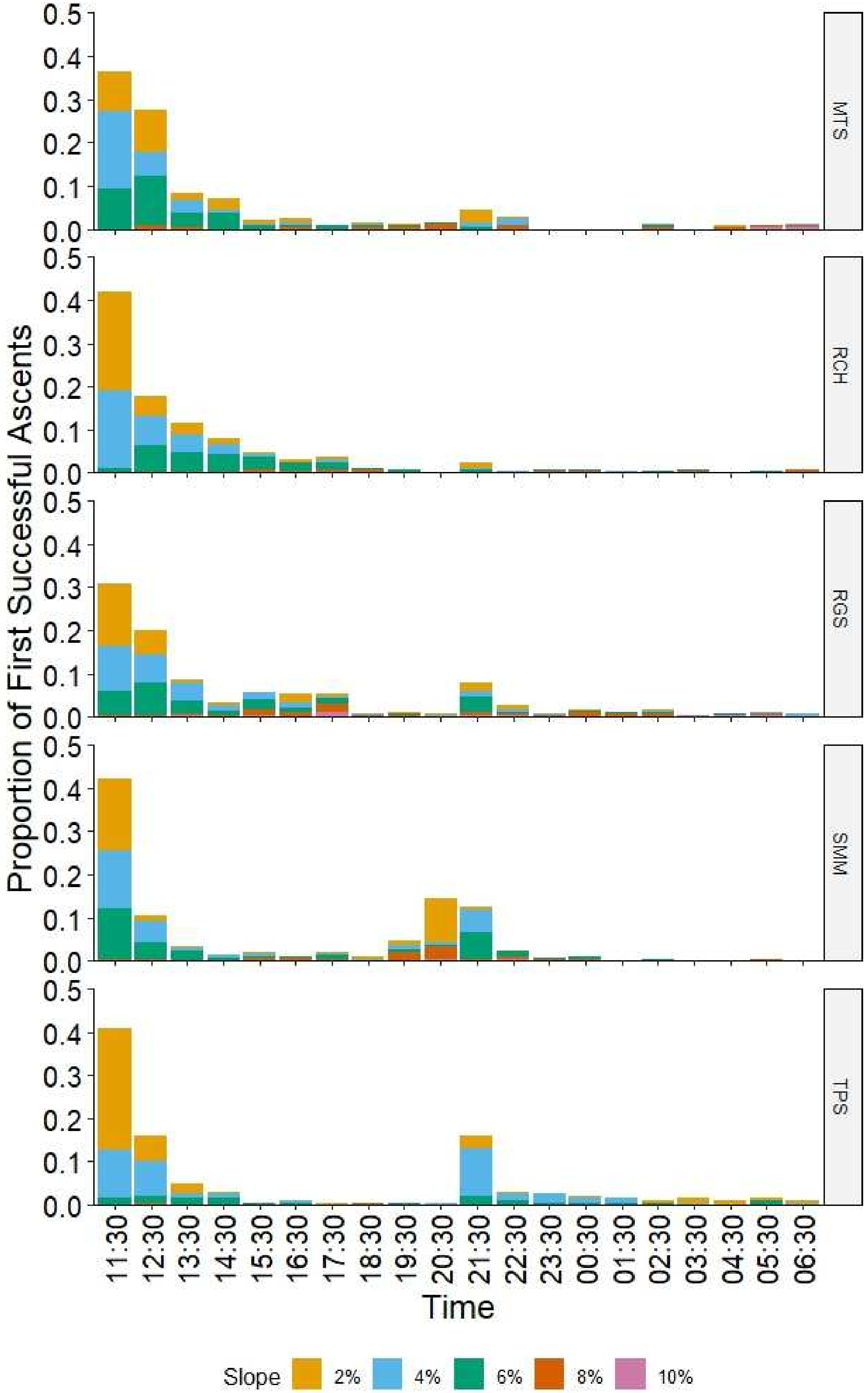

Figure 3. The proportion of all successful first ascents by hour for all slopes (2-10%) for Mottled Sculpin (MTS), Rio Grande Chub (RCH), Rio Grande Sucker (RGS), Suckermouth Minnow (SMM), and Topeka Shiner (TPS).

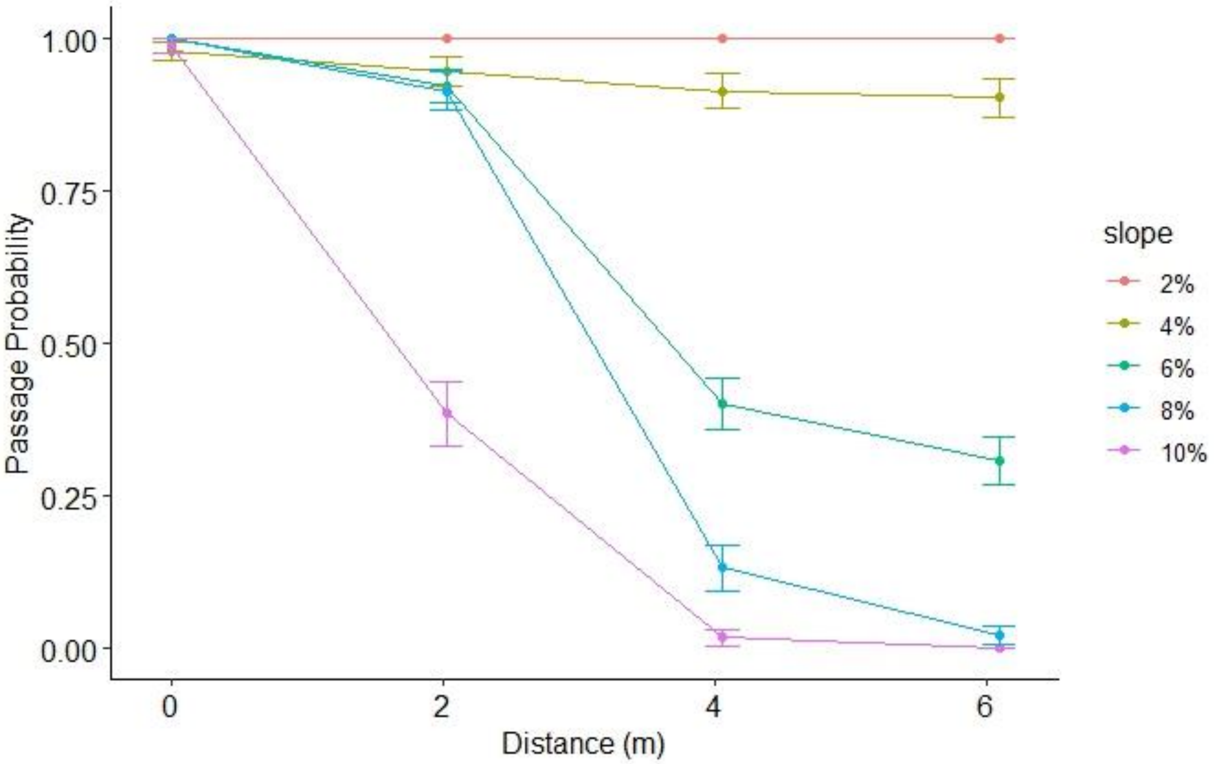

Figure 4. Estimated Topeka Shiner passage probabilities for each slope (2-10%) and distance (in 2.03-m intervals based on antenna location) from the top model *φ*(slope*distance+Experience+TL)*p*(antenna). Error bars represent the standard error.

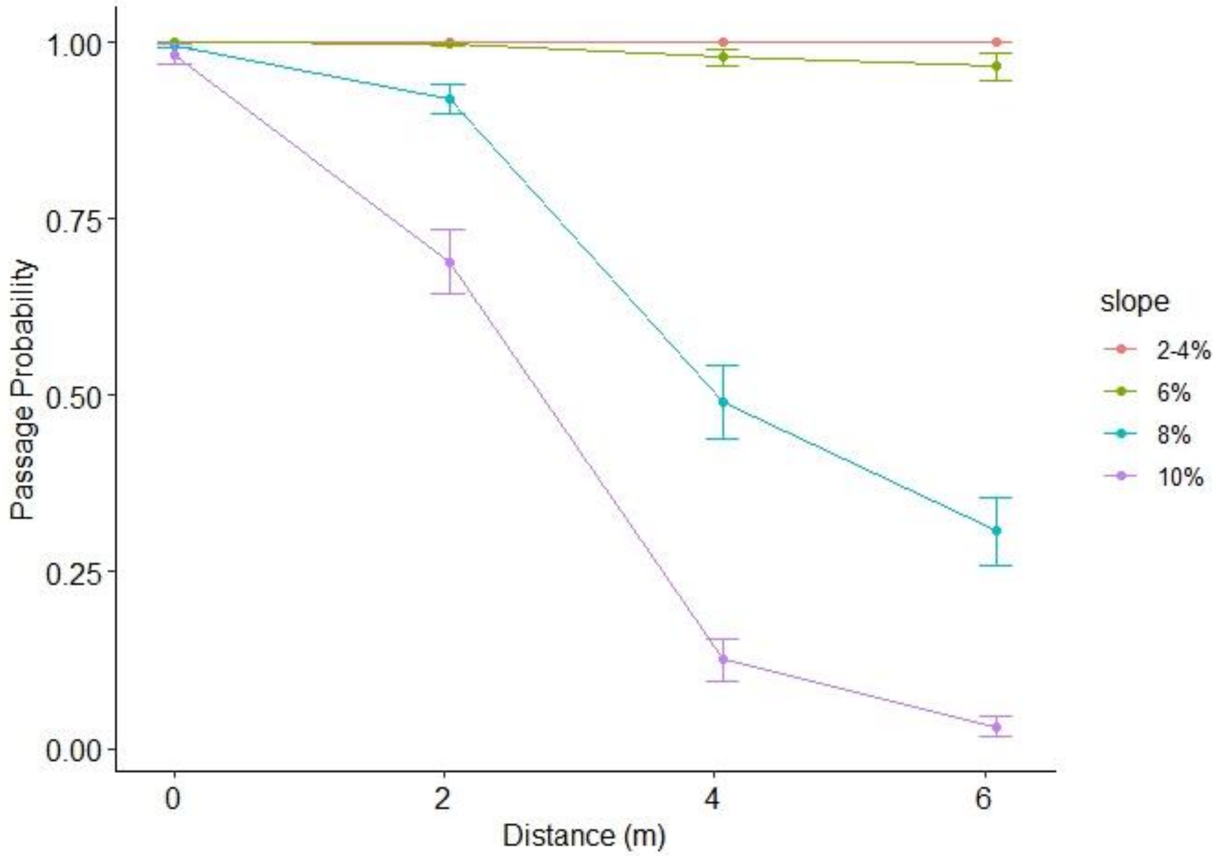

Figure 5. Estimated Suckermouth Minnow passage probabilities for each slope (2-10%) and distance (in 2.03-m intervals based on antenna location) from the top model *φ*(slope 2=4% + distance)*p*(.). Error bars represent the standard error.

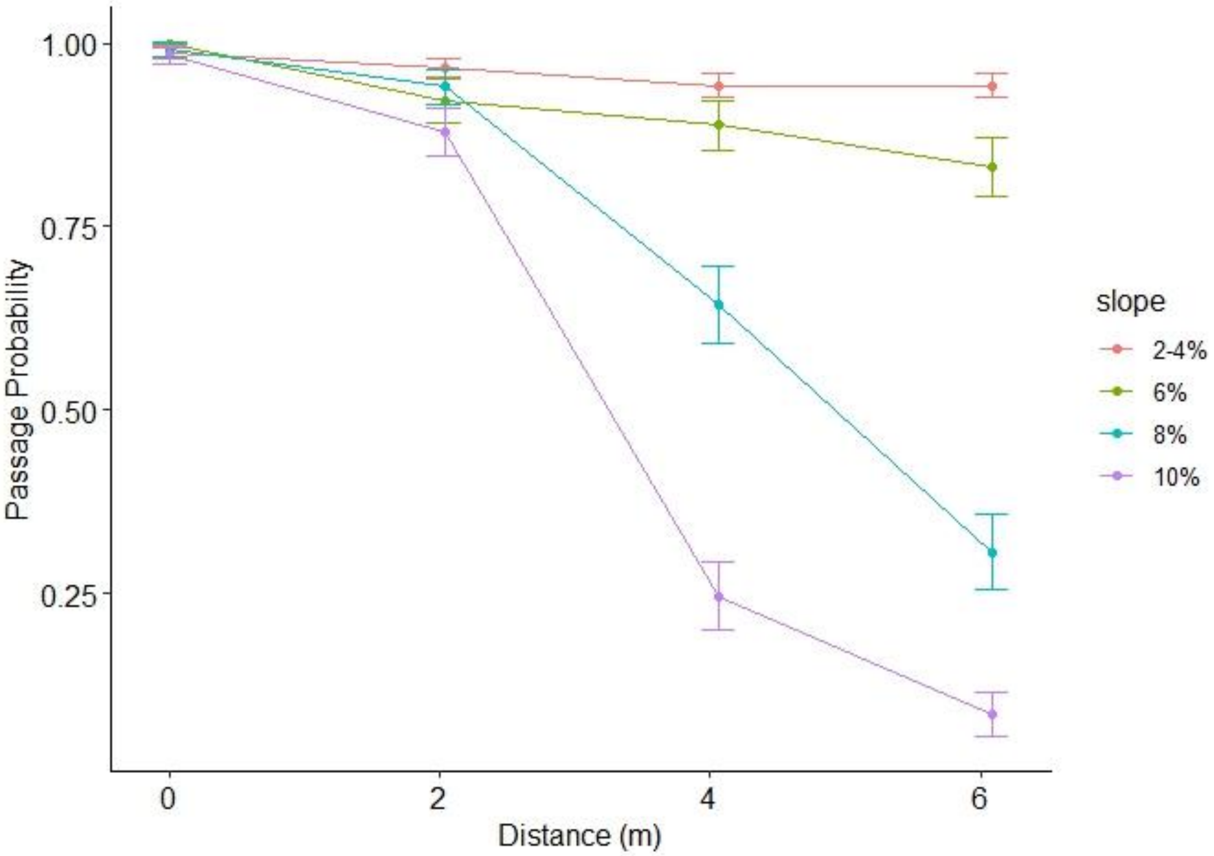

Figure 6. Estimated Rio Grande Sucker passage probabilities for each slope (2-10%) and distance (in 2.03-m intervals based on antenna location) from the top model *φ*(slope 2=4%*distance + Trial + TL)*p*(antenna). Error bars represent the standard error.

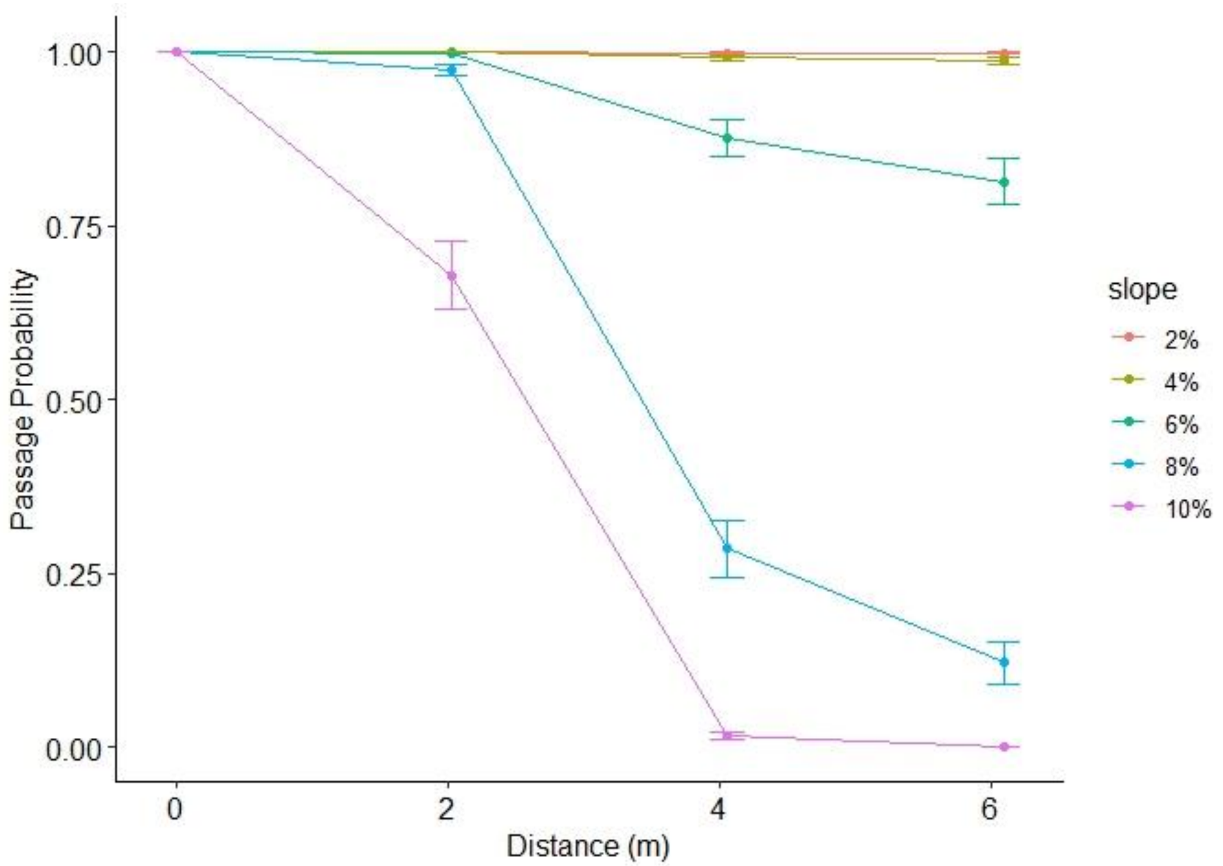

Figure 7. Estimated Rio Grande Chub passage probabilities for each slope (2-10%) and distance (in 2.03-m intervals based on antenna location) from the top model *φ*(linear slope + distance + Trial +TL)*p*(antenna). Error bars represent the standard error.

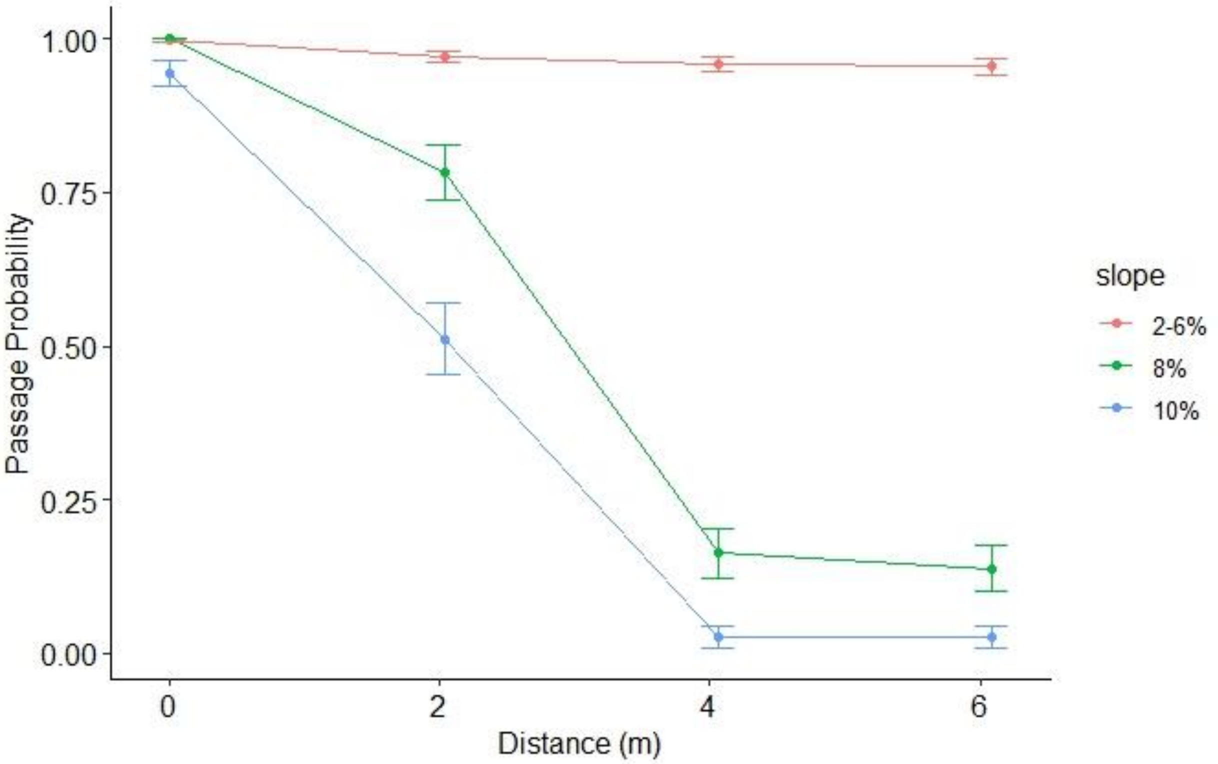

Figure 8. Estimated Mottled Sculpin passage probabilities for each slope (2-10%) and distance (in 2.03-m intervals based on antenna location) from the top model *φ*(slope 2=4=6% * distance + TL + Temp)*p*(slope + antenna). Error bars represent the standard error.

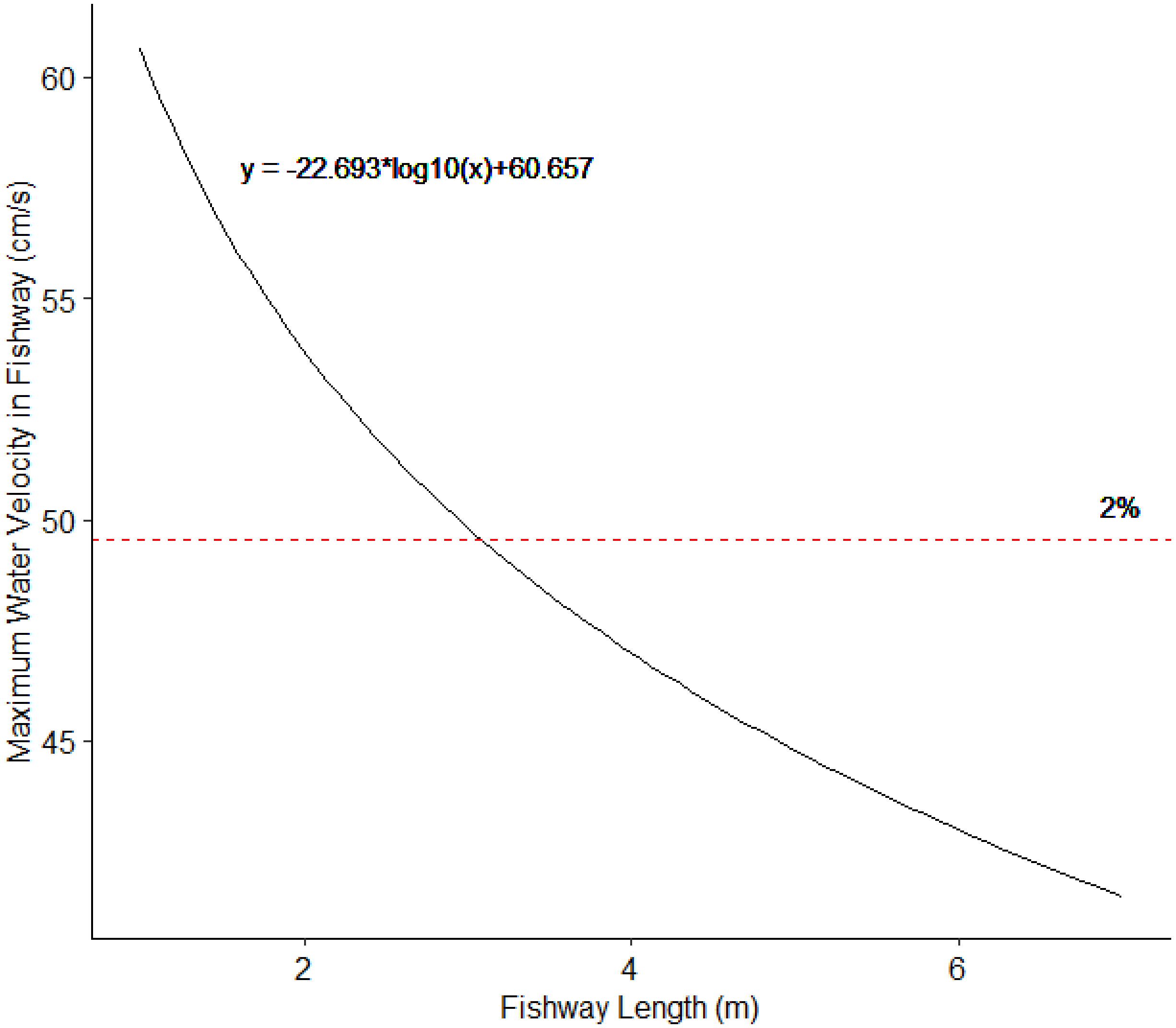

Figure 9. Recommended maximum water velocity and fishway length based off Adams et al. 2000 for Topeka Shiner. The dashed line represents the average velocity measured in the rock ramp fishway in this study (49.6 cm/s) using an acoustic doppler velocimeter. All other slopes (4-10%) had average velocities above what Adams et al. 2000 predicted as passable (velocities > 60 cm/s).

REFERENCES

Adams, S. B., D. A. Schmetterling, and D. A. Neely. 2015. Summer stream temperatures influence sculpin distributions and spatial partitioning in the Upper Clark Fork River Basin, Montana. Copeia 103(2):416–428.

Adams, S. R., J. J. Hoover, and K. J. Killgore. 2000. Swimming performance of the Topeka Shiner (*Notropis topeka*) an endangered midwestern minnow. American Midland Naturalist 144(1):178–186.

Aedo, J. R., M. C. Belk, and R. H. Hotchkiss. 2009. Morphology and swimming performance of Utah fishes: critical information for culvert design in Utah streams. UDOT Research Division, Report UT- 09.12, Salt Lake City, Utah.

Archdeacon, T. P., W. J. Remshardt, and T. L. Knecht. 2009. Comparison of two methods for implanting passive integrated transponders in Rio Grande Silvery Minnow. North American Journal of Fisheries Management (29):346–351.

Baki, A. B. M., D. Z. Zhu, and N. Rajaratnam. 2015. Turbulence characteristics in a rock-ramp-type fish pass. Journal of Hydraulic Engineering 141(2):1–14.

Barbarossa, V., R. J. P. Schmitt, M. A. J. Huijbregts, C. Zarfl, and H. King. 2020. Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide. Proceedings of the National Academy of Sciences - PNAS 117(7):3648–3655.

Belk, M. C., L. J. Benson, J. Rasmussen, and S. L. Peck. 2008. Hatchery-induced morphological variation in an endangered fish: A challenge for hatchery-based recovery efforts. Canadian Journal of Fisheries and Aquatic Sciences 65(3):401–408.

Bestgen, K. R., R. I. Compton, K. A. Zelasko, and J. E. Alves. 2003a. Distribution and status of Rio Grande Chub in Colorado.

Bestgen, K. R., K. Zelasko, and R. Compton. 2003b. Environmental factors limiting Suckermouth Minnow populations in Colorado.

Birnie-Gauvin, K., P. Franklin, M. Wilkes, and K. Aarestrup. 2019. Moving beyond fitting fish into equations: Progressing the fish passage. Aquatic Conservation: Marine and Freshwater Ecosystems 29(7):1095–1105.

Blank, M., B. Bramblett, S. Kalinowski, J. Cahoon, and K. Nixon. 2011. Impacts of barriers on Topeka Shiner populations. Boseman, MT.

Bouska, W. W., and C. P. Paukert. 2010. Road crossing designs and their impact on fish assemblages of Great Plains streams. Transactions of the American Fisheries Society 139(1):214–222.

Brittain, C. 2022. How does rock-ramp fishway surface texture affect the passage success of small-bodied great plains fishes. Colorado State Univerisity.

Bunt, C. M., T. Castro-Santos, and A. Haro. 2012. Performance of fish passage structures at upstream barriers to migration. River Research and Applications 28:457–478.

Burnham, K. P., D. R. Andersen, G. C. White, C. Brownie, and K. H. Pollock. 1987. Design and analysis methods for fish survival experiments based on release-recapture. Page American Fisheries Society. Bethesda, MD.

Calles, O., and L. Greenberg. 2009. Connectivity is a two-way street the need for a holistic approach to fish passage problems in regulated rivers. River Research and Applications 25:1268–1286.

Campbell, S. W., C. S. Szuwalski, V. M. Tabor, and F. deNoyelles. 2016. Challenges to reintroduction of a captive population of Topeka Shiner (*Notropis topeka*) into former habitats in Kansas . Transactions of the Kansas Academy of Science 119(1):83–92.

Comte, L., L. Buisson, M. Daufresne, and G. Grenouillet. 2013. Climate-induced changes in the distribution of freshwater fish observed and predicted. Freshwater Biology 58(4):625–639.

Costigan, K. H., M. D. Daniels, J. S. Perkin, and K. B. Gido. 2014. Longitudinal variability in hydraulic geometry and substrate characteristics of a Great Plains sand-bed river. Geomorphology 210:48–58. Elsevier B.V.

Dockery, D. R., T. E. McMahon, K. M. Kappenman, and M. Blank. 2017. Evaluation of swimming performance for fish passage of Longnose Dace *Rhinichthys cataractae* using an experimental flume. Journal of Fish Biology 90(3):980–1000.

Falke, J. A., K. R. Bestgen, and K. D. Fausch. 2010. Streamflow reductions and habitat drying affect growth, survival, and recruitment of Brassy Minnow across a Great Plains riverscape. Transactions of the American Fisheries Society 139:1566–1583.

Fausch, K. D., B. E. Rieman, J. B. Dunham, M. K. Young, and D. P. Peterson. 2009. Invasion versus isolation trade-offs in managing native salmonids with barriers. Conservation Biology 23(4):859–870.

Ficke, A. D. 2015. Mitigation measures for barriers to Great Plains fish migration. Colorado State University.

Ficke, A. D., C. A. Myrick, and L. J. Hansen. 2007. Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fisheries 17:581–613.

Ficke, A. D., C. A. Myrick, and N. Jud. 2011. The swimming and jumping ability of three small Great Plains fishes: Implications for fishway design. Transactions of the American Fisheries Society 140(6):1521–1531.

Fuller, M. R., M. W. Doyle, and D. L. Strayer. 2015. Consequences of habitat fragmentation in river networks. Annals of the New York Academy of Sciences 10(1335):31–51.

Galindo, R., W. D. Wilson, and C. A. Caldwell. 2016. Geographic distribution of genetic diversity in populations of Rio Grande Chub *Gila pandora*. Conservation Genetics 17(5):1081–1091.

Grasty, S., M. Messina, and J. Bryan. 2021. Upstream and Downstream – Exciting advances to modernize fish passage and improve data collection. Fisheries 46(10):481–484.

Hopper, G. W., K. B. Gido, C. A. Pennock, S. C. Hedden, B. D. Frenette, N. Barts, C. K. Hedden, and L. A. Bruckerhoff. 2020. Nowhere to swim: interspecific responses of prairie stream fishes in isolated pools during severe drought. Aquatic Sciences 82(2):1–15. Springer International Publishing.

Katopodis, C., J. A. Kells, and M. Acharya. 2001. Nature-Like and Conventional Fishways: Alternative concepts? Canadian Water Resources Journal 26(2):211–232.

Katopodis, C., and J. G. Williams. 2012. The development of fish passage research in a historical context. Ecological Engineering 48:8–18. Elsevier B.V.

Keefer, M. L., M. A. Jepson, T. S. Clabough, and C. C. Caudill. 2021. Technical fishway passage structures provide high passage efficiency and effective passage for adult Pacific salmonids at eight large dams. Page PLoS ONE.

Ketabdar, M. 2017. Study on sediment transport mechanics in shallow-grade storm drain systems. Lamar University.

King, S., and J. R. O'Hanley. 2016. Optimal fish passage barrier removal - revisited. River Research and Applications 32:418–428.

Lemoine, M. T., and L. R. Bodensteiner. 2014. Barriers to upstream passage by two migratory sculpins, Prickly Sculpin (*Cottus asper*) and Coastrange Sculpin (*Cottus aleuticus*), in northern Puget Sound lowland streams. Canadian Journal of Fisheries and Aquatic Sciences 71(11):1758–1765.

LeMoine, M. T., L. A. Eby, C. G. Clancy, L. G. Nyce, M. J. Jakober, and D. J. Isaak. 2020. Landscape resistance mediates native fish species distribution shifts and vulnerability to climate change in riverscapes. Global Change Biology 26(10):5492–5508.

Mallen-Cooper, M., and D. A. Brand. 2007. Non-salmonids in a salmonid fishway: what do 50 years of data tell us. Fisheries Management and Ecology2 14:319–332.

Mateus, C. S., B. R. Quintella, and P. R. Almeida. 2008. The critical swimming speed of Iberian Barbel *Barbus bocagei* in relation to size and sex. Journal of Fish Biology 73(7):1783–1789.

McDonald, D. G., C. L. Milligan, W. J. McFarlane, S. Croke, S. Currie, B. Hooke, R. B. Angus, B. L. Tufts, and K. Davidson. 1998. Condition and performance of juvenile Atlantic Salmon (*Salmo salar*): Effects of rearing practices on hatchery fish and comparison with wild fish. Canadian Journal of Fisheries and Aquatic Sciences 55(5):1208–1219.

Morin, D. J., C. B. Yackulic, J. E. Diffendorfer, D. B. Lesmeister, C. K. Nielsen, J. Reid, and E. M. Schauber. 2020. Is your ad hoc model selection strategy affecting your multimodel inference? Ecosphere 11(1).

Newbold, L. R., X. Shi, Y. Hou, D. Han, and P. S. Kemp. 2016. Swimming performance and behaviour of Bighead Carp (*Hypophthalmichthys nobilis*): Application to fish passage and exclusion criteria. Ecological Engineering 95:690–698. Elsevier B.V.

Ojanguren, A. F., and F. Brana. 2003. Effects of size and morphology on swimming performance in juvenile Brown Trout (*Salmo trutta L.*). Ecology of Freshwater Fish 12(4):241–246.

Olsen, A. H., and B. P. Tullis. 2013. Laboratory study of fish passage and discharge capacity in slip-lined, baffled culverts. Journal of Hydraulic Engineering 139(4):424–432.

Papanicolaou, A. N., P. Diplas, C. L. Dancey, and M. Balakrishnan. 2001. Surface roughness effects in near-bed turbulence: Implications to sediment entrainment. Journal of Engineering Mechanics 127(3):211–218.

Peake, S. 2004. An evaluation of the use of critical swimming speed for determination of culvert water velocity criteria for Smallmouth Bass. Transactions of the American Fisheries Society 133(6):1472–1479.

Perkin, J. S., and K. B. Gido. 2011. Stream fragmentation thresholds for a reproductive guild of Great Plains fishes. Fisheries 36(8):371–383.

Perkin, J. S., and K. B. Gido. 2012. Fragmentation alters stream fish community structure in dendritic ecological networks. Ecological Applications 22(8):2176–2187.

Perkin, J. S., K. B. Gido, A. R. Cooper, T. F. Turner, M. J. Osborne, E. R. Johnson, K. B. Mayes, and C. Nilsson. 2015. Fragmentation and dewatering transform Great Plains stream fish communities.

Ecological Monographs 85(1):73–92.

Pringle, C. 2003. What is hydrologic connectivity and why is it ecologically important? Hydrological Processes 17(13):2685–2689.

Quist, M. C., W. A. Hubert, and F. J. Rahel. 2005. Fish assemblage structure following impoundment of a Great Plains river. Western North American Naturalist 65(1):53–63.

Rees, D. E., and W. J. Miller. 2005. Rio Grande Sucker (*Catostomus plebeius*): A technical conservation assessment. Page USDA Forest Service, Rocky Mountian Region.

Reinbold, D., G. H. Thorgaard, and P. A. Carter. 2009. Reduced swimming performance and increased growth in domesticated Rainbow Trout, *Oncorhynchus mykiss*. Canadian Journal of Fisheries and Aquatic Sciences 66(7):1025–1032.

Richer, E. E., E. R. Fetherman, E. A. Krone, F. B. Wright III, and M. C. Kondratieff. 2020. Multispecies fish passage evaluation at a rock-ramp fishway in a Colorado transition zone stream. North American Journal of Fisheries Management 40:1510–1522.

Rio Grande Chub and Rio Grande, and S. C. Team. 2021. Rio Grande Chub Conservation Strategy.

Roscoe, D. W., S. G. Hinch, S. J. Cooke, and D. A. Patterson. 2011. Fishway passage and post-passage mortality of up-river migrating Sockeye Salmon in the Seton River, British Columbia. River Research and Applications 27(6):693–705.

Silva, A. T., M. C. Lucas, T. Castro-Santos, C. Katopodis, L. J. Baumgartner, J. D. Thiem, K. Aarestrup, P. S. Pompeu, G. C. O'Brien, D. C. Braun, N. J. Burnett, D. Z. Zhu, H. P. Fjeldstad, T. Forseth, N. Rajaratnam, J. G. Williams, and S. J. Cooke. 2018. The future of fish passage science, engineering, and practice. Fish and Fisheries 19(2):340–362.

Srean, P., D. Almeida, F. Rubio-Gracia, Y. Luo, and E. García-Berthou. 2017. Effects of size and sex on swimming performance and metabolism of invasive Mosquitofish *Gambusia holbrooki*. Ecology of Freshwater Fish 26(3):424–433.

Swarr, T. R. 2018. Improving rock ramp fishways for small-bodies Great Plains fishes. Colorado State University.

Swarr, T. R., R. M. Fitzpatrick, and C. A. Myrick. 2023. Design, construction, and preliminary hydraulic evaluation of a model rock ramp fishway. North American Journal of Fisheries Management 43(4):935–946.

Swarr, T. R., C. A. Myrick, and R. M. Fitzpatrick. 2022. Tag retention in and effects of passive integrated transponder tagging on survival and swimming performance of a small-bodied darter. Journal of Fish Biology 100(3):705–714.

Underwood, Z. E., C. A. Myrick, and R. I. Compton. 2014. Comparative swimming performance of five *Catostomus* species and Roundtail Chub. North American Journal of Fisheries Management 34(4):753–763.

US Army Corps of Engineers. 2020. National Inventory of Dams. https://nid.usace.army.mil/#/.

US Office of the Federal Register. 1998. Endangered and threatened wildlife and plants; Final rule to list the Topeka Shiner as endangered. Federal Register 63(240):69008–69021.

Vehanen, T., and A. Huusko. 2011. Brown Trout *Salmo trutta* express different morphometrics due to divergence in the rearing environment. Journal of Fish Biology 79(5):1167–1181.

Ward, D. L., and K. D. Hilwig. 2004. Effects of holding environment and exercise conditioning on swimming performance of southwestern native fishes. North American Journal of Fisheries Management 24(3):1083–1087.

Ward, D. L., A. A. Schultz, and P. G. Matson. 2003. Differences in swimming ability and behavior in response to high water velocities among native and nonnative fishes. Environmental Biology of Fishes 68(1):87–92.

Webb, P. W., C. L. Gerstner, and S. T. Minton. 1996. Station-holding by the Mottled Sculpin, *Cottus bairdi* (Teleostei: Cottidae), and other fishes. Copeia 1996(2):488–493.

White, G. C., and K. P. Burnham. 1999. Program mark: Survival estimation from populations of marked animals. Bird Study 46:S120–S139.

Wiberg, P. L., and J. D. Smith. 1989. Model for calculating bed load transport of sediment. Journal of Hydraulic Engineering 115(1):101–123.

Young, M. K., R. Smith, K. L. Pilgrim, D. J. Isaak, K. S. Mckelvey, S. Parkes, J. Egge, and M. K. Schwartz. 2022. A molecular yaxonomy of *Cottus* in western North America. Western North American Naturalist 82(2):307–345.