THESIS

RITES OF PASSAGE:

DETERMINING THE EFFICACY OF DIFFERENT FISH PASSAGE DESIGNS ALONG THE NORTHERN COLORADO FRONT RANGE

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ABSTRACT

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As historical instream barriers continue to be used and new man-made structures have the potential to further fragment river habitat, eastern Colorado fish communities face mounting challenges to survive in abbreviated river segments. Instream barriers are myriad in shape (dams, diversions, culverts, grade control, etc.) and serve a wide variety of economic and social necessities, often preventing their removal. In an attempt to restore longitudinal connectivity at instream barriers, fish passage structures of various types have recently been installed across the northern Colorado Front Range where rivers transition from high gradient mountain streams to low gradient eastern plains streams (often referred to as the transition zone). These structures are often designed with small-bodied native Plains fish species in mind. Frequently, little to no post-installation monitoring is performed for these fishways, so little is known of their comparative success. The goal of this study was to assess the passage success of the resident fish fauna at different passage structures to better understand how structure type and design affect efforts to restore connectivity. The study used long-term monitoring and short-term enclosure studies with stationary PIT tag antenna arrays that recorded movements of a free-ranging community of PIT-tagged fishes. A cast concrete rock ramp on the Cache La Poudre River and a grouted boulder wingwall bypass passage structure on the St. Vrain River were continuously monitored for nearly two years, offering insights into passage success, differences in functionality between the

fishways, and the variable movement patterns of the local fish communities. Successful fishway passage was observed at both sites by numerous species over a variety of conditions, with the rock ramp passing 71% of tagged species with an overall passage rate of 55% for individuals, and the wingwall bypass passing 61% of tagged species at an overall individual passage rate of 62%. The long-term monitoring study is described in Chapter 1 of this thesis.

Short-term enclosure experiments were used to evaluate both fish passage success at a given passage and to evaluate the method's capability to provide a rapid initial assessment of fishway performance. These trials added an additional pool-and-weir style passage to the two sites used in the long-term monitoring component of the study. Similar to the long-term monitoring study, the rock ramp and wingwall bypass structures both allowed passage of a majority of species, 63% and 70%, respectively, tested during the enclosure study producing overall passage rates of 49% and 64%, respectively. Conversely, fish passage at the pool-and-weir structure was largely non-existent (passage rate of 17%), suggesting it is not a satisfactory alternative for systems where the goal is to provide passage for non-jumping native fish species. The results from this study are described in detail in Chapter 2.

Given the differing effects of design features and slopes on passage success for the types tested, this project suggests that future fish passage projects in these systems consider rock ramp-style structures, with specific attention to low gradients and nature-like designs where possible. In addition, long-term monitoring should be considered paramount for post-installation monitoring as it provided the greatest insight into fish passage performance. Many species, not constrained by limited time and conditions, demonstrated higher rates of passage. Greater detail of movement patterns and preferences throughout time was also obtained. However, the short-term enclosure trial process, with some refinements, can provide a valuable initial assessment of fishway functionality following construction.

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Cole Brittain deserves a special commendation for his patience, excellent field expertise and steadiness throughout this project. Without his background knowledge and endless willingness to discuss and retread the minutiae, the final product of this endeavor would be much poorer for its lack, if even completed at all.

The magnitude of data generated by this project was staggering, even the most basic of sorting of it "by hand" would have been prohibitive. Indeed, without the considerable and expert help of David Jones, a Senior Director of Software Development at Oracle, who graciously invested a great deal of time the project may have require decades to complete, to say nothing of the far greater detail parsed from this project than I would have been capable of. I am very fortunate that it was also curiosity and not simply fatherly responsibility that garnered this contribution, but I am grateful for it in both regards. This support and encouragement extended beyond just the data work to the entirety of what is graduate school and to both of my parents, Wendy and David; to both, their kindness in this process was unerring.

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INTRODUCTION

Covering a magnitude of roughly 752,900 km^2 and numerous thermal, chemical, and hydrological conditions amongst its major rivers and hundreds of tributaries, the Great Plains ecoregion hosts a plethora of native fishes, including 49 endemic species (Fausch and Bestgen 1997; Laubhan and Fredrickson 1997; Falke et al. 2010). Fishes within the ecoregion may utilize several diverse habitat types to complete their life histories, making connectivity across the riverscape for these widespread habitats essential (Schlosser and Angermeier 1995; Fausch and Bestgen 1997; Falke et al. 2010; Perkin et al. 2015). Within this vast eco-region, the Colorado Front Range is a transition zone between the higher-gradient mountain portions of these lotic systems and the lower gradient plains portions. This "transition zone" is dominated by single thread channels with largely cobble substrates and cooler water temperatures, with its own uniquely adapted host of species (Fausch and Bestgen 1997) along with some representatives of both the montane and plains fish fauna. A long history of human habitation and heavy agricultural use has contributed to declines in native fish populations throughout the Great Plains region, often by processes that increase longitudinal fragmentation of lotic systems. Especially problematic for migratory species or those with pelagic life stages (e.g., buoyant eggs or drifting larvae), this fragmentation hinders species accessing high- or low-flow refugia, exposes them to higher degrees of predation, and can severely obstruct gene flow through the isolation of small populations (Fausch and Bestgen 1997; Platania and Altenbach 1998; Labbe and Fausch 2000; Falke and Gido 2006; Dudley and Platania 2007; Hoagstrom et al. 2011)

Increasing demands for water and changes in regional climate patterns result in reduced flows (Nilsson et al. 2005; Falke and Gido 2006; Dudley and Platania 2007; Ficke et al. 2007; Falke et al. 2010, 2011; Hoagstrom et al. 2011), which is further exacerbated by the staggering number of instream barriers present in river systems flowing into the Great Plains (Hoagstrom et al. 2011; Perkin et al. 2015). Though agricultural water diversions are amongst the most common instream barriers in the region, other structures, including culverts, erosion and flood control devices, and whitewater parks can both adversely affect habitat quality and restrict the movement of aquatic species (Wohl et al. 2005; Beechie et al. 2010; Stephens et al. 2015; Fox et al. 2016). Such structures, even when “only” low-head dams of a meter or less in height, can still be insurmountable obstacles for species that lack the ability to negotiate instream structures through behaviors such as jumping or high-velocity swimming (Ficke et al. 2011, Ficke 2015). To restore habitat connectivity while preserving structures needed for irrigation or for the protection of human property, natural resource managers are turning to the installation of fish passage structures (Ficke et al. 2011; Williams et al. 2012; Ficke 2015).

Fish movement over otherwise impassable barriers can be facilitated through the construction of a fish passage structure, or fishway. Historic development of fish passage technology relied heavily on anadromous salmonids’ superior jumping capacity or ability to navigate high velocity corridors. Such fishways do not work as well for smaller bodied fish, as are commonly found in the Great Plains region, or for smaller life stages (Francis 1870; Denil 1909; Katopodis and Williams 2012; Williams et al. 2012; Forty et al. 2016). To improve passage success for a wider range species and life stages, a number of authors have recommended adopting fishways such as rock ramps or nature-like bypasses that emphasize lower gradients and velocities, incorporate resting areas, and that are not restricted to species that jump over instream obstacles (Ficke et al. 2011; Williams et al. 2012; Ficke 2015; Swarr 2018). However, broad standardization of design features has not yet been achieved because each fishway installation must still address site-specific challenges. Key physical details such as fishway slope, the incorporation, spacing, and size of roughness elements and resting areas, and the selection of building materials are often highly site specific, while biological details such as the size and structure of the fish community also require consideration (Katopodis 2005; Williams et al. 2012).

Fish passage structures are generally built using the best information available at the time of their design, and are therefore subject to any limitations in our current knowledge of the species involved (Katopodis 2005; Williams et al. 2012). While laboratory studies provide the biological and hydraulic baselines required for basic structure design (Ficke et al. 2011; Ficke 2015; Swarr 2018), ideally, post-construction monitoring should occur after field installation of fishways to validate passage efficiency for the target species under actual operating conditions (Ficke and Myrick 2009; Williams et al. 2012; Cooke and Hinch 2013; Silva et al. 2018). Performance data from monitoring a species assemblage over a range of operating conditions at a given site, and from different iterations of similar passage designs amongst relatable conditions, serve to refine future designs, identifying unsuccessful approaches before future resources are committed.

This study focused on the long-term monitoring of a cast concrete rock ramp fishway on the Cache La Poudre River and a grouted boulder wingwall bypass fishway on the St. Vrain River, both installed after 2013 flooding along the Northern Colorado Front Range, on the western edge of the North American Great Plains. Both fishways can be broadly categorized as rock ramp fishways but differences in construction materials, site location, and site requirements produced different approaches to their design and implementation. Each site hosts a mixed species assemblage that includes introduced sport fish such as Brown Trout (*Salmo trutta*), and transition zone natives, including Creek Chub (*Semotilus atromaculatus*) and Longnose Dace (*Rhinichthys cataractae*), characterized by their typically smaller body size and capacity for surviving highly stochastic environments typical of Great Plains aquatic systems (Fausch and Bestgen 1997). While the smaller native species were the target group for the study, as they are typically the limiting species for community-level passage success, all taggable fishes (> 80 mm TL) were included in the study to evaluate overall passage performance of extant fish communities.

MATERIALS AND METHODS

Study Sites

A long-term monitoring study was conducted at an engineered cast concrete rock ramp on the Cache la Poudre River in Fort Collins, CO (UTM Zone 13N: 498310, 4489846) and a grouted boulder wingwall bypass structure on the St. Vrain River, CO (UTM Zone 13N: 492169, 4444988) (Figure 1.1). Engineered rock ramps and wingwall bypasses represent two of the most common approaches to fish passage along Colorado's Front Range. A third site, a constructed boulder riffle, was also considered for inclusion but eventually was omitted due to logistical limitations imposed by the COVID-19 pandemic. The two selected sites are described below.

Fossil Creek Reservoir Inlet Diversion, Cache la Poudre River, Fort Collins, CO, USA

The Fossil Creek Reservoir Inlet Diversion (FCRID) is located in the transition zone of the Cache la Poudre River. The diversion is a low-head concrete structure that diverts water into Fossil Creek Irrigation Ditch, serving both to fill Fossil Creek Reservoir and as a dilution source for a nearby municipal wastewater treatment facility (Figure 1.2). The diverted flow is controlled to some extent by a radial arm gate. When the diversion was repaired following a flood in 2013, a three-meter-long rock ramp was incorporated on the east side of the structure with a 5% average slope, a trapezoidal cross-section, and arrangeable roughness elements, as described in detail by Richer et al. (2020). These river rock roughness elements extend approximately 10-15 cm into the water column and are arranged in a chevron pattern. In 2018, the structure was extended downstream an additional six meters to alleviate issues with a hydraulic jump and a small vertical drop at the fishway entrance (Richer et al. 2020), decreasing the total height drop by 0.3 meters, and increasing backwatering at the bottom of the passage.

The radial arm gate opening provided an additional route for fish movement, depending on whether the gate was open or closed. The gate was open sporadically from December 2018 until November 2019, after which it was closed for the remainder of the August 2019 – November 2020 monitoring period.

Dickens Farm Natural Area, St. Vrain River, Longmont, Colorado, USA

The study site on the St. Vrain River was located within the Dickens Farm Natural Area, which includes a dozen grouted boulder-sided pool and drops surrounded by open space tailored for public recreation (Figure 1.3). The recreation-focused design was conceived prior to the 2013 flood but was amended to include greater flood control measures and bank stabilization after the flood occurred. Despite a gentler gradient and a lack of consistently high summertime flows, river recreation, such as tubing and kayaking, was a main goal of the construction, thus the channel was heavily altered with nine drop-pool structures to provide higher water velocities (City of Longmont 2014). A high number of native fish are still found in the St. Vrain (Nesler et al. 1997). Therefore, grouted boulder wingwall bypass channels were installed along the edge of each drop feature to provide lower velocity routes for fish passage. Created through the placement of grouted boulders, the channels have an average slope of 2% over roughly 15 meters, characterized by a complexity of different flow zones, interstitial spaces, and numerous exits for both fish and water. The presence of small boulders (~1.15 m diameter) grouted into the channel, along with the natural deposition of sand and gravel, create conditions within the fishway that are analogous to more natural channels.

The downstream-most drop structure was chosen for the study, as it fell largely outside the primary public recreation area. Additionally, though separated by a final pool and low-grade flow control structure, its proximity to the less altered downstream reach of the St. Vrain and a small but habitat-diverse side channel, the Slough, which flows in just above the fishway, allowed for connectivity to a larger fish population during the study.

Long-term Fishway Monitoring

Antenna Construction and Installation

Fish movements at each site were tracked using passive integrated transponder (PIT) tag antenna arrays installed within each fishway. To provide directionality of movement and a stepwise assessment of each passage's success, each antenna array consisted of four custom-designed half-duplex (HDX) antennas spaced equidistant between the downstream entrance and upstream exit. HDX antennas and tags were chosen to maximize durability, read range and compatibility with other tags already deployed in the two river systems. Larger antennas that could have been used to track rates of approach (e.g., Hodge et al. 2017) were not installed in the rivers below or above the fishways due to the large number of recreational users at both sites, and installation permissions being limited to the fishways themselves.

Schedule-80 polyvinyl chloride pipes (PVC) housed the two loops of 12-gauge thermoplastic high-heat-resistant nylon (THHN) wire that formed the antennas. Each antenna was connected to an individual tuning box, and all four antennas at each fishway were connected to an Oregon RFID HDX multiplexing antenna reader. Each multiplexer ran the antennas in a continuous sequence to reduce read interference between antennas while recording the date, time, tag ID number, and antenna number for each tag detected by a given array (Oregon RFID 2014). Antennas were numbered 1 through 4 from downstream to upstream.

Antenna shape, construction, and installation varied widely between the two sites due to differences in the fishway designs and site-specific characteristics. Placement of the upper two antennas at the FCRID mirrored the 2016 placement by Richer et al. (2020) in the original 3–m fishway, with two new antennas placed in the recently retrofitted downstream portion of the fishway (Figure 1.2). The FCRID antennas were uniform trapezoid loops bolted into the roughness element bolt casings set into the sides of the fishway. This convenience was not enjoyed at the Dickens Farm site; rather, each antenna varied in size and shape to allow it to cover the variable width of the fishway and fit around the irregularly sized and shaped internal boulders (Figure 1.3). Power for the antennas and readers was supplied by three 12 V/100 AH sealed lead acid batteries connected in parallel, that were charged by power-width-modulated (PWM) Grape Solar STAR-180W-US panels.

Following installation, a comprehensive set of baseline detection distances were taken for each antenna at a variety of locations, with three orientations (vertical, horizontal, and 45 degrees) and with two tag directions (perpendicular and parallel to the antenna) with both 32-mm and 12-mm HDX tags. This provided information on the efficacy of the “cloud” of detection surrounding each antenna and gave a performance baseline for each antenna. Antenna performance was checked against these baseline measurements regularly throughout the study.

The FCRID antenna array was installed in December 2018 and the Dickens Farm array was installed in April 2019; both operated until the study concluded on November 12, 2020. This provided 23 months of monitoring at FCRID and 20 months at Dickens Farm, although software issues at the latter site led to the loss of two-week periods of detection records in January 2019 and again in June 2020.

Fish Tagging

Fish were collected by backpack electrofishing from the areas roughly 400 m upstream and downstream of the fishways (Table 1.1). All fish of all species over 80 mm total length (TL) were tagged with HDX PIT tags and measured (total length; mm) and weighed to the nearest gram. Fish in the 80 – 200 mm TL range received 12-mm tags, those in the 200 – 250 mm TL range received 23-mm tags, and fish over 250 mm TL received 32-mm tags.

Fish were anesthetized (AQUI-S, 30 mg/L) prior to tagging. The tag was inserted through a surgical incision made in the abdomen and gently massaged to guide the tag into the abdominal cavity. Surgical implantation has shown the highest retention and survivability of fish compared to tag injection as it decreases collateral internal damage on smaller bodied fish (Archdeacon et al. 2009; Ficke et al. 2012); for similar reasons, the incision was not sutured (Swarr et al. 2021). Once recovered from anesthesia, all fish were released downstream of the fishway to capitalize on any homing instinct that might encourage navigation of the fishway (Halvorsen and Stabell 1990; Fox et al. 2016).

Antenna installation preceded large-scale tagging efforts by several months at each site due to the time of install and high flows during spring and summer 2019. A small number of resident tagged fish from prior (e.g., Richer et al. 2020) or concurrent studies were detected during this period. All movements of fish tagged during the study detected by the antenna arrays were included in the analyses. However, there were potential paths (e.g., through the radial arm gate opening, over the crest of the weir, or through the drop structure) that were not monitored with antennas as they were considered outside of the study scope.

Hydrology Monitoring

Staff gages were installed at each site, with water depth recorded during bi-weekly antenna checks. These measurements were compared with nearby automated stream gages to develop a correlation between staff gauge readings and stream gauge values. The following stream gages were used for each study site:

- Cache la Poudre River USGS 06752260 at Fort Collins and USGS 06752280 near Timnath for the FCRID site.
- Colorado Division of Water Resources SVCLOPCO for St. Vrain Creek below Ken Pratt Blvd at Longmont for the Dickens Farm Site.

Additionally, a pair of HOBO U2 Water Level Data Loggers were installed at each site to record hourly data on water depth and temperature. The continuous data were supplemented with periodic cross-sectional discharge profiles taken at the mouth and within the fishways with a Hach FH950 Portable Velocity Meter. Within both fishways, a series of point measurements for water depth and velocity helped characterize fishway hydraulics through the structure at four cross-sections. The cross-sections were comprised of five points across the width of the fishway; instantaneous velocity measurements were taken at bottom, depth-average, and surface depths. These were gathered over the course of the monitoring period during a variety of flows.

Data Analyses

All fish information, tag identification numbers, and detection data generated during the monitoring period were processed through custom Java code that allowed fish movement and journeys at each site to be parsed. This enabled the determination of numerous movement factors, foremost of which was the number of successful journeys made by an individual, where a journey is defined as a complete transit of the fishway in either direction when a fish was detected on successive antennas in order before ending on one of the antennas closest to an entrance or exit. Thus, a fish detected on antennas 1, 2, 3, and a final detection on antenna 4 would be a complete upstream journey, as would a fish detected on antenna 1, 3 and 4 in succession. An incomplete journey would show detections on only antenna 2 and 3, or 3 and 4, etc. or only a single end antenna. Journeys, complete and incomplete, could then be tracked across the entire time period with associated flow and temperature data. The database was queried to extract summary statistics by species, fish size ranges, time of day, and temperature, allowing comparisons within and across all sites.

In addition to the passage proportions calculated using the complete journeys (Silva et al. 2018) and summary statistics generated by the database, two general linearized models (GLMs) were constructed for each site in R (Version 4.0.3, including MuMIn, car, and Emmeans packages, R Core Team 2020). The first model grouped all fish species together to model passage performance against time period, daily mean flow, and daily mean water temperature; the average length of all fish to pass successfully on a given day was also included (Table 1.2). Discrete time periods were used in place of dates to minimize correlation effects with temperature and flow and were selected to reflect large periods in the site hydrographs; the time periods used at each site are listed in Table 1.2a. To assist in controlling for the increasing number of tagged fish in each system, a percent of the total of tagged fish was included as a covariate. In the interest of individual performance, the second model was run by specific fish, with passage success used as a proportion of completed to incomplete journeys modeled by species, and length, which was standardized within each species (Table 1.3). Interactions were limited to two-way, and the selection of top models used Akaike's information criteria (AIC). Pairwise comparisons using estimated marginal means (EMM) were used for categorical variables, i.e., species, when possible.

Detection probabilities were not directly investigated for this study, as they were calculated for each site during the related enclosure trials (see Chapter 2). Detection probabilities were high for each individual antenna, >0.70 for all FCRID antennas and >0.98 for Dickens Farm antennas, during those trials. Baseline detection measurements indicated that the detection distances at the FCRID were not exceeded by water levels for 89% of the monitoring period and for 64% at Dickens Farm at the top antenna. Consistent antenna performance and distances fluctuating no more than ± 3.83 cm per antenna at each site assured a high likelihood of detection. As detection probabilities were not formally estimated for this study, the estimates of movement or detection rates assumed a detection probability of 1.0. Given the antenna efficiencies, and detection probabilities from the enclosure study, it is likely that some movements were missed over the course of the study, and therefore movement and detection rates are conservative estimates.

RESULTS

FCRID Study Site

Antenna arrays were installed at the FCRID study site on December 5, 2018 and ran continuously until November 12, 2020. Fish tagging was delayed until August 2019 because of high flows. Five tagging events took place in the fall of 2019, followed by a further six in 2020, resulting in 829 tagged fish from fourteen species (Table 1.4). Of these 829, 330 were detected over the course of monitoring, producing a 39% detection rate for the site. Through detection histories, 182 of the 330 detected fish are known to have made at least one successful passage, for a 55% overall passage rate; 71% of the species successfully ascended the structure. Ninety individuals tagged by the other studies were detected at the FCRID over the course of the project (Table 1.5), but they were not utilized in modeling.

Detection of tagged individuals after their initial release was low at this site, with Creek Chub (n tagged = 36) being the only large species group (n tagged > 20) to exceed 50% detection (Figure 1.4). All Rainbow Trout (*Oncorhynchus mykiss*; n tagged = 2) and Bluegill (*Lepomis macrochirus*; n tagged = 2) were detected, but demonstrated opposite performance, with all Rainbow Trout successfully passing the fishway, whereas all Bluegill did not. Longnose Sucker (*Catostomus catostomus*) and Creek Chub showed the next highest rate of successful passage, at 65 and 62%, respectively, with Brown Trout, Longnose Dace, and White Suckers showing rates in the 50% range. Three other species, Largemouth Bass (*Micropterus salmoides*), Green Sunfish (*Lepomis cyanellus*), and Common Carp (*Cyprinus carpio*), saw successful passage but at rates below 50%, and three species, Stonecat (*Noturus flavus*), Fathead Minnow (*Pimephales promelas*) and Central Stoneroller (*Campostoma anomalum*) failed to travel through the fishway.

Modeling conducted on the performance of individual fish at the FCRID site indicated species had an effect ($p = 2.0e^{-14}$) on successful passage through the fishway, as did the interaction between species and length ($p = 0.03$). Length alone did not present significance ($p = 0.68$). Comparisons using EMM did not identify significant differences in performance between the species (Figure 1.5).

The frequency of detections on the antennas fluctuated throughout the year (Figure 1.6). Detections can be seen rising in mid spring, remaining high throughout the summer, and tapering off in the fall before ceasing in winter (Figure 1.6). Detections for the FCRID appear to roughly track the river hydrograph, although some peaks in detection also occur around tagging events. This finding was further sustained by time-based modeling where, when species delineation was disregarded, the second greatest impacting factor on passage was time of year ($p = 0.008$), with fish length having the greatest positive effect from length ($p = 8.2e^{-16}$) larger fish passing more successfully. Average daily flow and temperature did not show direct significance, but rather as interaction factors with time period ($p = 0.008$ and 0.05, respectively). The percent of total fish tagged by the project on a given day was included in the model and displayed high significance ($p = 0.002$).

Hydrology

Hydrologic measurements were collected over the course of the study, with four comprehensive sets of measurements taken at different flows. The 2019 year saw flows greatly above the period of record average throughout the year, while flows in 2020 tracked closely to previous averages. Evaluation of the fishway during peak flows was difficult given structure design and safety considerations, thus measurements occurred outside the highest flows. At the other extreme, river water depth falling below approximately 0.24 m effectively dewatered the fishway, prohibiting passage (Figure 1.7). This condition occurred for at least 38 days during the monitoring period.

Bottom water velocities in the fishway were consistently less than roughly a third of surface water velocity, even at the highest flows measured, indicating the preservation of a slower benthic region created largely by the roughness elements (Figure 1.10). Depth-averaged and surface velocity measurements, however, were more similar, especially at higher flows. Froude values in the FCRID exceeded the target value of less than 0.3 (Yu and Peters 1997; Richer et al. 2020); the measured flows were equal to or higher than the recorded values from

Richer et al. (2020). Point measurements conducted at four different cross sections in the fishway substantiate the presence of desirable slower velocities, potentially 0.6 m/s or less, near all margins of the fishway, with a central high-velocity region increasing in magnitude from the upstream exit to the bottom entrance, where central surface velocities exceeded 2.13 m/s at the displayed flow (Figure 1.11).

Dickens Farm Study Site

Antenna installation occurred at Dickens Farm in April 2019, and fish movement monitoring ran until November 12, 2020, with two short interruptions in service. Fish tagging began at the end of July 2019, with seven tagging events in 2019 and two more in 2020. Fish were more abundant in the area immediately surrounding the study site, accelerating the tagging process in 2019 as compared to FCRID. In total, 794 fish from seventeen species were tagged and released below the passage structure (Table 1.6). The Dickens Farm detection rate was higher (59%) than at FCRID, with 471 fish recorded through the monitoring period. Upstream passage was also slightly higher at this site (62%), with 290 of the 471 detected individuals completing a successful trip through the fishway, accounting for 61% of the tagged species.

Some species, such as Largemouth Bass (*Micropterus salmoides*) and Creek Chub, showed over 50% detection for tagged individuals, with all sizable species groups, except Black Bullhead (*Ameirus melas*), demonstrating passage success at 50% or higher (Figure 1.4). Few Brown Trout and Red Shiners (*Cyprinella lutrensis*) were tagged for the study, however, all of those that were detected successfully ascended the fishway. Six other species, such as Gizzard Shad (*Dorosoma cepedianum*) and Yellow Perch (*Perca flavescens*), were represented by few tagged individuals, which were rarely detected, if ever, after release. All failed to successfully pass the fishway (Figure 1.4).

Species was the most significant factor in predicting individual fish performance at Dickens Farm ($p = 2.2e^{-16}$), as was the interaction between species and length ($p = 1.2e^{-10}$), though length alone did not have a significant effect. Higher numbers of attempted and completed journeys at Dickens Farm produced more robust EMM species comparisons, with significant differences between Creek Chub, Longnose Sucker, Largemouth Bass, Longnose Dace, Green Sunfish (*Lepomis cyanellus*), Stonecats, and White Suckers (*Catostomus commersonii*) (Figure 1.5).

Total detections were higher at the Dickens Farm site overall, with some individuals detected thousands of times during the study. In contrast to the FCRID site, activity around the antennas does not closely track hydrograph patterns, instead showing high activity from the onset of tagging through the warmer months before declining sharply into winter (Figure 1.6). This pattern was repeated in the second year of monitoring, and again lacked distinct peaks in detections around spring runoff. Daily movement timing showed a stronger adherence to diurnal or nocturnal patterns, depending upon the species groups (Figure 1.8). The duration of successful journeys, and thus time spent within the fishway, was markedly greater at the Dickens Farm site in comparison to the FCRID, frequently occupying hours instead of minutes (Figure 1.9).

Despite the lack of distinctive peaks in detections (Figure 1.6), the model results showed time period playing a significant role in passage (p-value = $1.095e^{-14}$). Length and the length x period and length x temperature interactions were significant variables in movement ($p = 0.001$, $1.9e^{-11}$, and 0.005, respectively). Temperature played a larger role at Dickens Farm, not significant alone, but in combination with period ($p = 2.2e^{-16}$) and length, as stated above. Understandably, the percent of total fish tagged was also significant at Dickens Farm ($p = 2.2e^{-16}$).

Hydrology

The Dickens Farms structures were not specifically designed to impound water for diversion. The bypass channels were never dewatered during the study period, unlike the FCRID structure, as they carried the majority of water during low flow periods. The passage is built as part of the lowest terrace and flows can spill over the fishway boulders onto upper terraces, during especially high flow events. Such flows only occurred briefly during the exceptional flow year of 2019, during which flows in the fishway were not measured; otherwise, flows did not crest the side boulders.

Overall, the Dickens bypass structure consistently maintained greater depths than the FCRID (>0.25 m) throughout the year, even at much lower discharges (Figure 1.10). During survey times, average velocities throughout the fishway were also markedly lower, never exceeding 1.0 m/s at the surface at the recorded discharges, which were also lower. Froude values at Dickens Farm never exceeded the 0.3 threshold under the recorded conditions (Figure 1.10). Cross sections along the length of fishway show the thalweg switches from side to side due to the placement of boulders within the channel (Figure 1.12). The overall magnitude of the velocity gradient is lower throughout the passage, with a far wider area of slower, even negative, velocities along the fishway margins.

DISCUSSION

This study was the longest (> 1.5 years) effort to date to monitor fish movements at two sites representing common types of fish passage structures installed on Colorado rivers and streams transitioning into the Great Plains – engineered rock-ramp structures (FCRID site) and grouted boulder bypass channels (Dickens Farm site). Both structures provided fish passage over a range of conditions. The study was able to show differences between the passage success and characteristics of rock-ramp type and bypass channel type fishways, and also provided insight into the plastic nature of fish movement timing; sometimes it seemed to be seasonally cued, and at other times it seemed more closely coupled with flow patterns.

Passage rates show that both sites were successful at passing fish from a broad array of species throughout the year, effectively reconnecting the surrounding river reaches when flows were high enough to provide water in the fishways. In cases where a species passage success was low, it appeared more dependent on the number of tagged fish than on the type of structure, as all species with more than 20 tagged individuals saw both detection and successful journeys, although a few smaller groups still achieved passage (Figure 1.4). Journeys and detections also occurred through a variety of flows throughout the year, indicating that both fishways were functioning for the vast majority of the time for most species, especially in the pre- and post-runoff periods (Figure 1.6 and 1.7).

While both were successful, it is apparent the fishways functioned on different levels and in different ways for their respective fish assemblages. Detection was much lower at the FCRID site (39%) compared to Dickens Farm (59%), a situation potentially explained by the size difference of the rivers and the nature of the surrounding habitat. The Cache la Poudre River, while not dissimilar in average width in the area adjacent to the FCRID diversion compared to the St. Vrain in the Dickens Farm area, sees markedly higher flows during runoff (Figure 1.6). Also, unlike Dickens Farm, where over a kilometer of river underwent heavy habitat augmentation for the recreational area, adequate and less recently altered habitat existed beyond the FCRID in both directions. Even though fewer individuals made contact with the passageway, the FCRID had a 55% passage success rate, indicating the FCRID is working, but at a slightly lower rate than the 62% passage success rate recorded at Dickens Farm.

Numerous design differences exist between the structures, the foremost being the difference in slope (FCRID: 5% vs. Dickens Farm: 2%). While a five percent slope is surmountable by many of the weaker swimming native species, it is at the top end of their capacity, a capacity that could be outweighed by increases in flow or a lack of sufficient surface texture or roughness elements in certain design situations (Ficke et al. 2011; Swarr 2018; Brittain 2022; see also Chapter 2). It is likely this effect is greater for fish below the 80-mm TL tagging cutoff (Swarr 2018; Brittain 2022) that may have reduced absolute swimming abilities, but this was not evaluated in the study. While slope is not the only factor in success—attraction flow, low flow capacity, depth and channel complexity also matter—it does provide more evidence that the fish found in Colorado's transition zone and plains streams are capable of negotiating fishways when the slopes are kept to 5% or less.

Regardless of the slope selected, the combined hydraulic measurements and fish passage results provided evidence that incorporating within-structure heterogeneity in the form of large roughness elements and variable surface texture (with rougher apparently better) are design components worth considering. The hydraulic evaluations at both sites demonstrated that these features helped establish slower velocity regions for fish to utilize and created velocity refugia behind them (see the second cross section on Figure 1.11). When possible, adopting an approach similar to that used at Dickens Farm, where the fishway was constructed largely from boulders with variable substrate sizes intentionally or naturally deposited between the grouted boulders, provides greater complexity in terms of entrances and exits, greater side roughness, low velocity interstitial areas under and around boulders, and thalweg sinuosity created by in-channel rocks, which taken together contributed to both its lower velocities and potentially to its greater passage success.

This increased complexity may have also contributed to the long residence time of some fish within the Dickens Farm structure. The Dickens Farm site antenna array collected a larger volume of detections (>350,000 during the course of the study) than recorded at the FCRID site. The possible reasons for this divergence include the lack of Stonecats at the FCRID site, which consistently accumulated the highest numbers of detections and journeys at Dickens Farm. The Stonecats likely used the Dickens Farm site in this manner because of the presence of more rock habitat within the fishway compared to the surrounding river. When the fish passage structures were installed, post-flood restoration and stabilization efforts altered natural riffle habitat within the reach, and removed accumulations of large wood and other forms of habitat complexity favored by natives and introduced species alike. The bypass channels of the Dickens Farm structures not only served as a fish passage, but also created a complex, albeit artificial habitat within that reach. This extended residence time was reflected not only in the number of detections, but also the large number of partial journeys undertaken within the fishway, indicating day to day habitat use. The FCRID site did not demonstrate these lengthy residence times within the fishway; once fish advanced beyond the first backwatered antenna, they either completed their upstream passage or returned to the downstream fishway entrance. This indicates the FCRID is functioning primarily as a passage structure, as intended, while Dickens Farm serves as both passage structure and as habitat, which is an unintended aspect of its design. While it is typical for a fish to ascend a fishway rapidly through burst swimming, slower ascents may indicate an ability to conserve resources during the passage rather than simply an inability to pass (Crossin et al. 2004; Pon et al. 2009). As such, passages like Dickens that can provide cover and resting areas, increasing residency time, and could decrease the strain of passage and increase the likelihood of overall success. This duality of passage and habitat is not essential to fishway design, given that re-connectivity is typically paramount, but when the site and situation allow for it, the incorporation of design elements that improve the habitat suitability should be considered, particularly in areas where the surrounding habitat has been degraded from the natural state.

Fish size, an often-cited concern for fish passage success (Ojanguren and Brana 2003; Richer et al. 2020), did play a role in passage, as the modeling results indicated that success increased with length across all time periods at both sites, yet small fish also saw good passage. As might have been expected larger individuals (or large-bodied species) such as Longnose Suckers and Brown Trout demonstrated frequent passage, but smaller-bodied species such as Longnose Dace, Creek Chub, and smaller suckers performed well under a variety of conditions. Successful passage was observed not only for smaller-bodied species that happened to be in the upper limits of their size class, but even by those barely over the 80-mm minimum tagging size. While the success of smaller-bodied fish successfully ascending the fishways is encouraging, this study did not expressly evaluate the passage of smaller fishes, as antenna requirements limited the minimum tag size to 12-mm. Thus, these long-term results excluded juveniles of some of the larger fish species and smaller species such as darters (*Etheostoma* spp.) or Plains Topminnows (*Fundulus sciadicus*) that rarely reach 80 mm TL. An attempt was made to address this gap in information during the associated enclosure trials at each site (see Chapter 2). Ongoing improvements in both tag size and antenna design and performance may allow more comprehensive monitoring of the passage of these smaller individuals in the near future.

The use of PIT tag systems for monitoring provided information on passage success and also gave insights into some of the behaviors and movement timings of species within the system. Activity patterns, represented by journeys, were documented for each site, with the fish community at Dickens Farm showing distinct groupings into diurnal and nocturnal species. Fish activity at the FCRID had more diffuse diel patterns, and species that were strongly nocturnal or diurnal at Dickens Farm instead showed movement throughout the day or with less distinct time preferences. Longnose Suckers at Dickens Farm moved largely at night, seeming to favor the early hours of the morning, but at the FCRID their movements were concentrated in the late afternoon and evening. This difference between the sites likely relates to how fish are utilizing the passages, as discussed previously, with Dickens Farm being used as a long residence time passage, whereas FCRID is used as a short-residence time passage. Surprising, though, were Longnose Dace, who were almost exclusively daytime movers at Dickens Farm, but demonstrated more nocturnal preference at FCRID, a potential response to greater predation risk while moving through shallower water (Gelwick et al. 1997).

Tagging at both sites occurred in a repeated, sporadic, and temporally clustered manner, largely in late 2019 and several times in spring and fall 2020, resulting in sporadic increases in the number of tagged fish in the passage vicinity, complicating later analyses. In regard to the main objective of the project—determining how successful fish were at passing the fishway—these events did ensure that the number of tagged fish in the area remained high, especially as all tagged fish were released directly below the fishway, with many continuing to reside in the pools. Not surprisingly, tagging events were consistently followed by spikes in the number of detections and journeys recorded by the antennas. From a fish movement standpoint, however, these inflated spikes were artificially created, rather than naturally influenced by a seasonal or hydrographic event, and added noise to the natural movement patterns. Modeling consistently indicated the greatest differences between the "Post-Runoff" period (July 10th to September 20th at FCRID and July 15th to September 15th at Dickens Farm) and all other periods, however the post-runoff period was when the greatest amount of tagging took place, likely confounding results to some degree. However, it should be pointed out that while more fish were tagged during this period, fish entry into and through the fishways was still voluntary. For future studies it may be more ideal if a large cohort of fish were tagged at the beginning of the project and allowed to persist in the system throughout the course of the project, although additional tagging events may occasionally be needed to increase or supplement the number of tagged individuals depending on the length of the monitoring project.

This being said, there were periods during monitoring when no additional fish were added that movement patterns emerge. One of particular interest is the interval between late October 2019 to late May 2020, where fish movements decreased as winter approached, were minimal through the coldest months, and began to increase with the beginning of spring runoff. The peak in fish movement appears to precede the hydrograph's peak, especially at the FCRID site, where the greatest observed fish movement occurs from early April to early May, and even begins to decline prior to the first large increase in the hydrograph. This provides support for the notion that transition zone natives are indeed moving early in the water year (Fausch and Bestgen 1997 and Falke et al. 2010). Peaks in movement can also be seen throughout the later summer and early fall, when short duration increases in flow occur. These would have historically been created during monsoon rains but may now be driven by the operation of water diversions. Regardless of source, the increased movement indicates that fish are moving opportunistically, likely redistributing themselves as water conditions change through autumn dry periods into winter (Fausch and Bestgen 1997). These peaks in movement were less pronounced at the Dickens Farm site, but it is evident that movement at the site began well in advance of peak flows. Passage data from Dickens Farm also show that while fish residence times in the structure were long during the majority of the year, it was not uniformly used as an overwinter area, as evidenced by fish that moved upstream after months of continual detections in late summer or fall and then were redetected in the spring.

Flows and access to fish passage structures in the weeks leading up to peak runoff appear just as important, if not more so, for riverscape connectivity as peak runoff itself, and should be kept in mind by water managers whenever further allocation of water is possible. Additionally, late season opportunistic movement is crucial when water and connectivity are in short supply, allowing movement following spawning, recruitment, and stochastic water conditions (Fausch and Bestgen 1997; Durham and Wilde 2006; Falke et al. 2010). Allowing such pulses or managing available late season water to artificially create such pulses may provide this connectivity through both the passages and the larger river system.

Periodic dewatering was an issue at the FCRID site but not at Dickens Farm, an obvious concern for passages connected to diversion barriers. At minimum, water levels at the FCRID were low enough for 38 documented days when water was either not flowing through the fishway or the flow was low enough that the water depth was less than 5 cm in the upper passage. This no-flow threshold typically occurred around a 0.24 m river depth measured on the pressure transducer, corresponding to a fishway flow of less than 0.028 m^3/s. Interestingly, Longnose Dace were able to complete successful journeys up the fishway at 0.27 m recorded river depth, while the minimum depths for other species ranging from 0.3 to 0.48 m river depth. Thus, the fishway functioned even at very low flows for species that were willing or capable of transiting very shallow water.

Connectivity, or lack thereof, at the FCRID was two-fold, as a lack of water in the fishway often coincided with a loss of downstream connectivity in the river itself, sequestering fish in the large pool just below the diversion. This problem did not arise at the Dickens Farms during the monitoring period, as the combination of an in-stream water right obtained for the recreation area (City of Longmont 2014), the overall design, and lack of a severe diversion ensured the passage maintained water year-round. Such conditions are site specific but, given the movement patterns seen during this study for transition zone natives, working to keep minimum flows in the fishways and thus the surrounding river corridor throughout the year when possible is ideal (Durham and Wilde 2006).

The degree of riverscape modification that has occurred in the riverscape surrounding a fish passage structure should be taken into account for long-term monitoring projects. Only a single passage required navigation at the FCRID site for fish to access over half a kilometer of river upstream and nearly a dozen kilometers downstream before encountering another potential barrier or obstacle to movement. Dickens Farm, in contrast, consisted of nearly a kilometer of extensive habitat augmentation with nine drop structures, all of which required moving through a wingwall bypass before fish came into contact with less modified river segments. During this study only one bypass was monitored, as the interest was on the individual design. However, while the passage of a single 2% grade passage was achievable, navigating the full modified reach could be exhaustive, prohibiting movement further beyond the nearest pools. A simple assumption of a 50 to 60% rate of passage for a given individual through a single fishway would extrapolate to barely a 1% chance of successful passage through nine structures, assuming a consistent and cumulative probability of passage. However, the simplistic approach does not necessarily reflect what happens in the field, as during sampling efforts, a tagged Longnose Dace was recaptured five passages above its release site, indicating that more extensive passage through multiple structures was occurring. If passage success is not cumulative, but rather reflects the passage success of fish encountering any of the structures, then the series of structures would not pose a challenge to migrating fish. Clearly, the best way to understand this potential effect would be to track fish movements over the full series of structures, but that was outside the scope of this project.

This is a consideration for a larger scale as well, as rarely is it only a single impediment to passage that must be corrected. This is often a lengthy process achieved with varying designs and restrictions, leading to a larger question of true fish passage over the entire reach (Silva et al. 2018). The introduction of multiple fishways can have immediate positive effects on the distribution of some species (Rourke et al. 2018), but the cumulative effect of navigating successive passages should be accounted for, especially when movement is time sensitive (Naughton et al. 2005). Monitoring at the FCRID and Dickens Farm showed movement around the respective fishways was possible but monitoring such riverscapes over both distance and time as broader connectivity is restored will be essential in understanding how designs function in a variety of situations and how they can additively affect overall fish movements in a river system.

TABLES AND FIGURES

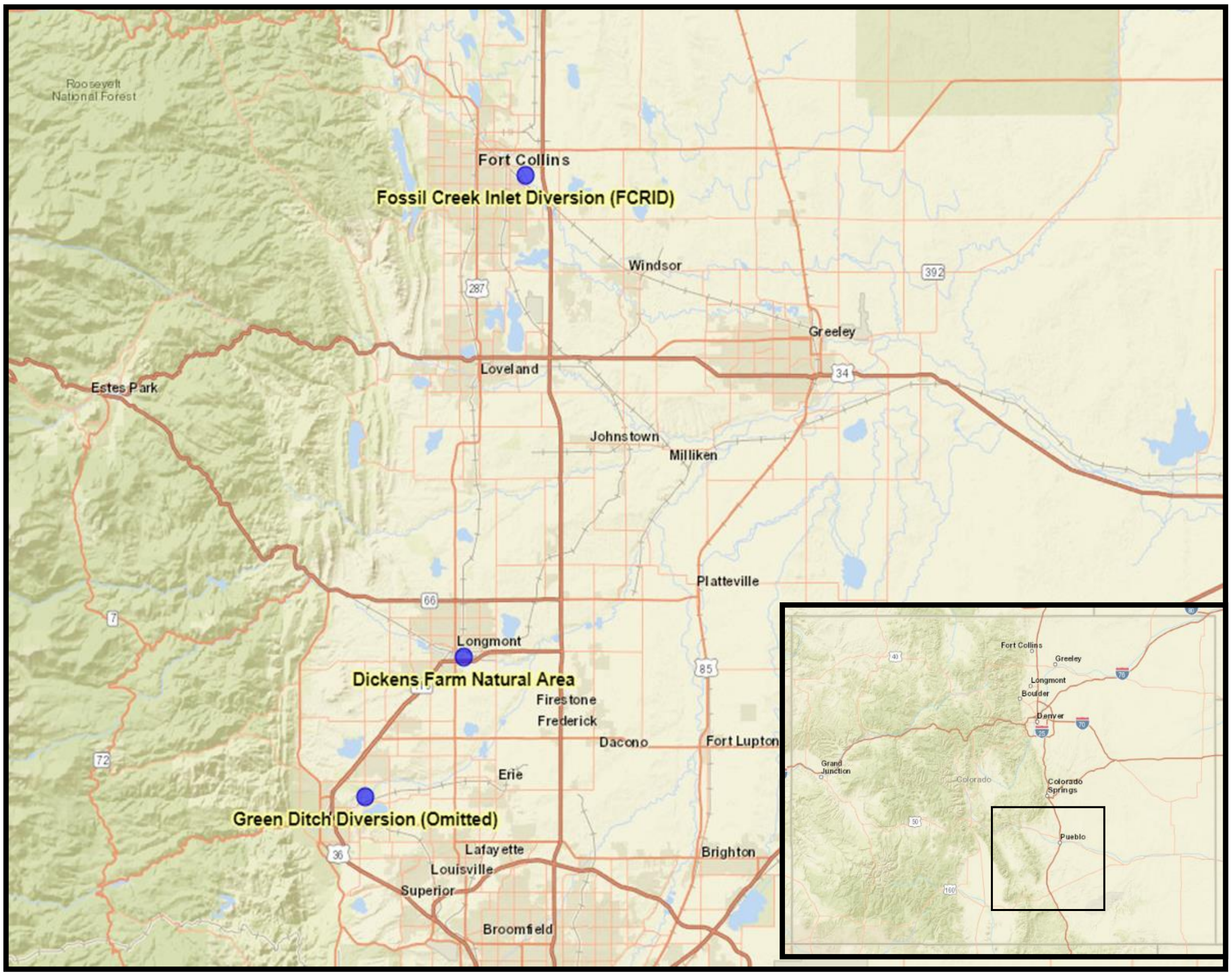

Figure 1.1- Map showing the locations of the two monitoring sites: the FCRID and Dickens Farm Natural Area, with pop out map showing the specific area of the Front Range of Colorado. The third proposed but omitted location is included for reference.

Figure 1.2- Top photo shows the Fossil Creek Inlet Diversion low head concrete dam including the fish passage on the far right and the radial and ditch gates on the far left. Bottom left shows the inner configuration of the fish passage, with trapezoidal cross section and cobble roughness elements. Bottom right shows the antenna placement (grey pipes) within the passage.

Figure 1.3- Top left shows the downstream-most portion of the Dickens Farm Natural Area, including grouted boulder pool drops, grouted boulder wingwall bypass fish passages on the left side terraces and bank stabilization. A closeup of the studied passage structure is shown at the bottom left, with the locations of the four antennas denoted by red lines. Photos to the top and bottom right illustrate the various approaches taken to secure the antennas in the passage for the duration of the study.

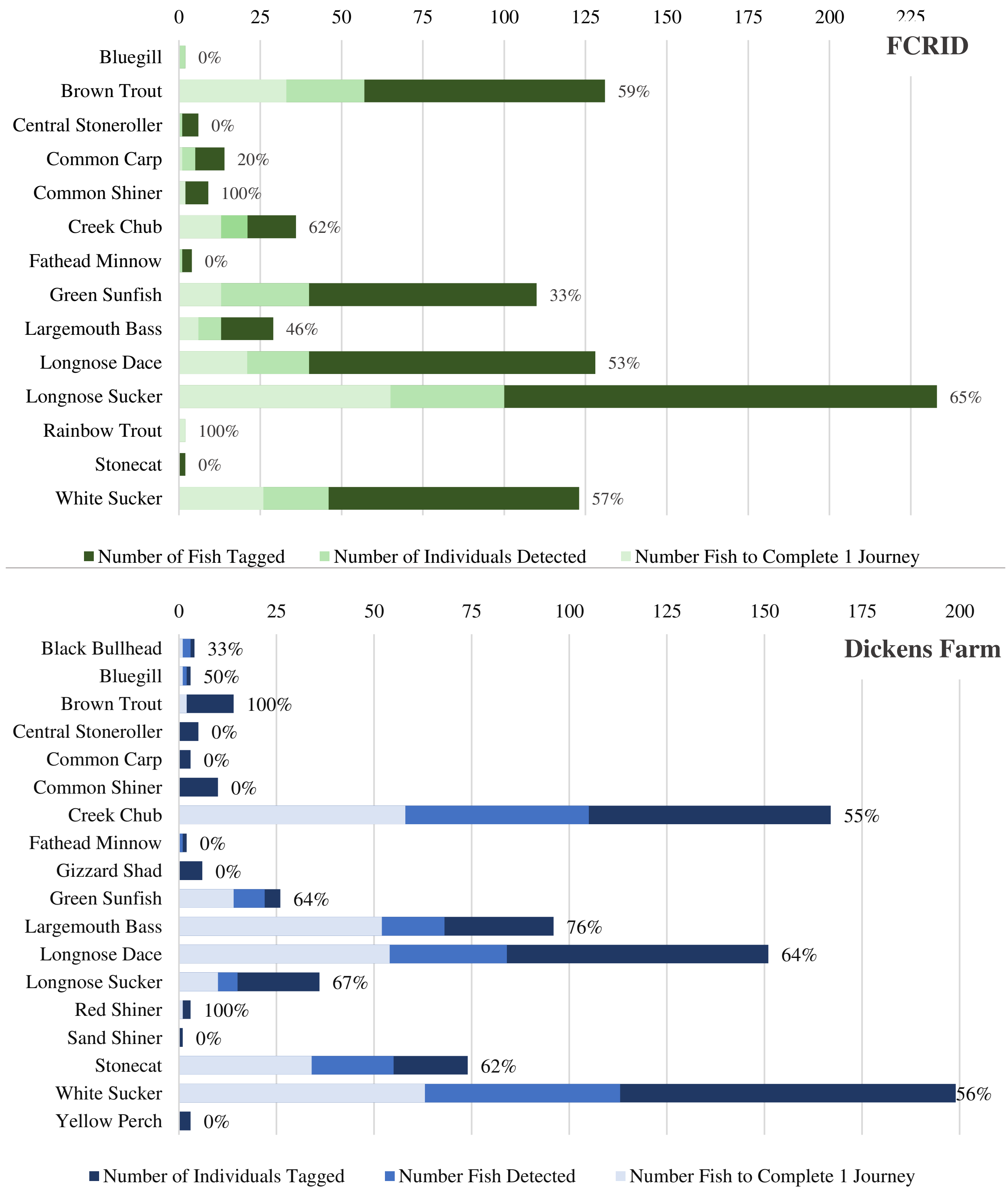

Figure 1.4- Summary of fish tagging efforts and movements at the FCIRD (upper panel) and Dickens Farm (lower panel) study sites. The entire bar (all colors) shows the total number of each individual species tagged with dark portion of the bars indicating how many fish were never detected after release, the medium bar overlay shows the number of that species that were detected, and the lightest overlay showing the number of fish in each species that completed at least one full journey. The percentages indicate the rate of successful passage for the species.

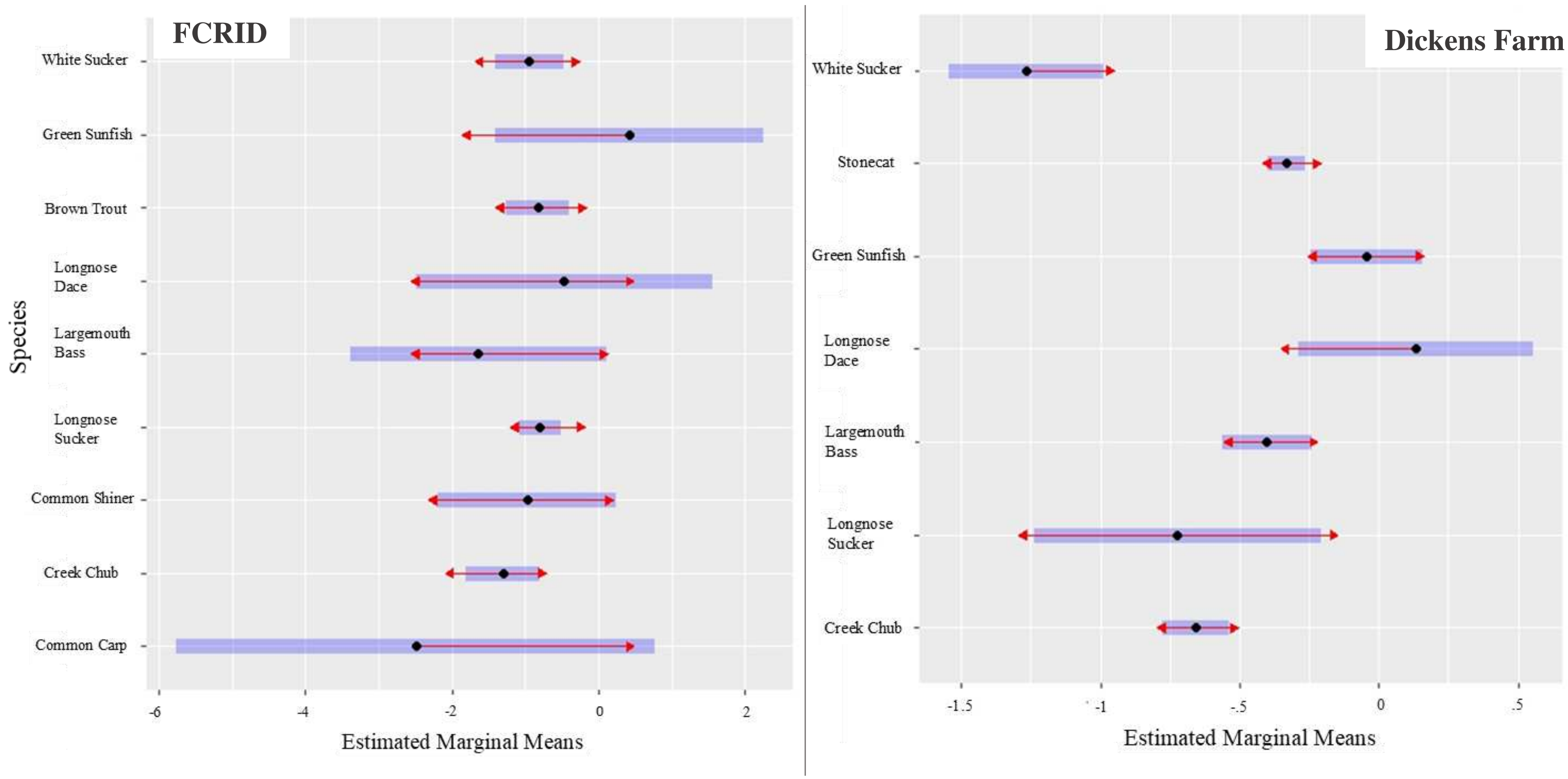

Figure 1.5- Pairwise comparison of performance between species groups at each respective site using estimated marginal means. Red overlap arrows show the difference in significance between each species, those arrows that do not overlap indicate a statistically significant difference ($p < 0.05$) in performance between the species, such as Stonecats and White Suckers at the Dickens Farm site. Purple bars show estimated 95% confidence intervals for each species.

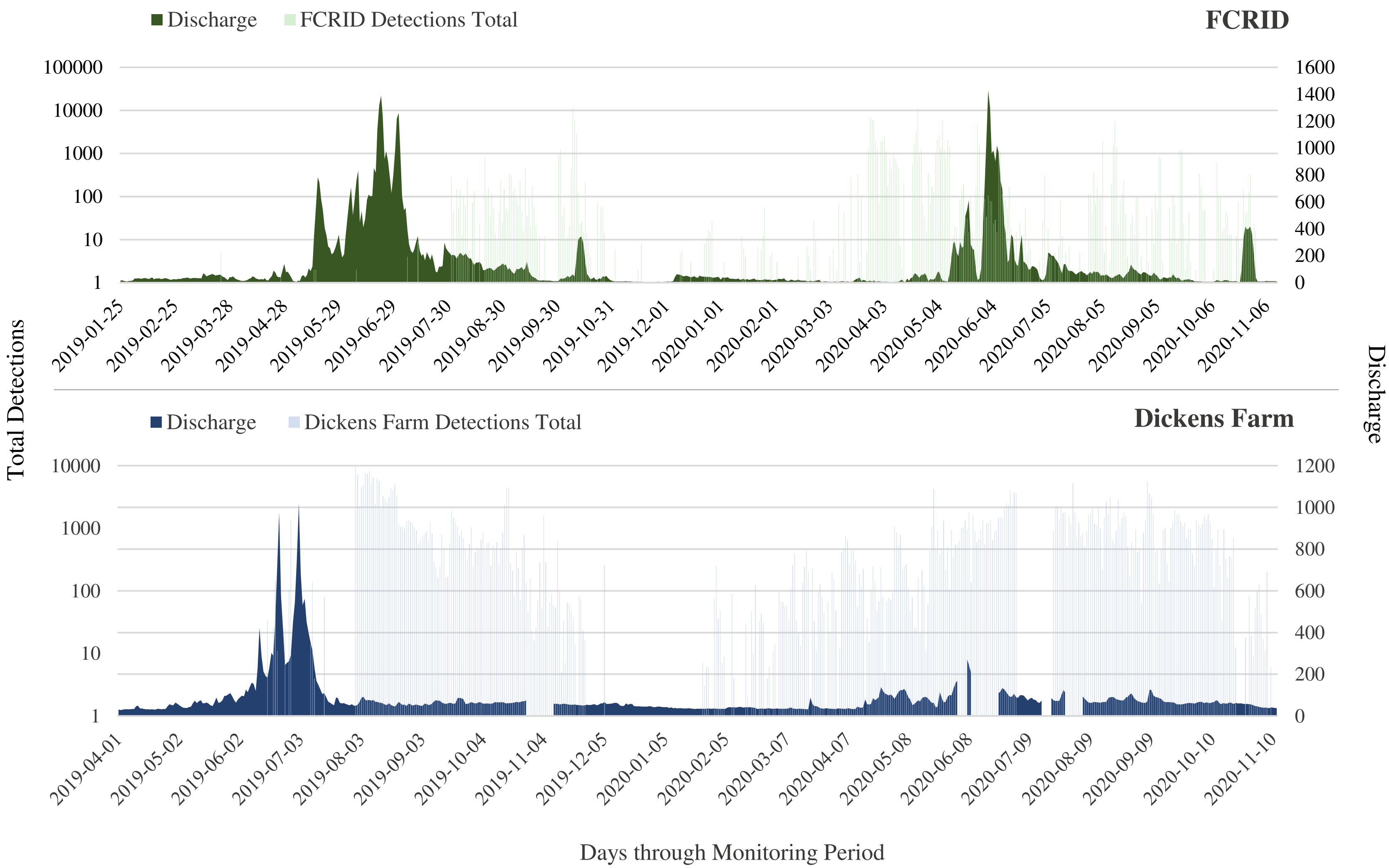

Figure 1.6- Daily average discharge (CFS) for each site as recorded by the nearest upstream river gauge as the solid area graph, with an overlay of the total number of daily detections. Gaps can be seen in the flow data were caused by periodic gage malfunctions.

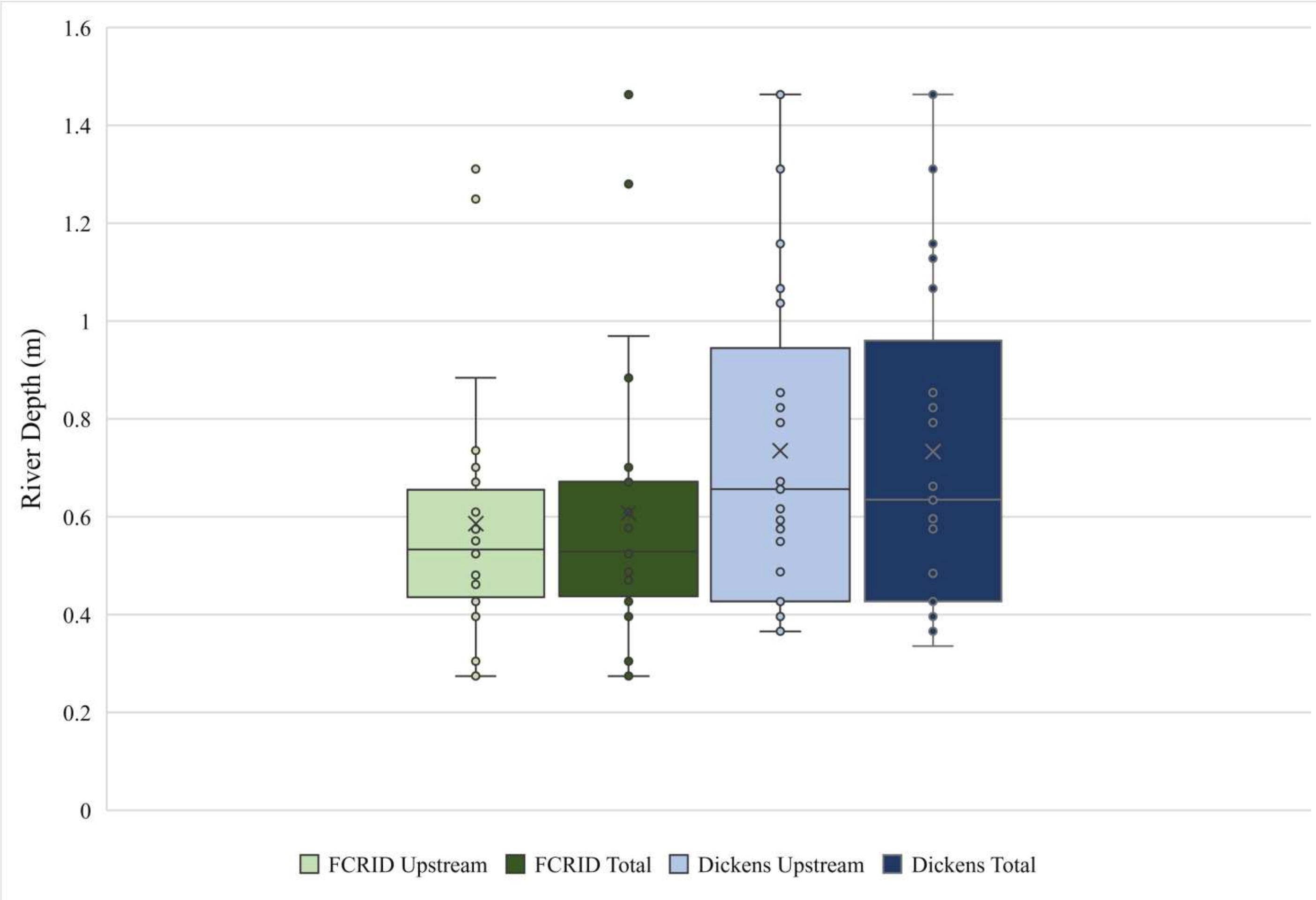

Figure 1.7- The range of river depths (m) at which journeys were completed at both sites, with separate boxes showing just upstream passages and then all complete journeys made. The dotted lines show the minimum and maximum recorded depths for each site over the monitoring period. When river depth < 0.24 m at the FCRID, the fishway was dewatered. The Dickens Farm fishway was not dewatered during the study period.

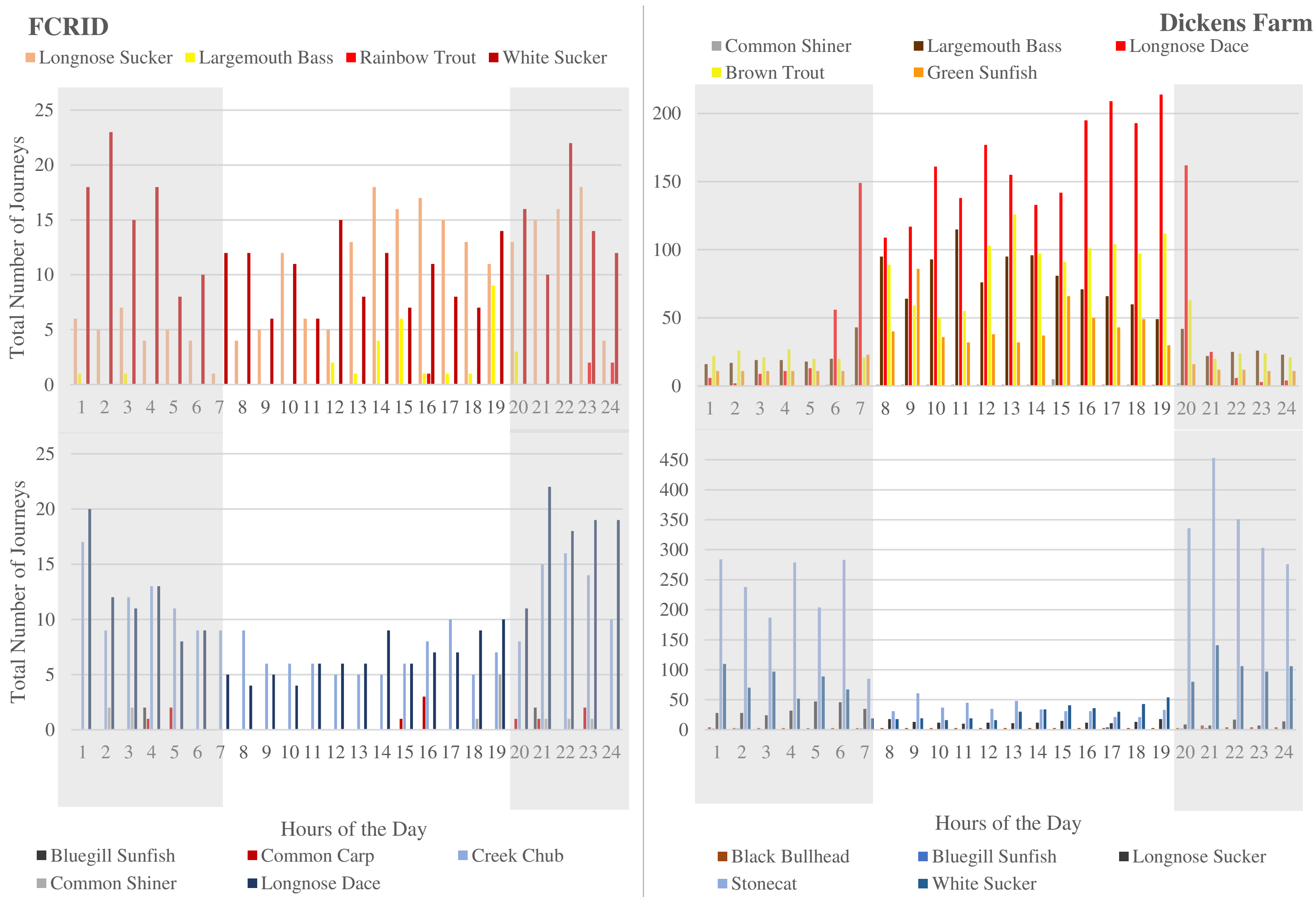

Figure 1.8- Diurnal patterns in fish movements (based on the time of initiation of complete and incomplete journeys) on a species-specific basis. The top graphs show species that tend to move during the day and bottom graphs show species that move more at night. Nighttime shading is approximate.

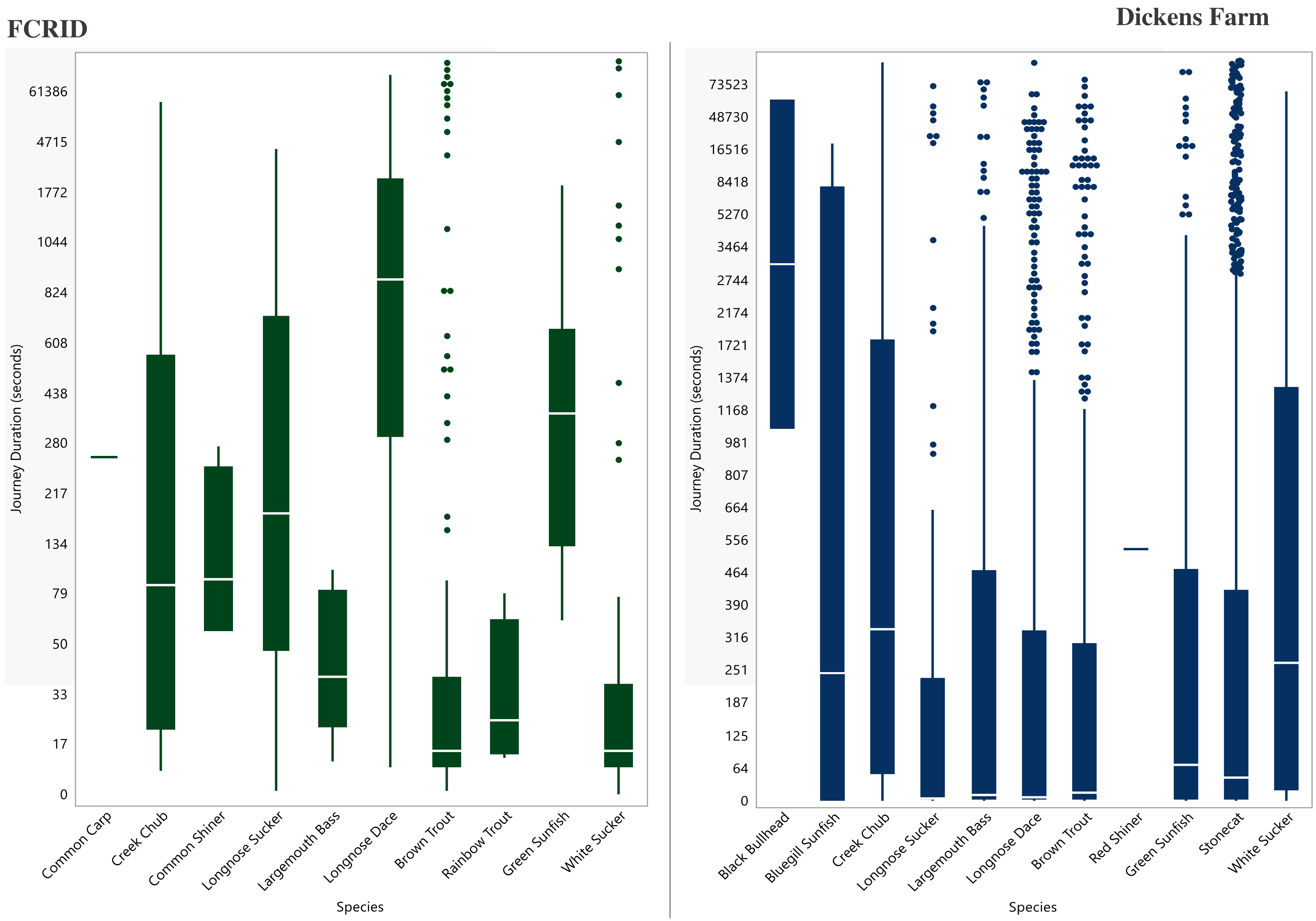

Figure 1.9- Passage duration in seconds for all completed trips through a fishway at each study site, separated out by species, regardless of time of day or year.

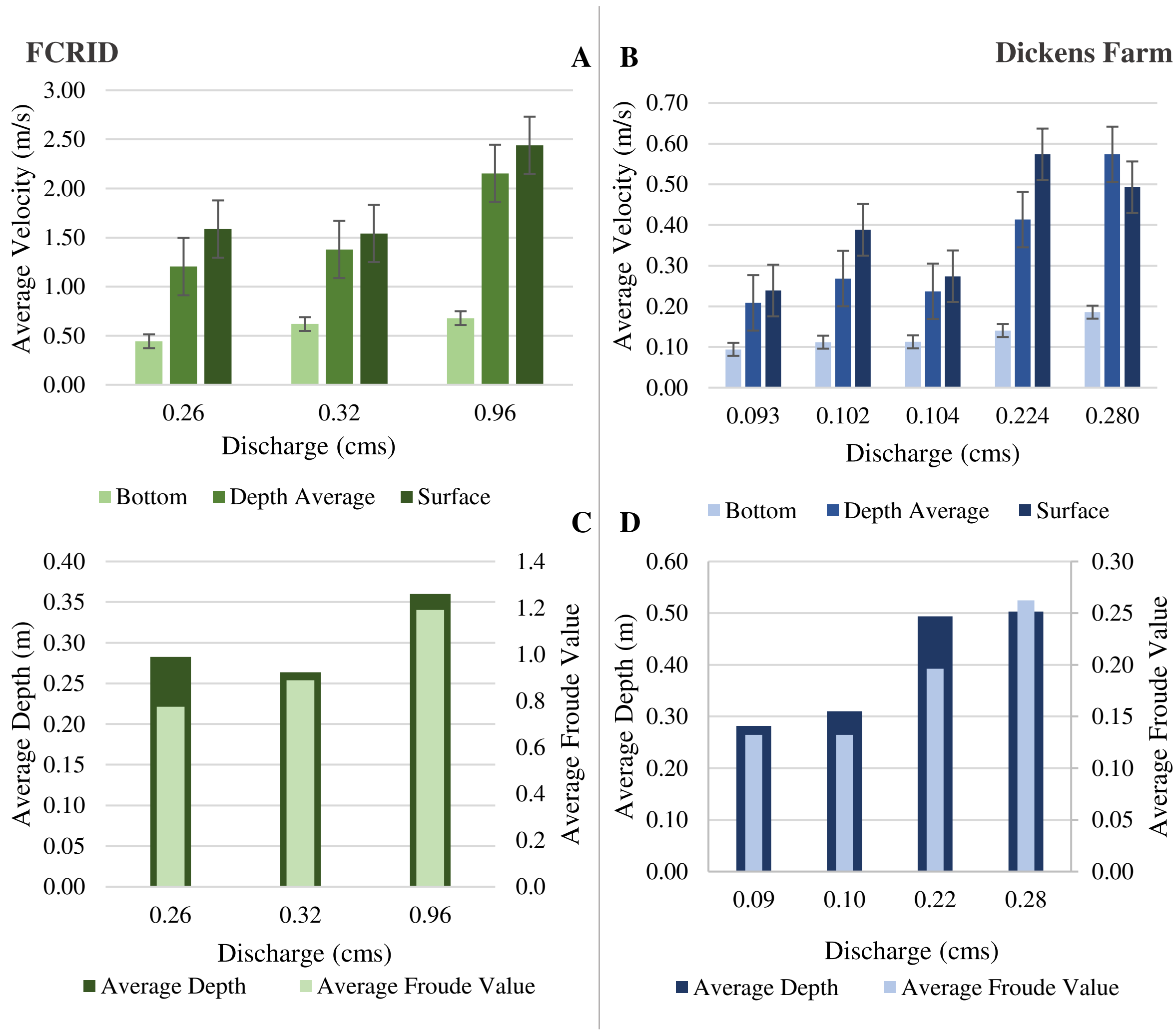

Figure 1.10- Summary of the hydraulic measurements taken within the fishways at each site, with top graphs (A, B) comparing the bottom, depth-average, and surface water velocities, and bottom graphs (C, D) showing the average depth and Froude number all across a series of fishway discharges.

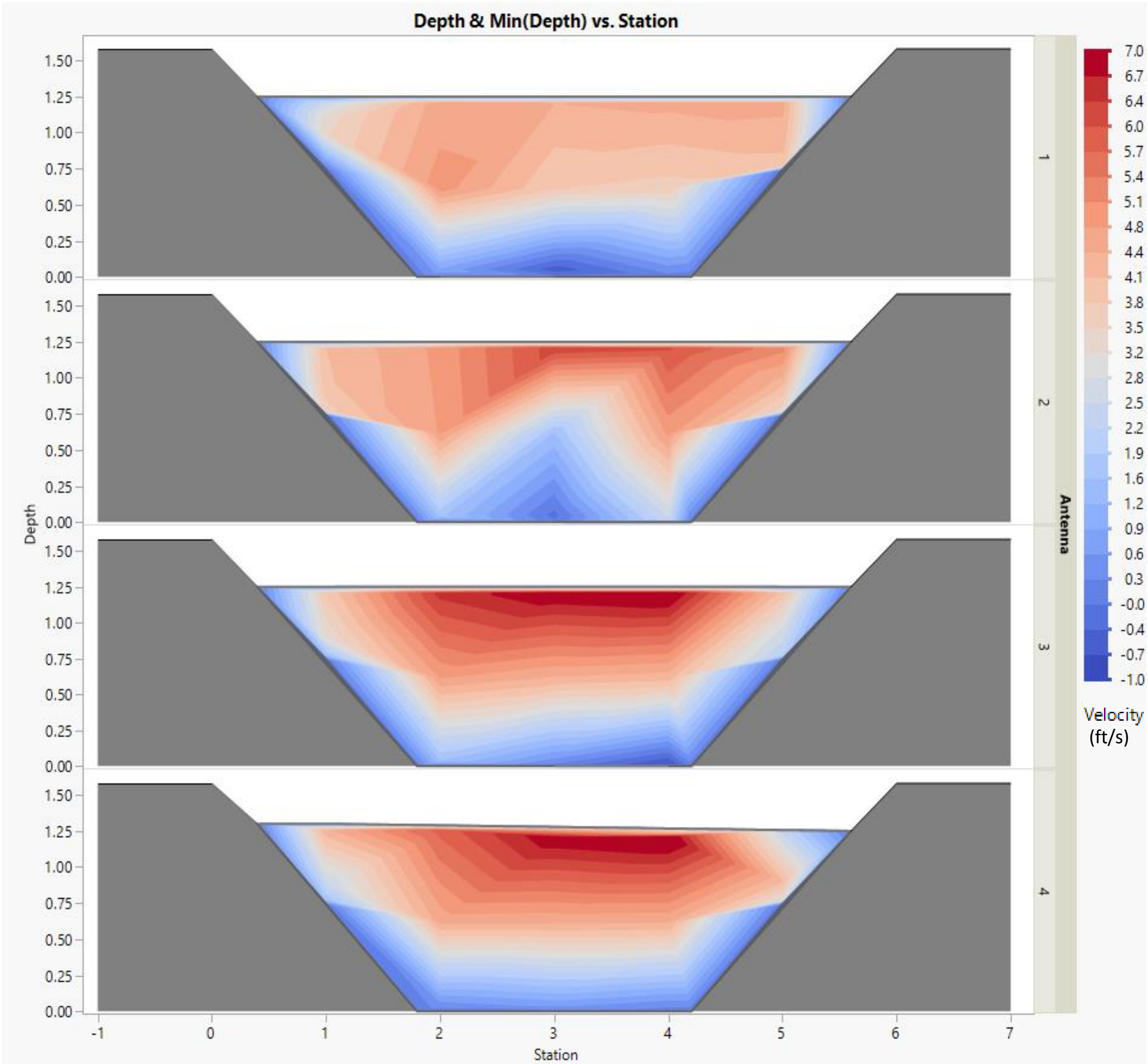

Figure 1.11- Contour plots showing the gradient of flows found through the FCRID fishway, at four different cross sections from the top quarter of the fish to the bottom quarter, roughly around the placement of the four antennas. Instantaneous velocities were recorded at bottom, average, and top depths at five locations across the channel over ten second intervals. Figure displays flows on July 30, 2020, during which total discharge through the fishway was measured at 0.26 m^3/s (9.33 cfs).

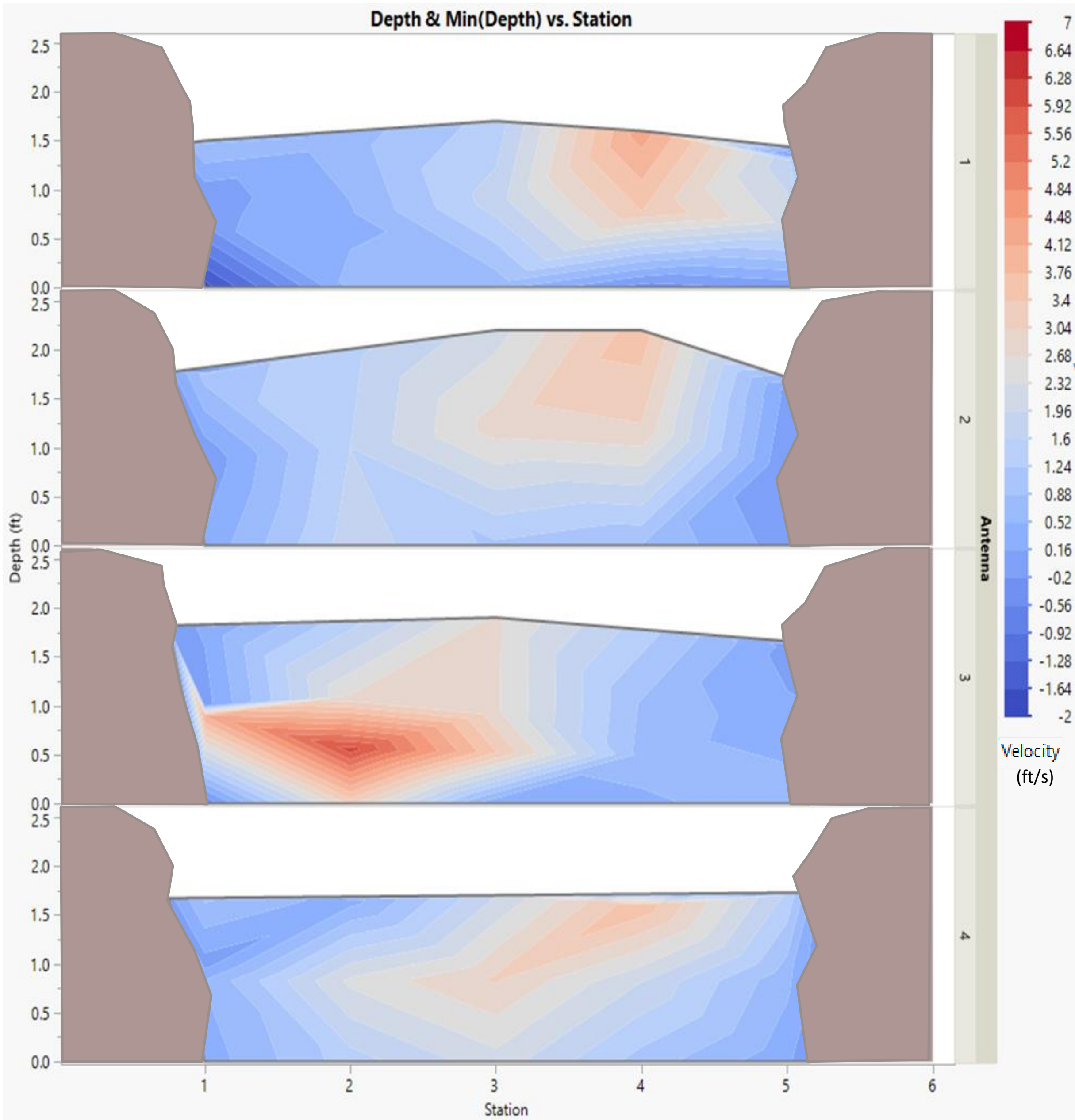

Figure 1.12- Contour plots showing the water depth and velocity found through the Dickens Farm fishway, at four different cross sections from the top quarter of the fishway to the bottom quarter, roughly around the placement of the four antennas (Shape of barrier sides are strictly representational). Real time velocities were recorded at bottom, average, and top depths at five locations across the channel over ten second intervals. Figure displays flows on May 19, 2020, during which total discharge through the fishway was measured at 0.28 m^3/s (9.9 cfs).

Table 1.1- Fish species included in the long-term monitoring at each site, with **X** denoting successful passage through that fishway. Species native to the Front Range transition zone are marked by an asterisk. A small number of fish species were brought in low numbers during the associated enclosure trial at each site to expand the testing pool and released into the river following the conclusion of the trial, these species are denoted by (I).

Common Name	Species Name	FCRID	Dickens Farm
Black Bullhead*	*Ameiurus melas*		**X**
Bluegill	*Lepomis macrochirus*	X	**X**
Brown Trout	*Salmo trutta*	**X**	**X**
Central Stoneroller*	*Campostoma anomalum*	X (I)	X (I)
Common Carp	*Cyprinus carpio*	**X**	X
Common Shiner*	*Luxilus cornutus*	**X** (I)	
Creek Chub*	*Semotilus atromaculatus*	**X**	**X**
Fathead Minnow*	*Pimephales promelas*	X	X
Gizzard Shad	*Dorosoma cepedianum*		X
Green Sunfish*	*Lepomis cyanellus*	**X**	**X**
Largemouth Bass	*Micropterus salmoides*	**X**	**X**
Longnose Dace*	*Rhinichthys cataractae*	**X**	**X**
Longnose Sucker*	*Catostomus catostomus*	**X**	**X**
Rainbow Trout	*Oncorhynchus mykiss*	**X**	
Red Shiner*	*Cyprinella lutrensis*		**X**
Sand Shiner*	*Notropis stramineus*		X
Stonecat*	*Noturus flavus*	X (I)	**X**
White Sucker*	*Catostomus commersonii*	**X**	**X**
Yellow Perch	*Perca flavescens*		X

Table 1.2a-Variables included for the time-based model without delineation by species. An asterisk denotes use in a two-way interaction. The dates for each of the five time periods are included below by site. **b-** AIC model selection table for the top three models displayed for each study site, and their two-way interactions, a value for continuous variables or a plus sign for categorical variables indicates its suggested inclusion in that model set.

<table>
<tr><td colspan="6">Time Dependent Model</td></tr>
<tr><td colspan="3">Average Water Temperature per Day*</td><td colspan="3">Year Period</td></tr>
<tr><td colspan="3">Average Flow per Day*</td><td colspan="3"></td></tr>
<tr><td colspan="3">Average Total Length of All Fish to Complete a Full Journey per Day*</td><td colspan="3">Percent of Total Tagged Fish Present at Site per Day</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td>Periods</td><td>Winter</td><td>Pre-runoff</td><td>Peak- runoff</td><td>Post- runoff</td><td>Fall</td></tr>
<tr><td>Dickens Farm</td><td>November 1</td><td>March 15</td><td>May 1</td><td>July 15</td><td>September 15</td></tr>
<tr><td>FCRID</td><td>November 1</td><td>April 1</td><td>June 1</td><td>July 15</td><td>September 15</td></tr>
</table>

FCRID- Time, Single Group																	
Model	(Int)	Mean Flow	Mean Length	Mean Temp	Year Period	% Tagged	mFlow: mLength	mFlow: mTemp	mFlow: Period	mLen: mTemp	mLen: Period	mTemp: Period	df	logLik	AIC	Δ AIC	weight
1184	-1.75	-1.03	0.0065	0.0127	+	1.55			+			+	17	-226.132	486.3	0	0.10
1696	-2.14	-1.40	0.0104	0.0192	+	1.57			+		+	+	21	-222.205	486.4	0.15	0.09
672	-2.25	-1.46	0.0107	0.0200	+	1.72			+		+		17	-226.51	487	0.76	0.07
Dickens Farm- Time, Single Group																	
Model	(Int)	Mean Flow	Mean Length	Mean Temp	Year Period	% Tagged	mFlow: mLength	mFlow: mTemp	mFlow: Period	mLen: mTemp	mLen: Period	mTemp: Period	df	logLik	AIC	Δ AIC	weight
1952	-3.74	0.04	0.02	0.08	+	-1.935			+	-0.000305	+	+	22	-562.952	1170	0	0.22
1984	-4.22	0.32	0.02	0.07	+	-1.90	-2.29E-03		+	-0.000287	+	+	23	-562.408	1171	0.91	0.14
2016	-0.87	-1.46	0.02	0.03	+	-1.938		0.02484	+	-0.000311	+	+	23	-562.564	1171	1.22	0.12

Table 1.3- AIC model selection table for the top three models displayed for each study site for a model based on the performance of individual fish over the entire monitoring period, with two predictor variables: average length and species, and their two-way interactions.

FCRID - By Individual Fish									
Model	**(Int)**	**Length**	**Species**	**Length:Species**	**df**	**logLik**	**AIC**	**Δ AIC**	**weight**
4	-2.905	0.00349	+		10	-323.516	667	0	0.781
8	-1.528	-0.00699	+	+	18	-316.816	669.6	2.6	0.213
3	-2.303		+		9	-329.365	676.7	9.7	0.006
Dickens Farm - By Individual Fish									
Model	**(Int)**	**Length**	**Species**	**Length:Species**	**df**	**logLik**	**AIC**	**Δ AIC**	**weight**
4	1.075	0.003506	+	+	14	-860.043	1748.1	0	1
8	-0.9897	0.002781	+		8	-885.893	1787.8	39.7	0
3	-0.6625		+		7	-898.709	1811.4	63.33	0

Table 1.4- Number of fish tagged by species, with the range of total lengths (TL) and average lengths for long-term monitoring at the FCRID study site. Italics indicate fish species not native to Colorado's South Platte drainage.

Species	Count	All fish TL Range (mm)	Average Length (mm)
Bluegill	2	85 – 107	96.0
Brown Trout	131	82 – 457	198.4
Central Stoneroller	6	93 – 99	96.5
Common Carp	14	84 – 572	141.4
Common Shiner	9	120 – 178	155.5
Creek Chub	36	80 – 196	113.8
Fathead Minnow	4	72 – 81	76.8
Green Sunfish	110	76 – 138	93.2
Largemouth Bass	29	76 – 168	109.2
Longnose Dace	128	80 – 121	88.0
Longnose Sucker	233	80 – 306	142.5
Rainbow Trout	2	359 – 390	374.5
Stonecat	2	115 – 160	137.5
White Sucker	123	84 – 452	173.0
Total	828	72 – 572	142.5

Table 1.5- Number of fish tagged by species, with the range of total lengths (TL), average lengths, detections, and total journey counts for fish tagged by the other concurrent studies near the FCRID site and detected by the FCRID antenna arrays during the monitoring period.

Species	Number Fish Detected	All fish TL Range (mm)	Average Length	Total Detections	Number that Completed One Journey	Total Completed Journeys
Common Carp	2	491 - 512	501.5	3	0 (0%)	0
Creek Chub	1	131	131.0	322	1 (100%)	1
Longnose Sucker	20	120 - 300	200.5	2272	7 (35%)	9
Brown Trout	22	146 - 492	341.0	298	9 (41%)	29
Rainbow Trout	2	321 - 460	390.5	10	2 (100%)	2
White Sucker	43	122 - 467	315.7	369	20 (47%)	24
Totals	**90**			**3274**	**39**	**65**

Table 1.6- Number of fish tagged by species, with the range of total lengths (TL) and average lengths for long-term monitoring at the Dickens Farm study site.

Species	Count	All fish TL Range (mm)	Average Length (mm)
Black Bullhead	4	183-240	201.5
Bluegill	3	108-122	117.0
Brown Trout	14	99-277	170.9
Central Stoneroller	5	87-125	104.2
Common Carp	3	91-132	114.3
Common Shiner	10	81-181	157.6
Creek Chub	167	81-179	112.2
Fathead Minnow	2	78-84	81.0
Gizzard Shad	6	106-136	117.5
Green Sunfish	26	75-145	101.3
Largemouth Bass	96	80-248	106.3
Longnose Dace	151	79-112	86.3
Longnose Sucker	36	80-242	146.1
Red Shiner	3	69-81	76.0
Sand Shiner	1	80	80.0
Stonecat	74	88-195	133.6
White Sucker	199	81-321	148.2
Yellow Perch	3	93-93	96.0
Total	**803**	75-321	119.5

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CHAPTER 2: USING SHORT-TERM ENCLOSURE TRIALS TO DETERMINE FISHWAY DESIGN EFFICACY FOR COLORADO TRANSITION ZONE FISH

INTRODUCTION

Human population continues to expand, placing ever-increasing strain on ecosystems worldwide and demanding creative and efficient solutions to preserve wildlife populations. This is especially true for river ecosystems, where expansive water needs for both human, agricultural consumption, and transportation or recreation have led to the building of numerous dams, low head diversions, white water parks, and other instream structures. These structures disrupt river corridors, fragmenting diverse habitats exploited by fish to persist through stochastic environmental conditions from year to year (Schlosser and Angermeier 1995; Fausch and Bestgen 1997; Falke et al. 2011; Perkin et al. 2015). Studies conducted in the Great Plains ecoregion on its diverse native fish fauna have shown that loss of riverscape connectivity can inhibit gene flow through the isolation of upstream populations, prevent access to ideal habitats used for successful spawning and refuge, and expose them to high degrees of predation (Fausch and Bestgen 1997; Platania and Altenbach 1998; Labbe and Fausch 2000; Falke and Gido 2006; Dudley and Platania 2007; Hoagstrom et al. 2011). Due to the economic and societal value of these instream structures, their removal in most cases is not feasible, which means that fish passage structures (sometimes referred to as fishways) are the best remaining option for mitigating their effects on longitudinal connectivity (Williams et al. 2012; Duncan et al. 2018; Silva et al. 2018).

Modern fish passage structure designs draw from a conglomeration of natural history, field observations, and a wealth of laboratory studies to define the workable parameters for numerous species across the world (Katopodis and Williams 2012) (Figure 2.1). Such efforts often focus on identifying design criteria for individual species, and, ideally, lead to the design and installation of a fish passage structure at potential migration barriers that incorporate well-tested and accepted features within the engineering parameters. (Ficke et al. 2011; Ficke 2015; Dockery et al. 2017; Rodgers et al. 2017; Swarr 2018; Brittain 2022).

Field installations of fish passage structures often deviate from the carefully controlled conditions of laboratory trials and face more variable environmental conditions such as flow and water temperature. Determining the success of a constructed fishway is further convoluted by the behavior of the subjects—a fish's ability to locate the passage entrance, the quality of attraction flow, heightened predation—which further obscure whether a passage is successfully allowing fish movements (Katopodis 2005; Williams et al. 2012). Therefore, post-installation monitoring is necessary to address the efficacy of a given passage and can provide design-refining feedback for future structures (Baumgartner et al. 2010; Cooke and Hinch 2013; Silva et al. 2018). Under ideal conditions, monitoring would be long-term (e.g., at least one year) but such evaluations may be hobbled by the substantial investment of funds, time, planning, and effort required.

Short-term monitoring trials are a more brute-force approach for assessing passage success under a known set of field conditions for a target fish assemblage. Such studies could provide a rapid answer to the question of a species' success at negotiating the fishway under a known set of conditions, data which would help guide long-term studies and future fishway design efforts and which may also help identify operational parameters when passage is possible.

This study undertook a series of short-term enclosure trials following the Richer et al. (2020) approach at three fish passage structures along the Colorado Front Range where Great Plains rivers transition from high gradient montane rivers to their lower gradient plains form, an area often referred to as the transition zone. Two of the locations were also the site of long-term monitoring studies while the third was not. For these short-term studies, an enclosure was constructed around the length of each fishway before tagged individuals were introduced below the fishway for a set number of hours to attempt the passage. These trials were designed to answer the basic question of which species could successfully negotiate the fishways, to compare performance both within and between fishway types and, secondarily, to contrast the results of the short-term studies with those of the long-term studies at the two sites to see whether short-term studies are an acceptable surrogate for the more labor-and resource-intensive long-term studies.

MATERIALS AND METHODS

Site selection

Three sites were selected for enclosure trials - an engineered cast concrete rock ramp, a grouted boulder wingwall bypass, and a pool-weir-and-orifice style passage (Figure 2.2). The former two represent the most common structure designs along Great Plains transition zone in Colorado, while the latter is more common in regions with anadromous salmonids. A brief description of each site follows:

Fossil Creek Reservoir Inlet Diversion, Cache la Poudre River, Fort Collins, CO, USA:

The Fossil Creek Reservoir Inlet Diversion (UTM Zone 13N: 498310, 4489846) is a low-head concrete dam structure (0.46 m vertical drop) on the Cache la Poudre River that diverts water into Fossil Creek Ditch. The east side of the structure includes a 9-m-long rock ramp fishway with a 5% average slope, trapezoidal cross-section, and arrangeable roughness elements (Figures 2.3, 2.4). These river rock roughness elements extend approximately 10-15 cm into the water column, and for the duration of this study, were arranged in a chevron pattern as described by Richer et al. (2020).

Flows at this site were highly variable, sometimes varying by a degree of magnitude of cubic meters per second (m^3/s) in less than an hour, or maintaining artificially high or low flows for extended periods, as is common for regulated rivers in Colorado, complicating trial timing (Richer et al. 2018). Flows ranged from 0.21 m^3/s to 0.32 m^3/s over the course of the enclosure trial (Figure 2.5).

Dickens Farm Natural Area, St. Vrain River, Longmont, CO, USA

The Dickens Farm Natural Area site (UTM Zone 13N: 492169, 4444988) is located in a recreation-focused natural area in downtown Longmont, where the river channel was heavily altered with drop pool structures to provide higher velocity water for tubing and kayaking (City of Longmont 2014). Grouted boulder wingwall bypass passage structures were installed along the edge of each drop to provide lower velocity connections between pools. These channels have an average slope of 2% over approximately 15 m, incorporating a complexity of different flow zones, interstitial spaces and numerous exits for fish and water alike (Figure 2.6). This study monitored the lowermost drop in a series of 9 because of its proximity to robust native fish populations downstream. Flows at this site during the enclosure trial ranged from 0.09 m^3/s to 0.1 m^3/s (Figure 2.5).

Rough and Ready/Palmerton Ditch Diversion, St. Vrain River, Lyons, CO, USA

The Rough and Ready/Palmerton Ditch Diversion site (UTM Zone 13N: 478486, 4451363) on the St. Vrain River is closer to the higher gradient, mountain portion of the watershed than the other sites (Figure 2.2), and thus has a slightly different species assemblage due to generally cooler water temperatures (Table 2.1). The diversion structure includes an ersatz passage created by retrofitting a sediment sluice with metal weir plates to create a pool-weir-and-orifice style passage (Figure 2.7). The passage is a concrete channel that drops 1.52 m over a

20.4-m horizontal run, with eight weir panels inserted roughly 2 m apart and a 6% average slope from top to bottom. However, unlike the other two sites, the slope is not consistent throughout the fishway, instead increasing from a 1% slope at the bottom entrance, to 9% in the lower half, 12% in the upper half, before leveling out at the upstream exit. The orifice slots located on the base of the panels are 15.2 cm^2 in size, alternating from left to right on subsequent panels.

For the enclosure study, the metal plates were temporarily replaced with marine-grade plywood weir plates (Figure 2.7) to allow installation of the antenna system. These plates were based upon the original panel design specifications but were 5 cm shorter to keep water, and fish, completely within the fishway channel. Additional check boards, with no orifice slot, were inserted at the top of the channel during the study, to form a top enclosure; fish could only exit the system by jumping. There was an interval of several days between the removal of the permanent plates and the installation of the experimental plates, allowing accumulated sediment to flush out of the fishway. Thus, testing was conducted under what might be considered new or recently maintained conditions rather than the conditions that might exist during long-term operations. Water turbulence within the weir pools and around the mouth of the fishway complicated flow measurements during the trial, but flows averaged 0.08 m^3/s when they could be measured.

Trial Set Up and Conditions

Antenna Array Construction

Fish movements in each fishway were monitored with an array of four half-duplex (HDX) passive integrated transponder (PIT) antennas to provide directionality of movement and to identify regions of the fishway that reduced passage rates. Antennas were constructed using two loops of 12-gage thermoplastic high-heat-resistant nylon (THHN) wiring running through schedule-80 PVC pipe. The antennas were distributed along each fishway at 0%, ~33%, ~66% and 100% of the fishway length. Antennas at the FCRID site conformed to the trapezoidal cross-section of the channel and were attached using pre-installed bolt casings. The Dickens Farm antennas had variable shapes determined by the irregular channel geometry. The antennas at the Rough and Ready site were attached to the temporary wooden weir plates. All antennas were monitored by multiplexing HDX Oregon RFID readers (Oregon RFID, Portland, Oregon). Power for the FCRID and Dickens Farm antennas was provided by solar panels, while the Rough-and-Ready antennas employed batteries for the short (2 d) duration of the trial. Readers recorded date, time of detection, tag number, antenna number, and number of individual detections continuously throughout each trial. Maximum detection distances (Fetherman et al. 2014) were measured for each antenna, both to establish the spatial extent of the detection cloud and to provide a baseline for antenna performance.

Enclosure Trial Procedures

As the purpose of the enclosure trials was to evaluate the physical capability of selected fish species to ascend different fishways, so trials were scheduled for periods when conditions were most ideal for fish passage through the structures. Therefore, trials were conducted in late summer, when temperature-based swimming performance should be optimized and flows would be moderate for each site, typically between 0.85- 1.98 m^3/s, ideal for both swimming conditions and detection distances.

Enclosures at each end of the fishway contained the known test population of fish (Richer et al. 2020). The use of upstream enclosures allowed us to evaluate the movement of fish that were too small to PIT tag because they could be physically recaptured at the top of the fishway, providing confirmation of successful passage. Metal or PVC enclosures (0.9 m x 1.2 m, covered with 6-mm mesh netting) were fitted snugly at the downstream and upstream entrances of each fishway. Further 6-mm mesh netting was used to guide fish between the downstream enclosure and fishway entrance.

Fish used in the study were collected by backpack electrofishing the surrounding river system, with fish 80 mm TL or longer receiving an HDX PIT tag through a small incision in the abdomen (Archdeacon et al. 2009; Swarr et al. 2021) after being anesthetized (AQUI-S, 30 mg/L). Fish in the 80 – 200 TL range mm received 12-mm tags, those in the 200 – 250 mm TL range received 23-mm tags, and any fish over 250-mm TL received 32-mm tags. Fish recovered from the anesthetic and tagging for a minimum of an hour before being placed in the downstream enclosure. The majority of the tagged fish were collected from the immediate vicinity of each fishway, though a small number of Brassy Minnows (*Hybognathus hankinsoni)*, Central Stonerollers (*Campostoma anomalum*), and Creek Chub (*Semotilus atromaculatus*) from the South Platte River were used at Dickens Farm to expand the number of species being tested (Table 2.1). However, a low capture rate at the South Platte site led to the discontinuation of this practice for later trials. Plains Topminnows (*Fundulus sciadicus*) and Common Shiners (*Luxilus cornutus*) were trapped and transported from other locations within the drainage for inclusion in every trial. Species selection, collection, and transportation were done with the approval and direction of Colorado Parks and Wildlife biologists.

Each enclosure trial lasted for 44 hours, with two 22-hour periods conducted back-to-back. Because of potential predatory interactions, fish were run in two groups. When possible, all smaller-bodied native species, including untagged fish, were grouped together, and run in the first 22-h period, with larger PIT-tagged species (including potentially predatory trout) introduced during the second 22-h period. Antenna arrays were monitored remotely for the duration of the trial, while the upstream enclosures were visually checked for the presence of fish. For the Dickens Farm trial, both enclosures were left in place for the duration of the trial, however, higher flows during the second FCRID trial period necessitated the removal of the upstream enclosure, thereby allowing the larger fish to exit the system if they successfully transited the structure. All fish were released upon conclusion of the trials.

Water temperature and flow were monitored throughout each trial by the use of staff gages, pressure transducers, and temperature loggers. Total discharge within the fishway was measured during each enclosure trial, along with point measurements for water depth and velocity along four transects within each fishway.

Data Analyses

All fish information, tag identification numbers, and detection data collected during the trials were entered into a custom database that allowed individual fish journeys to be parsed out and tracked during a given trial period. This enabled the determination of the number of successful journeys, defined by the detection of a fish on each antenna in succession with the journey ending at one of the antennas closest to an entrance or exit, depending on direction of movement through the fishways by individual and species. The database was queried to extract summary statistics by species, fish size ranges, time of day, and temperature, allowing comparisons within and across all sites.

A Cormack–Jolly–Seber (CJS) model in Program MARK was used to generate the probabilities of fish movement and detection through the fishway. Encounter histories were generated for each individual fish, a set of binary responses based on their detection at five points: all fish received a 1 confirming their initial release into the system, and then a 1 (detected) or 0 (undetected) at each of four antennas in the fishway. These encounter histories were used in a variation of the CJS model to estimate the apparent success (ψ) of upstream movement *i* based on the equation:

$$\psi_i = \varphi_i \text{ x } p_i$$

where the probability of a fish moving by antenna *i* is represented by φ_i, and the probability of detection at that antenna is p_i (Burnham et al. 1987). Two model sets were run, the first with all fish included as a single group, which allowed estimation of the parameters for the fishway in general. The second saw species represented as a group for an estimation of the parameters by species; some species were not represented in this analysis given their low numbers in the trial (any n<6), though these species' success was examined through their actual logged journeys. Each model set included intercept-only models, and models where φ and *p* varied by antenna, fish length, which was included as an individual covariate, or both (Table 2.2). The models were ranked using Akaike's information criterion as corrected for small sample sizes (AIC_c) and those with an AIC weight of greater than 0 were reported, from which the model-averaged parameter estimates, and standard errors were derived for each species by antenna.

Fishway efficiency by species was evaluated from the parameter estimates (Horton et al. 2011; Fetherman et al. 2015; Hodge et al. 2017). The probability of a fish entering the fishway was based upon detection at the lowermost antenna (φ_1), while the uppermost antenna provided the passage efficiency, or the likelihood of the fish exiting the fishway after a successful ascent (φ_4). Total fishway efficiency (φ_T) is the product of the probability of passage at all four antennas ($\varphi_1 \times \varphi_2 \times \varphi_3 \times \varphi_4$). The product of detection probabilities by antenna ($p_1 \times p_2 \times p_3 \times p_4$) similarly produced an estimate of total detection probability (p_T).

RESULTS

FCRID Study Site

The enclosure trial was completed between August 12th to 14th, 2020. In total, 123 tagged fish were tested at the fishway in two trial groups, along with 129 fish too small to be tagged (Table 2.3). All eight tagged species, though not all individuals, were detected by the antennas during the trial, for a 78% total redetection rate based on detection history. Five of the eight species made at least one complete upstream journey through the fishway, for an overall passage rate of 49%. Longnose Dace and Longnose Suckers were the most successful species, with passage success rates of 82% and 47% percent, respectively (Figure 2.8). Brown Trout, Creek Chub, and Fathead Minnows, each represented by a relatively low sample size of tagged individuals, were unsuccessful at passing the fishway (Table 2-3).

The CJS model output indicated that all six species included in the analysis had a high probability of entering the fishway, ranging from 60% for Brown Trout to 99% for Longnose Dace (Table 2.4). The total passage probability was 0.65, though success between species was highly variable, ranging from Longnose Dace (0.99) to White Sucker (0.44) and Brown Trout (0.37; Table 2.4). Fish that entered the fishway (φ_E) had a high probability (≥ 0.91) of making it to the second antenna (φ_{LQ}), but probability of success declined somewhat at the third antenna for all species except Longnose Dace and Green Sunfish. Fish that reached the third antenna (φ_{UQ}) had a high probability of successfully passing the fourth antenna (φ_P), with passage probabilities between 0.96 and 1.0. Brown Trout did not log a successful passage in the detection record though they did attempt the passage, these attempts coupled with their low estimated detection probability (0.12) produced an estimation of possible passage (0.37). Detection probabilities varied between species, but the likelihood of detection at each antenna consistently exceeded 0.72 (Table 2.4). The betas for the effect of fish length indicate that larger fish were more likely to enter and move up the fishway, but smaller fish had greater likelihood of being detected when they do move (Table 2.5).

Flows were higher than desired during the trial period. Because of these high flows, no small untagged fish were visually confirmed attempting the journey or were physically recaptured from the top box, and thus passage success could not be assessed for Brook Stickleback (*Culaea inconstans*), Johnny Darter (*Etheostoma nigrum*), Largemouth Bass (*Micropterus salmoides*), or Plains Topminnow given the size of these species during this study.

Dickens Farm Study Site

In total, 125 tagged fish and 96 untagged fish were tested at the Dickens Farm fishway from July 31 to August 2, 2019 (Table 2.6). Redetection rates for this site were high, with 76% of tagged individuals and 70% of tagged species redetected at least once. All seven species that were redetected made at least one complete journey, for an overall passage success rate of 64% (Figure 2.8). Once detected as having entered the fishway, Green Sunfish, Longnose Sucker, and White Suckers had 100% passage success rates, with most other species ranging from the 70 – 80%. Stonecats, the exception, were the one poorly performing species of those with documented journeys, with only 7% completing the full upstream passage.

The CJS model estimated that the probability of a fish in the six modeled species (those with $n<6$) to successfully enter and pass the Dickens Farm passage was 0.46 (Table 2.7). Passage success varied widely by species at this site, ranging from high passage probability for Common Shiners (0.93) to very low values for Stonecats (0.09). Some species probability estimates contrasted starkly to the overall success rates indicated by their detection records; for example, Green Sunfish and White Suckers estimates of successful passage were 19% compared to the 100% success rate shown by their detections. Creek Chub and Longnose Dace had passage probabilities of 0.65 and 0.70, respectively. As expected, the three species with the overall lowest performance (both in detection-based journeys and MARK modeling results) showed the least likelihood to enter the fishway (≤ 0.50), whereas probabilities of entrance for the other three species exceeded 0.83 (Table 2.7). Somewhat similar to the FCRID, the third upstream antenna was associated with a slight decline in passage success. Detection probabilities across all species and antennas at this site were uniformly high (≥ 0.98; Table 2.7). Fish passage success through the bypass channel at Dickens Farm showed an inverse relationship with fish length, in contrast with observations at FCRID, with smaller fish being more likely to move, but larger fish were more likely to be detected (Table 2.5).

Untagged Plains Topminnows released in the first group successfully ascended the fishway, being physically confirmed in the top enclosure within the first half an hour of the trial. Additionally, untagged Longnose Dace, Creek Chub and Green Sunfish were recovered from the upstream enclosure during or just after the completion of the trial.

Rough-and-Ready Study Site

A total of 124 tagged fish representing 11 species and 90 untagged Plains Topminnows were placed in the Rough and Ready fishway for the August 24 to 26, 2020 enclosure trial (Table 2.8). Of those, 83% (104 individuals) of the tagged individuals were redetected during the trial, however, only 17 fish from 4 species successfully completed a full passage through the fishway, for a passage rate of 17% based on the detection records (Figure 2.8). Brown Trout and Largemouth Bass were the most successful species groups, with a 54% and 50% likelihood of successful passage, followed by Longnose Dace (10%) and Longnose Suckers (11%). With the exception of Common Shiners, which were never redetected, all other species were redetected but failed to successfully negotiate the fishway.

The probability of overall passage success, as indicated by the CJS analysis, was only 0.10, although fish had a high probability of entering the fishway (0.91) and encountering the lowermost antenna (Table 2.9). Somewhat surprisingly, Largemouth Bass were the only species with a considerable probability of successful passage (0.68), with the probabilities for the other species of 0.15 or below. Even the predicted probability of successful passage for Brown Trout, which had a 54% passage rate from the detection records, was estimated at only a 0.15. Movement probabilities were relatively high for the two lowermost antennas, over 0.75 for all detected species, but the probabilities decline precipitously on the third antenna with the majority of species having less than a 0.20 probability of transitioning to the fourth antenna. Fish that made it past antenna three had a very high probability (1.0) of successfully completing movement upstream through the fishway. The beta for length suggests that larger fish were more successful and were more likely to be detected at this site (Table 2.5). Detection probabilities were high for all species and antennas (0.69 overall), with only antenna 3 showing a detection probability below 0.85 for any species other than Common Shiners (Table 2.9).

Although untagged Plains Topminnows were observed in the lowermost fishway pool, none were ever found in any of the upper pools for the duration of the trial. Water turbulence within the pools may have made a visual confirmation of movement difficult but given the low performance of other species at this site, it seems unlikely that topminnows successfully ascended the full structure.

DISCUSSION

All is not equal when it comes to the passage performance of some of the common fishway types installed along Colorado's Front Range, with nearly non-existent passage at the more traditional pool-weir-orifice design at Rough and Ready, to the consistently high passage success at two modern rock ramp structures, FCRID and Dickens Farm. Several factors contributed to differences in passage success between the major designs, with slope perhaps being the most salient, followed by fishway length. While all structures saw some decline in success related to distance ascended (success declined as fish passed the 3rd antenna), the substantial drop in passage performance at the pool-weir-orifice structure, with both completed journeys and passage estimates, indicate the decline was closely associated with the change from a 9% slope to a 12% slope adjacent to the third antenna. The impact of this change in slope configuration is illustrated by the high number of fish detected on the second antenna that were never detected on the third antenna. However, fish that were detected at the third antenna were consistently able to transit to the fourth antenna and exit the fishway. Although a few Longnose Suckers and Longnose Dace, both species with presumably low jumping capabilities (Ficke et al. 2011; Gardunio 2014; Dockery et al. 2017), moved through the fishway to the fourth antenna, it seems evident that a pool-weir-and-orifice design, particularly one with a slope in excess of the suggested 5% (Ficke 2015; Swarr 2018), is impassable to a majority of the fish in the system. While a small number of fish may be passing through the structure, the fishway is generally not navigable for small-bodied natives, indicating that it has failed to restore river connectivity.

It is worth noting that the orifice slots in the fishway appeared to be utilized by some smaller fish. In the detection records, this was assumed by fish making transits up and down the fishway, rather than a journey up the fishway without a corresponding trip down, the assumption being a fish that was jumping over the weir plates to ascend the passage would similarly be able to jump the check boards at the top entrance of fishway, thereby successfully exiting the system. Several trout, competent jumpers that they are (Kondratieff and Myrick 2006), made single upstream transits and were not subsequently detected by any antenna, indicating that, rather than utilizing the orifice slot, they were traveling over the weir plates and check boards as their mode of passage. Conversely, fish utilizing the orifice slots would be forced to turn around in the top pool, unable to jump and pass the final check boards since they did not include an orifice slot. This was highlighted by the behavior exhibited by a Longnose Dace that made six complete bidirectional transits of the structure, a number that would not have been accomplished had the dace jumped over the final check boards and exited the fishway. Several other individuals show an equal number of bidirectional transits, suggesting that if a pool-and-weir fishway is used in these systems, then the inclusion of slots may help smaller fish pass. The number of fish successfully transiting this type of fishway was so small, however, that is a worthy suggestion only if an existing pool-weir type structure cannot otherwise be replaced with another design (Bravo-Córdoba et al. 2018). Additionally, the structure as a whole accumulated a significant amount of sediment in the pools, fully obstructing the orifice slots over time. For these slots to be practical, frequent maintenance would be required, or the design changed so that the slots remain unobstructed.

In stark contrast to the pool-weir-and-orifice structure, passage rates at both of the rock ramp-style structures were both notably higher, a trend observed in other evaluations of similar structures (Bunt et al. 2012; Ficke 2015; Forty et al. 2016; Stoller et al. 2016). Dickens Farm Natural Area, with its gradual 2% slope, performed best with passage for the widest range of fish species and sizes, including Plains Topminnows and other small-bodied species, movements of which were unable to be confirmed at the FCRID site. Based on the detection records, all species that attempted the fishway, with the exception of Stonecats, were able to achieve passage with success rates of at least 70%. Passage estimates declined some at the third antenna, but given the low passage probabilities of Green Sunfish, White Sucker, and Stonecat on all antennas, the decline appears more species-dependent at this site, rather than a function of travel fatigue.

The FCRID site performance was slightly lower than that of the Dickens Farm bypass since no species exceeded 50% percent success during the trial, with the exception of Longnose Dace. This structure was extended in 2018 by an additional 6-m encourage backwatering and eliminate the presence of a vertical drop that would develop around the downstream entrance, with a goal of improving passage performance over that documented by Richer et al. (2020). The observed improvements were highly species-dependent, with Longnose Dace entering and passing the fishway at a much higher rate (82% vs. 50% success), while Creek Chub and Brown Trout failed to pass during this study compared to the 100% and 87% passage rates, respectively, reported by Richer et al. (2020). Sample sizes of these two species were small in both studies (n=3 and n = 6 for Creek Chub and Brown Trout respectively in this study versus n = 1 and n = 15 in Richer et al. (2020). However, it is worth noting that discharges within the fishway were much higher during the FCRID trial than those during the Dickens trial or in Richer et al. (2020; Figure 2.5), providing information on passage success under less-than-ideal conditions. A successful fishway is one that not only passes the whole suite of fish species but can also function at the widest variety of flows throughout the year outside some extreme periods (Katopodis 2005; Williams et al. 2012). The passage rates for the FCRID may have been lower than expected, but given the higher flows, passage may still be partially possible for many species even as flows increase drastically within the fishway.

The relatively low performance of Brown Trout and Stonecats at both sites was surprising, given their success as documented in other trials (See Chapter 1; Richer et al. 2018). Laboratory trials performed using Stonecats show that while they are not the fastest swimmers, their passage success in an experimental rock ramp fishway is considerable (Swarr 2018; Brittain (unpublished)), particularly at slopes of 6% or less. Similarly, Brown Trout have been widely documented as strong swimmers and capable jumpers in numerous studies (Peake et al. 1997; Ojanguren and Brana 2003; Forty et al. 2016; Richer et al. 2020). Small sample sizes in three of the instances (n = 6 and 5 for Brown Trout at FCRID and Dickens Farm, respectively, and n = 2 for Stonecats at FCRID) likely contributed to the low measured performance. Additionally, the trial timing in late summer, although ideal for many native Great Plains species, exposed Brown Trout to a greater number of stressors, such as higher water temperatures, especially in the case of the Dickens Farm trial (20-25^{o}C range during trial), which could have led to decreased swimming capacity and/or motivation (Elliott and Elliott 2010). This late summer timing also affected the size of Brown Trout available for testing, with most captured individuals falling between 90- and 110-mm TL. While this was ideal for testing the passage performance of smaller trout, this group did exhibit higher overall mortality than any other species during the trial. Given the effect of these factors, a trial scheduled for periods of cooler water temperatures may be more conducive for more realistic evaluations of Brown Trout performance. Comparatively, during long-term monitoring efforts made at both of these sites (see Chapter 1), Brown Trout showed extremely high success rates at both passages (100% success rate at Dickens, 58% at FCRID), indicating that the short-term enclosure trials definitely underestimated Brown Trout passage performance, perhaps because of stressors associated with trial timing and with the size of fish available.

Even more surprising was the poor performance of Stonecats during the Dickens Farm trial, given that the sample size was adequate (n = 19) and habitat, hydraulic, and thermal conditions were favorable. Only a single Stonecat was documented as completing a full journey, despite over 50% being redetected on antennas within the structure. This is in stark comparison to long-term monitoring conducted at Dickens Farm, where Stonecats displayed the highest numbers of individual detections and the most complete journeys made by any species (see Chapter 1). Stressors such as handling, tagging, and the presence of other fish at artificially high densities seem likely contributors to the observed low passage success, although physiological measures of stress were not directly evaluated.

Tagging stressors and trial factors were not limited to Stonecats, and may exclude the use of certain species, such as Brassy Minnows or juvenile trout, from these short-term trials. Unlike the extended recovery time provided by lab trials, recovery from tagging or a lengthy transport from another site is subject to fluctuating water temperatures, flows and limited acclimation time, especially for smaller or sensitive species (Swarr et al. 2021). While the sample size of Brassy Minnows captured for the Dickens Farm study was already small (n = 7), transport and overnight captivity lead to complete mortality, not dissimilar to the results of Richer et al. (2020). This identifies one possible drawback of enclosure trials — while they can provide a quick assessment of fishway design efficacy, there may be some species that do not respond well to short-term testing, thus leading to underestimates of their passage success. In cases where the hardiness of a target species is in question, pilot studies may be necessary to determine if adjustments in the trial conditions can improve survivability and performance.

The energetic cost of successfully negotiating a passage is an ongoing concern for some species and fish passage structures (Katopodis 2005; Thiem et al. 2016; Silva et al. 2018). However, detection histories demonstrated that fish were capable of making multiple journeys up and down the fishway during the short enclosure period, especially at the rock ramp sites. Longnose Dace were especially active, with 204 complete journeys up and down the FCRID fishway, including one 85-mm fish that attempted 119 journeys, 66 of which were complete transits. Longnose Suckers at FCRID made 44 complete journeys, while Creek Chubs and Common Shiners accumulated 30 trips apiece during the Dickens Farm trial. These repeated trips within a short time window would indicate that the metabolic demand of passing relative short, low-velocity, low-slope fishways was not so great that a single trip precluded future ones.

Concerningly, the nonnative Largemouth Bass were one of the species with the highest degree of passage success at the pool-weir-orifice fishway, showing an unexpected motivation and capacity to negotiate an otherwise difficult passage. This highlights a recognized concern with the installation of such fishways — restored connectivity can result in the unintended consequence of passage for both native and invasive species, some of which may be more inclined to move than Largemouth Bass (Welsh and Loughman 2015; Cooper et al. 2021). Largemouth Bass are a known threat to the small native fish in these systems and increases in their abundance are correlated with declines in native fish abundance from predation (B. Wright, Colorado Parks and Wildlife pers. comm., 2018). It is evident that the design parameters required to pass Great Plains natives will also enable invasive species passage in these systems, as seen from the success of the rock ramps in passing whole suites of species. Unfortunately, given the weaker swimming capacity of some small native species, restoring connectivity may be an all or nothing endeavor, because there is too much apparent overlap in swimming performance to allow the development of species-selective passage designs.

Based on the modeling results, the probability of the antennas detecting a tagged fish were high at all sites, leading to a high confidence in the passage rates. This highlights an interesting discrepancy between the movement probabilities versus actual journeys recorded at the FCRID and Rough and Ready sites, both of which show total fishway performance probabilities similar or slightly better to the detection histories, and the Dickens Farm site, which is estimated at only 0.46 overall for successful movement despite species like White Sucker and Green Sunfish having recorded total passage up the fishway in actuality. The discrepancy may stem from the approach used in modeling. Certain species were culled from the modelling process based on group size, such as those with fewer than six individuals, but not performance. This was the case for Brown Trout at FCRID, which failed to successfully ascend the passage at any time, but Program MARK still attempted to produce estimates, and may not have differentiated between a missed detection or a lack of movement past the antennas. It appears that the Dickens Farm models were penalized by the poor passage performance of Stonecats that exerted more influence on the output because of their large sample size. This belies the importance of having well sorted detection and movement histories in addition to model outputs, providing information not only for single passage journeys, but over numerous journeys and attempts for each individual in the trial and also highlights the value of using multiple data analysis and evaluation approaches.

Short-term trials provide a relatively rapid assessment of passage success under a narrower set of physical and environmental conditions. This approach was adequate to demonstrate the limitations of the Rough and Ready structure design but understanding long-term passage success may require a more comprehensive approach. Apparent species performance in the enclosure trials may depend on time of year, cohort size, water temperature, and flows, and may have underestimated the passage success of a given species (see Chapter 1). Similarly, too selective of a test cohort, whether it be the selection of species chosen or a limited range of tagged fish sizes, might result in limited assessment of structure function. Larger species cohorts produced consistently better results during all trials but required the collection of sufficient fish sample sizes prior to the trial, a task that may be challenging when using wild fish. Hatchery fish could be used to supplement wild stock (Fox et al. 2016), but this method may introduce additional confounding factors, such as a difference in behaviors or performance, and is, of course, subject to the availability from hatcheries, which may be limited for non-game species.

This study recommends that enclosure trials be combined with long-term monitoring whenever possible, or that multiple enclosure trials take place over a series of flows and temperatures, including those that are presumed to be conducive to successful passage but also under suboptimal conditions, when logistically feasible. If the success of fish below taggable size is of interest in the study, thought should be given to the upstream enclosure's design, ideally augmenting the design to lead fish away from the fishway mouth into calmer waters while also preventing them from leaving the upstream enclosure, perhaps using a modified hoop net. The use of a top enclosure will invariably interfere with flows through the fishway. Additionally, a debris boom or other structure placed above the whole system to deflect debris away from the upstream enclosure may serve to maintain more consistent flows within the passage.

Although performance did vary between the different fishways, it is evident that those fishways categorized as rock-ramp were successful at passing the widest variety of the assemblage of fish under the testing conditions. Adherence to a slope at or below 5% appeared crucial to such successful passage, as indicated by the meager passage at the high slope pool-weir-orifice site and should be a prime consideration in future rock-ramp fishway designs for transition zone fish. Success or failure of the fishway designs was immediately apparent during this set of trials, an indication that short-term enclosure trials can assist in determining the efficacy of a fishway under set conditions. However, given other considerations such the fragility of certain target species or wider site conditions like attraction flow throughout seasonal change, long-term monitoring is recommended in conjunction with or instead of enclosure trials to better understand the entirety of a fishway and the surrounding environment.

TABLES AND FIGURES

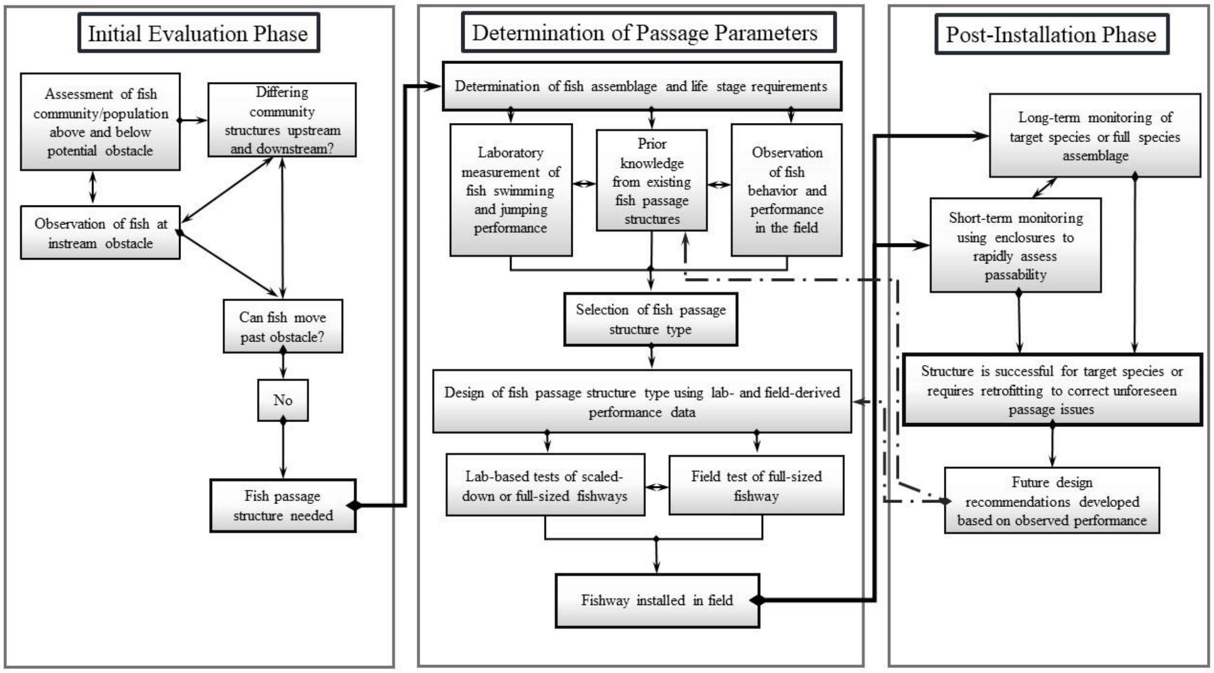

Figure 2-1. Schematic diagram of the idealized process followed by fish passage projects that are realized, designed, installed, and refined following post-installation monitoring.

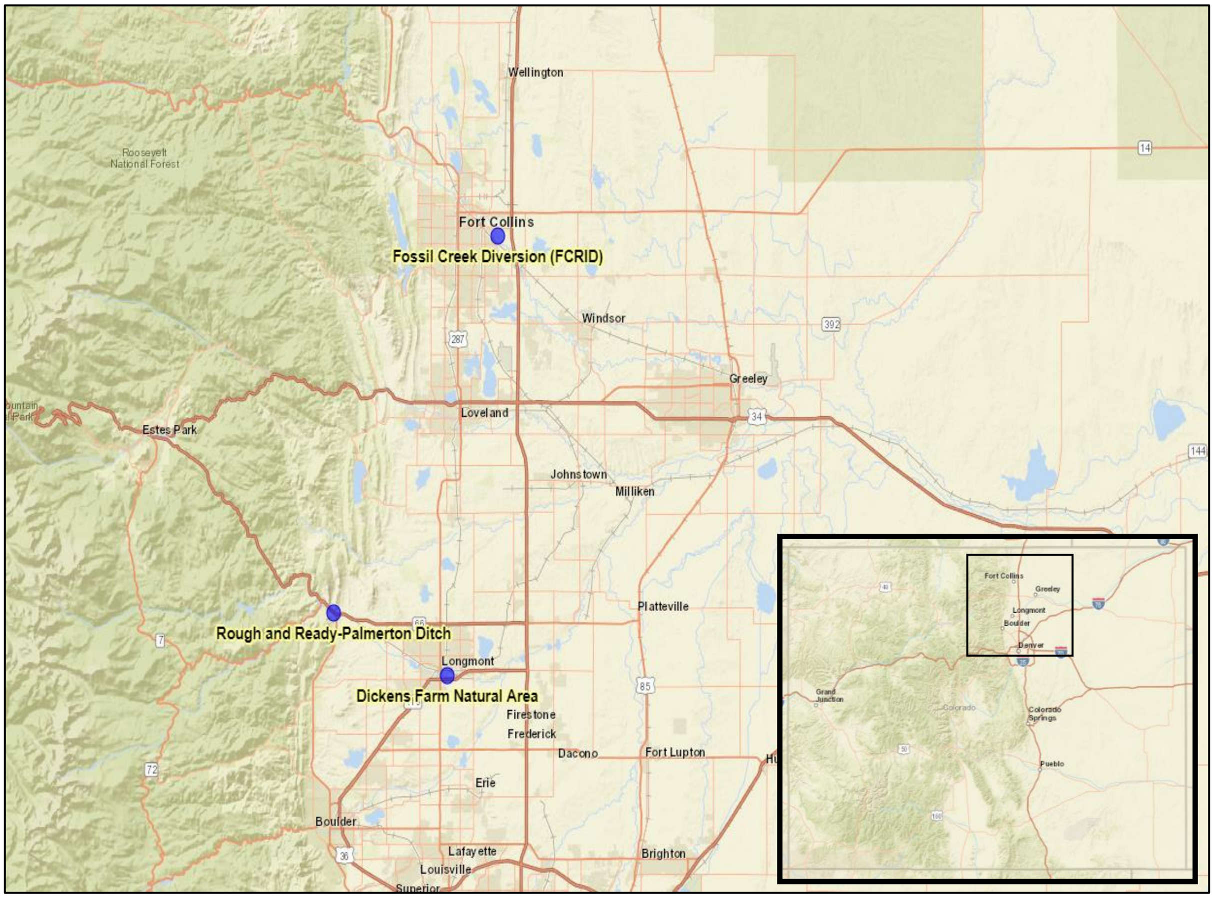

Figure 2.2- A map of northeastern Colorado showing the location of the three study sites, with inset map of Colorado for orientation.

Figure 2.3- The Fossil Creek Reservoir Irrigation Diversion (FCRID) site in Fort Collins, CO, USA, with the left photo (A) showing the antenna placement on the interior of the rock ramp and the right photo (B) showing the fishway during moderate flows.

Figure 2.4- Images showing the installation of the top (at left) and bottom (at right) enclosure boxes for the trial at the FCRID site.

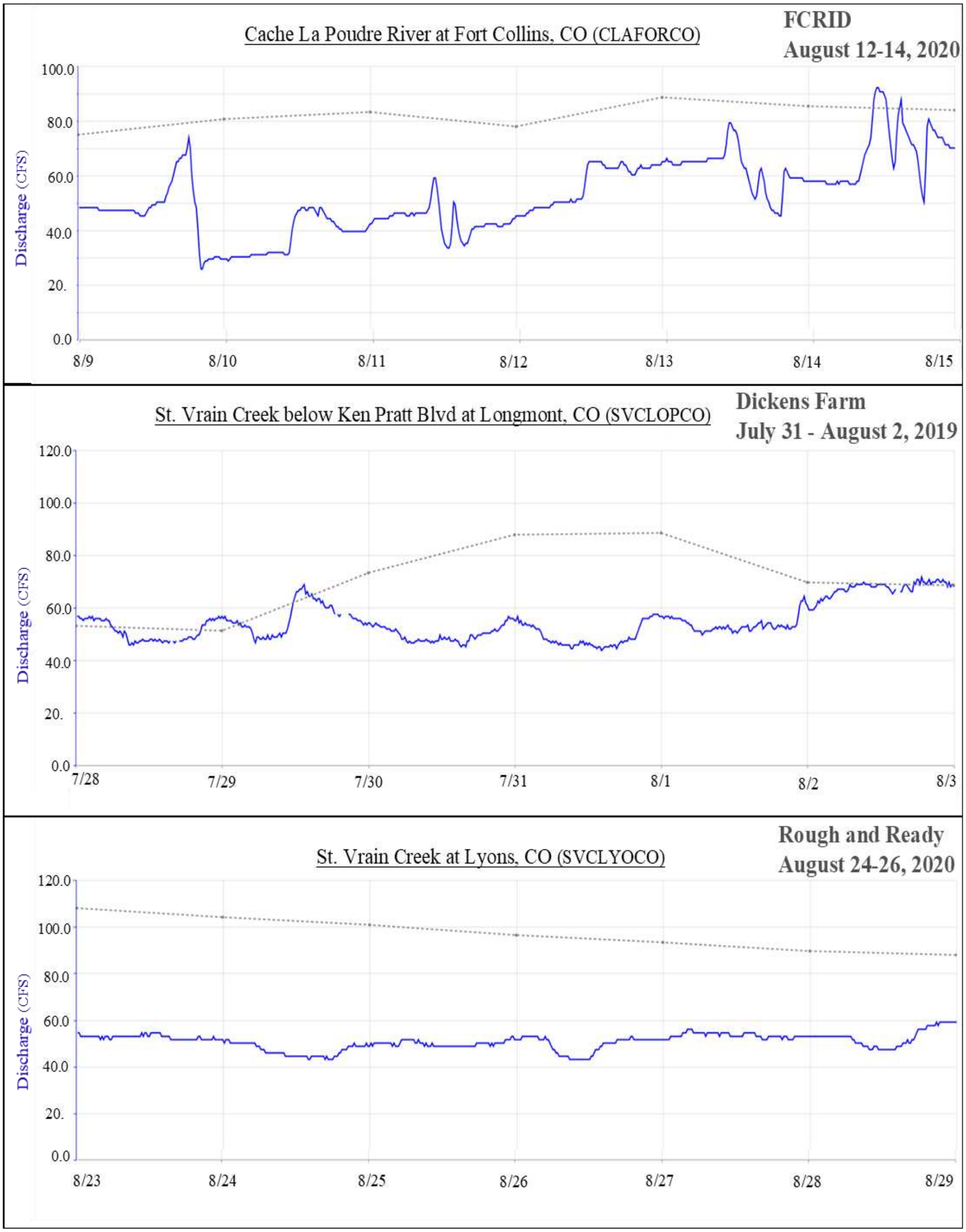

Figure 2.5- Hydrographs showing a period of five days around and containing the enclosure trials for each of the three study sites, as generated from the nearest river gage to each site. Site title and specific trial dates are denoted in the top right of each graph. The blue line shows hourly average discharge while the grey line displays the historic average daily discharge for the site.

Figure 2.6- The top photo (A) shows the wingwall bypass fishway design at the Dickens Farms Natural area site. Bottom left (B) photo shows the placement of both enclosures looking in the upstream direction and bottom right (C) shows specifically the lower enclosure placement.

Figure 2.7- Top left (A) photo shows the design and day to day operating conditions of the Rough and Ready/Palmerton site's pool-weir-and-orifice style fishway. Bottom right (B) photo includes the temporary replacement weir plates used during the trial and the lower enclosure box set into the channel exit. At bottom left (C) is shown the checkboards used both to control flow and to act as a top box during the trial.

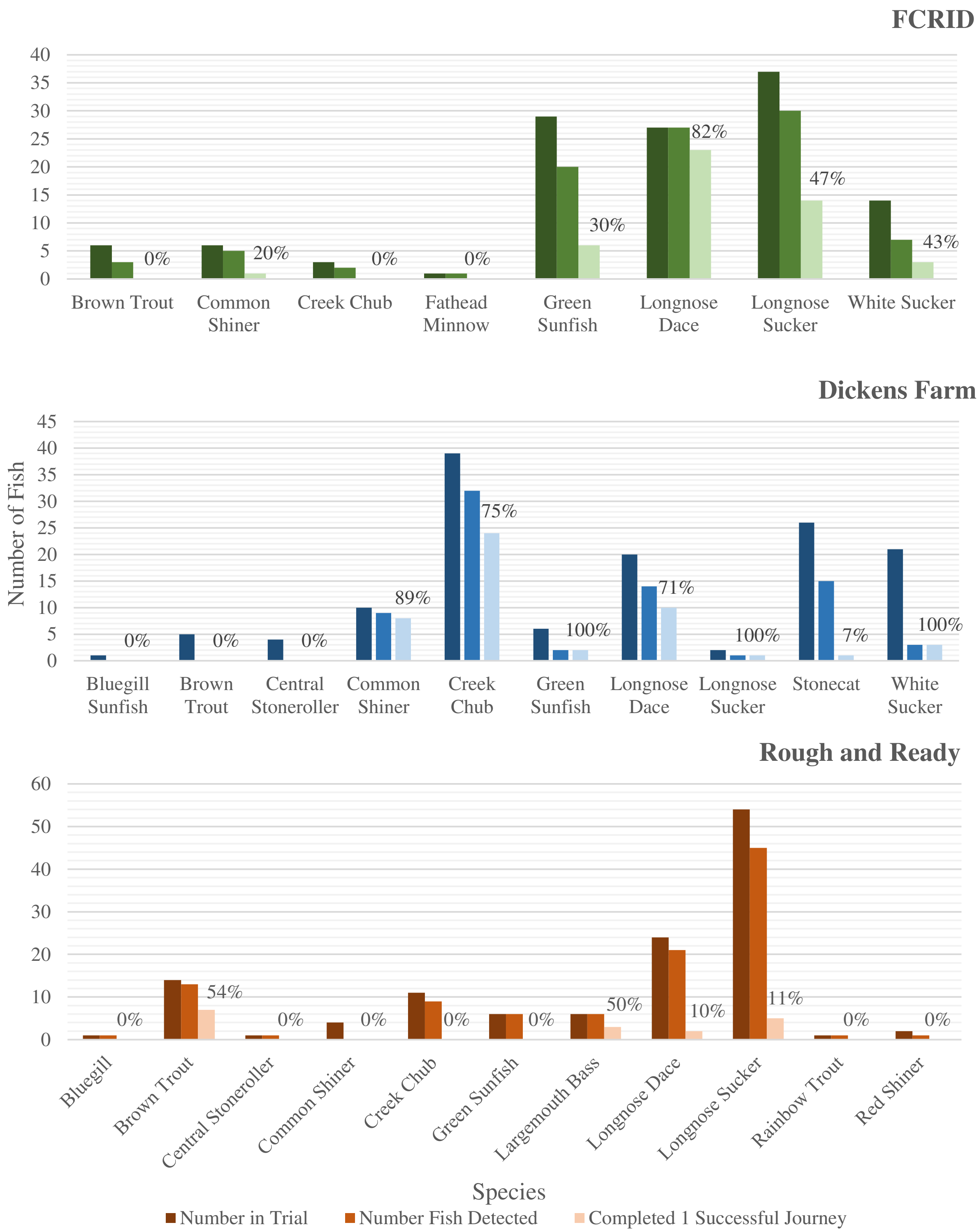

Figure 2.8- Comparison, on a species-by-species basis, of the number of fish used (dark color bar), number of fish detected by the antennas (medium color bar), and the number of detected fish who successfully completed an upstream passage (light color bar) at the rock ramp fishway at FCRID (green), the wingwall bypass at Dickens Farm (blue) and the pool-weir-and-orifice passage at Rough and Ready (orange). The given percentages indicate the level of successful passage relative to the number of detected fish for that species.

Table 2.1- Fish species included in the enclosure trials at each site and whether individuals were obtained from the surrounding river system (local) or were brought in from another population to participate.

Common Name	Species Name	FCRID	Dickens Farm	Rough and Ready
Bluegill	*Lepomis macrochirus*		Local	Local
Brassy Minnow	*Hybognathus hankinsoni*		South Platte	
Brown Trout	*Salmo trutta*	Local	Local	Local
Central Stoneroller	*Campostoma anomalum*		Local/South Platte	Local
Common Shiner	*Luxilus cornutus*	Foothills Fishery Refuge Population		
Creek Chub	*Semotilus atromaculatus*	Local	Local/South Platte	Local
Fathead Minnow	*Pimephales promelas*	Local		
Green Sunfish	*Lepomis cyanellus*	Local	Local	Local
Largemouth Bass	*Micropterus salmoides*			Local
Longnose Dace	*Rhinichthys cataractae*	Local	Local	Local
Longnose Sucker	*Catostomus catostomus*	Local	Local	Local
Plains Top Minnow	*Fundulus sciadicus*	Lincoln Ditch	Lyons Pond	
Rainbow Trout	*Oncorhynchus mykiss*			Local
Red Shiner	*Cyprinella lutrensis*			Local
Stonecat	*Noturus flavus*		Local	
White Sucker	*Catostomus commersonii*	Local	Local	

Table 2.2- Shows the AICc selection output for the top three models for each site as generated by Program MARK. The beta values shown in Table 2.5 and other non-averaged values are each derived from the top model shown for that site. Variable shorthand is as follows: Spec-species, Ant- performance differences at each antenna, Len- total length of that individual fish.

Model	AICc	Delta AIC_c	AIC_c Weights	Model Likelihood	Num. Par	Deviance	-2log(L)
FCRID							
φ (Spec+Ant+Len) **p**(Spec+Ant+Len)	499.11	0.00	0.38	1.00	22	451.86	451.86
φ (Spec+Ant+Length) **p**(Spec+Len)	501.91	2.80	0.09	0.25	19	461.49	461.49
φ (Spec+Len) **p**(Spec+Ant+Len)	502.41	3.30	0.07	0.19	19	461.99	461.99
Dickens Farm							
φ (Spec+Ant+Len) **p**(Ant+Len)	266.35	0.00	0.76	1.00	15	234.68	234.68
φ (Spec+Ant) **p**(Ant+Len)	270.64	4.29	0.09	0.12	14	241.18	241.18
φ (Spec+Ant+Len) **p**(Ant)	271.18	4.83	0.07	0.09	14	241.72	241.72
Rough and Ready							
φ (Spec+Ant+Len) **p**(Ant+Len)	276.75	0.00	0.33	1.00	16	242.80	242.80
φ (Spec+Ant+Len) **p**(Ant)	277.14	0.39	0.27	0.82	15	245.42	245.42
φ (Spec+Ant+Len) **p**(Spec+Ant+Len)	278.88	2.13	0.11	0.35	22	231.16	231.16

Table 2.3- Number of tagged and untagged fish by species release in the initial group (n_1) and the second group (n_2), total numbers of each species released into the enclosure, and the range of total lengths (TL) for all fish in the FCRID site trial.

Tagged Fish						**Untagged Fish**				
Species	$\mathbf{n_1}$	$\mathbf{n_2}$	$\mathbf{n_T}$	**Fish Length Range (mm)**		**Species**	$\mathbf{n_1}$	$\mathbf{n_2}$	$\mathbf{n_T}$	**Fish Length Range (mm)**
Brown Trout	4	2	6	99-116		**Brook Stickleback**	51	0	51	32-75
Common Shiner	6	0	6	139-203		**Fathead Minnow**	8	0	8	57-74
Creek Chub	3	0	3	86-100		**Green Sunfish**	14	0	14	65-77
Fathead Minnow	1	0	1	81		**Johnny Darter**	1	0	1	65

Green Sunfish	25	4	29	80-138		**Largemouth Bass**	3	1	4	43-74
Longnose Dace	19	8	27	80-100		**Longnose Dace**	30	2	32	57-78
Longnose Sucker	15	23	38	97-280		**Longnose Sucker**	1	0	1	78
White Sucker	10	3	13	92-126		**Plains Topminnow**	13	0	13	35-62
						White Sucker	5	0	5	66-75
Total	83	40	12 3	80-280		**Total**	126	3	12 9	32-78

Table 2.4- Passage (φ) and detection (p) probability estimates ± the unconditional standard errors for the most numerous tagged species for FCRID enclosure study. The variable φ_E is the probability that a fish entered the fishway, φ_{LQ} and φ_{UQ} are the probabilities that a fish that entered then crossed antennas two and three, respectively, and φ_P is the probability that a fish who passed antenna three successfully exited the passage. The detection probability (p) is similarly shown in the lower portion of the table. φ_T and p_T are the total fishway efficiency and detection probability, respectively, obtained as a product of the individual antenna probabilities (φ_E x φ_{LQ} x φ_{UQ} x φ_P, etc.)

Species	**Probability of Entering Fishway (φ_E)**	**Probability of Passing Lower Quarter Antenna (φ_{LQ})**	**Probability of Passing Upper Quarter Antenna (φ_{UQ})**	**Probability of Passing Out of Fishway (φ_P)**	**Total Passage Probability (φ_T)**
Common Shiner	0.75 ± 0.25	0.93 ± 0.12	0.81 ± 0.21	0.96 ± 0.12	0.54
Longnose Sucker	0.76 ± 0.09	0.95 ± 0.06	0.83 ± 0.08	0.98 ± 0.05	0.59
Longnose Dace	0.99 ± 0.01	1.0 ± 0	1.0 ± 0	1.0 ± 0	0.99
Brown Trout	0.60 ± 0.23	0.91 ± 0.13	0.70 ± 0.21	0.97 ± 0.10	0.37
Green Sunfish	0.88 ± 0.07	0.97 ± 0.04	0.91 ± 0.06	0.99 ± 0.04	0.77
White Sucker	0.66 ± 0.13	0.92 ± 0.10	0.75 ± 0.13	0.97 ± 0.08	0.44
Fishway	0.80 ± 0.04	0.95 ± 0.03	0.90 ± 0.04	0.96 ± 0.06	0.65
Species	**Probability of Detection on Lowermost Antenna (p_{LE})**	**Probability of Detection on Lower Quarter Antenna (p_{LQ})**	**Probability of Detection on Upper Quarter Antenna (p_{UQ})**	**Probability of Detection on Uppermost Antenna (p_{UE})**	**Total Detection Probability (p_T)**
Common Shiner	0.61 ± 0.16	0.73 ± 0.14	0.82 ± 0.13	0.73 ± 0.15	0.27
Longnose Sucker	0.73 ± 0.08	0.82 ± 0.06	0.89 ± 0.06	0.83 ± 0.06	0.44
Longnose Dace	0.90 ± 0.06	0.94 ± 0.04	0.97 ± 0.03	0.94 ± 0.03	0.78
Brown Trout	0.46 ± 0.23	0.59 ± 0.23	0.72 ± 0.20	0.60 ± 0.23	0.12
Green Sunfish	0.59 ± 0.11	0.71 ± 0.09	0.82 ± 0.09	0.72 ± 0.1	0.25
White Sucker	0.69 ± 0.13	0.80 ± 0.10	0.87 ± 0.08	0.80 ± 0.10	0.39
Fishway	0.72 ± 0.05	0.84 ± 0.04	0.91 ± 0.04	0.84 ± 0.06	0.47

Table 2.5- Cumulative AICc weights for the three factors included in each set of MARK models - species, antenna, and total length - for their effect on either probability of movement (φ) or detection (p) for all models averaged. Magnitude and direction of effect is shown for length for both movement and detection ($\beta\varphi_{length}$; βp_{length}).

	$C\varphi_{species}$	$C\varphi_{antenna}$	$C\varphi_{length}$	$\beta\varphi_{length}$		$Cp_{species}$	$Cp_{antenna}$	Cp_{length}	βp_{length}
FRCID	0.62	0.53	0.61	0.03		0.59	0.52	0.58	-0.01
Dickens Farm	0.97	0.97	0.11	-0.01		0.04	0.97	0.89	0.07*
Rough and Ready	0.83	0.84	0.84	0.03		0.23	0.84	0.56	0.01*

*Confidence interval for beta included zero

Table 2.6- Number of tagged and untagged fish by species release in the initial group (n_1) and the second group (n_2), total numbers of each species, and the range of total lengths (TL) for all fish in the Dickens Farm site trial.

Tagged Fish						**Untagged Fish**		
Species	n_1	n_2	n_T	**Fish Length Range (mm)**		**Species**	n_1	**Fish Length Range (mm)**
Bluegill Sunfish	0	1	1	121		**Central Stoneroller**	1	73
Brown Trout	0	5	5	200-277		**Creek Chub**	1	72
Central Stoneroller	4	0	4	87-125		**Green Sunfish**	1	69
Common Shiner	10	0	10	81-181		**Longnose Dace**	56	57-79
Creek Chub	34	1	35	83-198		**Plains Topminnow**	35	35-60
Green Sunfish	2	3	5	78-116		**Stonecat**	2	71-79
Longnose Dace	15	2	17	80-110				
Longnose Sucker	1	1	2	140-156				
Stonecat	19	6	25	100-185				
White Sucker	3	18	21	117-312				
Total	88	37	125	78-312		Total	96	35-79

Table 2.7- Movement (φ) and detection (p) probability estimates ± the unconditional standard errors for the most numerous tagged species for the Dickens Farm enclosure study. Parameter definitions are as described in Table 2-4.

Species	φ_E	φ_{LQ}	φ_{UQ}	φ_P	φ_T
Creek Chub	0.83 ± 0.06	0.95 ± 0.03	0.84 ± 0.06	0.98 ± 0.02	0.65
Common Shiner	0.97 ± 0.04	0.99 ± 0.01	0.97 ± 0.03	1.0 ± 0	0.93
Longnose Dace	0.85 ± 0.09	0.96 ± 0.03	0.86 ± 0.09	0.99 ± 0.02	0.70
Green Sunfish	0.50 ± 0.19	0.80 ± 0.14	0.52 ± 0.21	0.93 ± 0.09	0.19
Stonecat	0.37 ± 0.08	0.70 ± 0.11	0.38 ± 0.11	0.88 ± 0.11	0.09
White Sucker	0.50 ± 0.15	0.80 ± 0.12	0.52 ± 0.17	0.93 ± 0.08	0.19
Fishway	0.67 ± 0.05	0.90 ± 0.04	0.77 ± 0.06	1.00 ± 0	0.46
Species	p_{LE}	p_{LQ}	p_{UQ}	p_{UE}	p_T
Creek Chub	0.98 ± 0.03	1.0 ± 0	1.0 ± 0	1.0 ± 0	0.98
Common Shiner	0.98 ± 0.05	1.0 ± 0	1.0 ± 0	1.0 ± 0	0.98
Longnose Dace	0.98 ± 0.04	1.0 ± 0	1.0 ± 0	1.0 ± 0	0.98
Green Sunfish	0.99 ± 0.03	1.0 ± 0	1.0 ± 0	1.0 ± 0	0.99
Stonecat	0.98 ± 0.03	1.0 ± 0.01	1.0 ± 0.01	1.0 ± 0.01	0.98
White Sucker	0.98 ± 0.03	1.0 ± 0	1.0 ± 0	1.0 ± 0	0.98
Fishway	0.99 ± 0.02	1.00 ± 0	1.00 ± 0	1.00 ± 0.01	0.98

Table 2.8- Number of tagged and untagged fish by species release in the initial group (n_1) and the second group (n_2), total numbers of each species released into the enclosure, and the range of total lengths (TL) for all fish in the Rough and Ready/Palmerton site trial.

Tagged Fish						**Untagged Fish**		
Species	n_1	n_2	n_T	**Fish Length Range (mm)**		**Species**	n_1	**Fish Length Range (mm)**
Bluegill Sunfish	0	1	1	87		**Plains Topminnow**	90	29-70
Brown Trout	11	3	14	80-361				
Central Stoneroller	0	1	1	92				
Common Shiner	0	4	4	134-182				
Creek Chub	3	8	11	25-124				
Green Sunfish	4	2	6	90-130				
Largemouth Bass	6	0	6	85-93				
Longnose Dace	15	8	23	80-115				
Longnose Sucker	47	7	54	80-241				
Rainbow Trout	1	0	1	95				

Red Shiner	1	1	2	67-80				
Total	88	31	123	67-361				

Table 2.9- Movement (φ) and detection (p) probability estimates ± the unconditional standard errors for the most numerous tagged species for Rough and Ready enclosure study. Parameter definitions are as described in Table 2-4.

Species	φ_E	φ_{LQ}	φ_{UQ}	φ_P	φ_T
Brown Trout	0.95 ± 0.05	0.87 ± 0.09	0.18 ± 0.12	1.0 ± 0.01	0.15
Creek Chub	0.94 ± 0.04	0.88 ± 0.08	0.17 ± 0.12	1.0 ± 0.01	0.14
Green Sunfish	0.93 ± 0.06	0.82 ± 0.18	0.16 ± 0.21	1.0 ± 0.01	0.12
Largemouth Bass	0.99 ± 0.03	0.98 ± 0.05	0.70 ± 0.21	1.0 ± 0.01	0.68
Longnose Sucker	0.88 ± 0.04	0.75 ± 0.17	0.09 ± 0.09	1.0 ± 0.01	0.06
Longnose Dace	0.95 ± 0.03	0.87 ± 0.11	0.20 ± 0.13	1.0 ± 0.01	0.15
Fishway	0.91 ± 0.03	0.67 ± 0.05	0.17 ± 0.05	1.0 ± 0	0.10 ±
Species	p_{LE}	p_{LQ}	p_{UQ}	p_{UE}	p_T
Brown Trout	1.0 ± 0	0.94 ± 0.16	0.51 ± 0.33	0.98 ± 0.10	0.47
Creek Chub	1.0 ± 0	1.0 ± 0	0.88 ± 0.17	1.0 ± 0.03	0.88
Green Sunfish	1.0 ± 0.01	0.77 ± 0.29	0.32 ± 0.35	0.85 ± 0.56	0.21
Largemouth Bass	1.0 ± 0	1.0 ± 0	0.88 ± 0.17	1.0 ± 0	0.89
Longnose Sucker	1.0 ± 0.01	0.84 ± 0.18	0.35 ± 0.34	0.88 ± 0.36	0.26
Longnose Dace	1.0 ± 0	0.92 ± 0.14	0.41 ± 0.32	0.95 ± 0.19	0.35
Fishway	1.0 ± 0	1.0 ± 0	0.69 ± 0.15	1.0 ± 0	0.68

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