

DESIGN, HYDRAULIC EVALUATION, AND PASSAGE EFFICIENCY OF A ROUGHENED
CHANNEL ROCK RAMP FISHWAY FOR WHITE SUCKER AND LONGNOSE DACE

by

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DEDICATION

This thesis is dedicated to my parents for their unconditional love and support. Thank you for introducing me to the world, inspiring me to pursue my dreams, and always pushing me to become the best version of myself. Thank you for teaching me to value hard work, fresh air, good food, great company, and life's many gifts through all its ups and downs. None of this would have been possible without you. And to my late Uncle Terry Draeger, for sharing your love of nature with me.

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ABSTRACT

Effective fish passage structures are essential for maintaining connectivity in aquatic ecosystems, improving climate resilience, and supporting native fish populations. Rock ramp fishways have become popular due to their nature-like design and ability to accommodate a wide range of species. However, additional research is needed to develop species-specific design criteria for flow rate, slope, length, and boulder configuration. This study evaluated the design, hydraulic performance, and passage efficiency of a roughened-channel rock ramp fishway constructed and tested in the open-channel flume at the Bozeman Fish Technology Center. Nine hydraulic conditions were examined by combining two slopes (3% and 5%) with five flow rates (0.0315, 0.0631, 0.0946, 0.1262, and 0.1893 m³/s). Detailed depth and velocity measurements were collected to characterize the hydraulics at each treatment. Velocity contour plots were created to visualize the hydraulic conditions, providing insight into potential swim paths, resting refugia, and velocity barriers. Volitional swim trials were conducted with white sucker (*Catostomus commersonii*) and longnose dace (*Rhinichthys cataractae*), with fish movements tracked using four stationary PIT antennas. Each treatment was repeated three times for a total of 28 trials using 84 white sucker and 168 longnose dace. Participation rates were high for both species across all trials, but passage results revealed clear differences in swimming behavior and capabilities. White suckers exhibited consistently high passage success (97%) across all hydraulic conditions. In contrast, longnose dace showed high passage success at lower flows (83-100%) but success decreased sharply with increasing flow rate, particularly at the 5% slope. Travel-time analysis indicated that longnose dace rested in velocity refugia between bursts of swimming while suckers ascended the ramp in a single sustained effort. Logistic regression showed that flow rate, slope, and fish length were key predictors of longnose dace passage, and probability of passage curves were developed to estimate longnose dace passage across the test conditions. Passage models were not developed for white sucker because they achieved high passage at all test conditions. Overall, this study contributes valuable insight on the design, hydraulics, and biological performance of a roughened channel rock ramp. These results highlight the importance of considering slope, flow rate, and species-specific swimming abilities in rock ramp design and applications.

CHAPTER ONE

LITERATURE REVIEW

Introduction

Freshwater fishes in North America, and across the world, are among the most threatened groups of animals due to anthropogenic activities. One of the primary causes of this decline is the loss of longitudinal connectivity in rivers and streams, a critical factor for the persistence of many freshwater fish species (Cooke et al., 2005; Ficke, 2015; Perkin & Gido, 2011). Lotic environments are inherently variable across space and time, requiring fish to migrate upstream and downstream to access suitable habitat throughout different life stages and seasons (Bunt et al., 2001). Barriers such as dams, culverts, and water diversions, combined with channel alterations and flow regime changes, disrupt these essential migration pathways and pose a significant threat to the survival of native fish populations (Curry & Spacie, 1984; Fausch et al., 2002; Graf, 1999; Larinier, 2000; Perkin & Gido, 2011).

To address these challenges, engineered fishways have been developed and implemented to facilitate fish passage past natural and artificial barriers. Historically, many fishway designs and swimming performance studies have focused on anadromous species such as salmon and trout, which have well known migration patterns and extensively studied swimming capabilities. However, the ecological importance of preserving biodiversity in freshwater systems has driven recent efforts to study and accommodate a broader range of native fish species, including those with weaker swimming abilities.

Minnows (Cyprinidae) and suckers (Catostomidae), are native fish families to North America with numerous non-game species that often receive less recognition and research compared to economically important species. Despite this, they play a vital ecological role in maintaining the health and balance of aquatic ecosystems (Cooke et al., 2005; Moyle & Cech, 2003). White sucker (*Catostomus commersonii*) and longnose dace (*Rhinichthys cataractae*) are among the most widely distributed species within their respective families, making them excellent representatives for studying fish passage. Because these species are abundant and more easily studied, understanding their passage efficiency and pairing it with their known swimming capabilities can provide a framework for inferring the passage success of rarer or endangered species with similar swimming abilities (Aedo et al., 2021; Ficke, 2015; Underwood et al., 2014).

Rock ramp fishways, a newer and increasingly popular type of fish passage structure, are made from natural materials to mimic conditions found in streams. The varied hydraulic environments they create show promise in accommodating the diverse swimming capabilities of many fish species and life stages (USFWS, 2019). The primary focus of this literature review is on the swimming abilities of white suckers and longnose dace, the effectiveness of conventional fishways for sucker passage, the performance of rock ramp fishways for suckers and small-bodied fish, and the application of CFD modeling to optimize rock ramp design and fish passage efficiency.

History of Technical and Nature-like Fishways

The scientific study and development of fish passage structures began in the early 20th century in Europe and expanded to North America in the 1940s (Katopodis & Williams, 2012).

This early work led to the development of various fish passage systems, such as Denil fishways, pool-and-weir fishways, and vertical slot fishways, as well as more engineered solutions like fish lifts and transport systems. Each design offered unique advantages and trade-offs, tailored to specific site conditions and target species. However, these traditional designs often struggled to accommodate the swimming capabilities and behaviors of non-salmonid species, emphasizing the need for more versatile solutions.

Nature-like fishways emerged in the 1970s as a response to these limitations, aiming to replicate natural stream conditions and provide passage for a broader range of fish species and life stages (Katopodis & Williams, 2012). They are constructed of boulders, cobbles, and other natural materials to create diverse hydraulic conditions that dissipate energy while accommodating both migratory and resident fish assemblages (USFWS, 2019).

There are two main types of nature like fishways: step-pool and roughened channel designs. Step-pool fishways function similarly to pool-and-weir technical fishways, consisting of a series of pools separated by rock weirs. Fish ascend by making short burst swims over the weirs before resting in the upstream pools (USFWS, 2019). In addition to facilitating fish passage, step-pool designs provide vertical stability in channel restoration projects and contribute to instream habitat complexity (DVWK, 2002; Mooney et al., 2007). The U.S. Fish and Wildlife Service Fish Passage Design Criteria recommend step-pool designs with slopes of 5% or less to produce suitable fish passage conditions (USFWS, 2019).

Roughened channel rock ramps, differ from step-pools in that they feature a continuous, sloped channel linking two pools of different elevations (USFWS, 2019). These structures incorporate large roughness elements, such as strategically placed boulders and cobbles, to

modify flow conditions and improve fish passage (Mooney et al., 2007; USFWS, 2019). By dissipating energy, reducing flow velocity, and increasing water depth, roughened channel rock ramps create hydraulics favorable for fish passage while offering resting areas for fish navigating upstream (Baki et al., 2014). However, steeply sloped roughened channels can produce velocities that cannot be effectively mitigated by larger roughness elements without introducing excessive turbulence, secondary flows, and air entrainment (USFWS, 2019). To address this, the USFWS recommends limiting roughened channel rock ramp slopes to 3% or less to ensure more stable hydraulic conditions conducive to fish passage.

Given that nature-like fishways, including step-pools and rock ramps, are relatively new compared to traditional fish passage structures, their design guidelines remain somewhat nuanced and require further research. The complexities of studying these systems, combined with the variability in hydraulic and ecological conditions, mean that current recommendations are based on limited research. While existing guidelines provide a foundation for effective design, additional in-depth studies are needed to better understand how varying slopes, flowrates, and configurations influence fish passage success across different species and environmental contexts.

Quantifying Fish Swimming Capabilities

Since fish inhabit dynamic environments, studying their swimming capabilities and behaviors presents significant challenges. Adding to this complexity, swimming speeds and endurance vary with species, body morphology, fish length, and water temperature (Brett, 1964; Ficke, 2015; Katopodis & Gervais, 2016; Myrick & Cech, 2000). Beamish (1978) outlines a foundational framework for categorizing swimming speeds under various conditions. This

framework classifies swimming speeds into three categories: sustained, prolonged, and burst, each differing in duration and exertion level. Sustained swimming encompasses long-lasting speeds used for activities like cruising, which can be maintained without muscular fatigue for over 200 minutes and depends primarily on aerobic metabolism. Burst swimming represents the highest speeds that a fish can swim, typically sustained for less than 20 seconds, often utilized for capturing prey, evading predators, or navigating swift currents. This type of swimming depends predominantly on anaerobic metabolism and results in rapid muscular fatigue. Prolonged swimming occupies the intermediate range, lasting approximately 20 seconds to 200 minutes, and culminates in fatigue. Critical swim speed falls within the prolonged category and represents the speed a fish can maintain for a specified time interval (Beamish, 1978; Brett, 1964).

There is no universal method for measuring fish swimming performance; instead, techniques have evolved over time to address varying objectives and advancements in instrumentation. These methods, which measure attributes like speed, endurance, and behavior, are generally categorized as forced or volitional swim tests, each with distinct approaches and applications (Katopodis & Gervais, 2016).

The original and most widely used tests for measuring swimming performance are forced swim tests, conducted in swim chambers under controlled conditions. These tests include fixed velocity tests (FVT), increasing velocity tests, and constant acceleration tests (CAT). In fixed velocity tests, fish are placed in a swim chamber and subjected to a constant water velocity until exhaustion, allowing researchers to measure endurance and time-to-fatigue at specific water velocities. In contrast, increasing velocity tests incrementally raise water velocity in fixed steps

to determine a fish's critical swim speed (U_{crit}) (Katopodis & Gervais, 2016). U_{crit} estimates the maximum aerobic speed a fish can sustain for 5 to 10 minutes before fatigue (Katopodis & Gervais, 2016). Constant acceleration tests start at a baseline velocity and increase continuously at a fixed rate over time, which is useful for identifying gait transitions, or shifts between distinct swimming styles, and provides a better estimate of the maximum sprinting speed of a fish (Farrell, 2008; Underwood et al., 2014). These methods ensure a consistent test environment, enabling precise measurement of swimming thresholds and comparisons across species or experimental conditions. However, the forced nature of these tests may not fully replicate natural behaviors and have been shown to underestimate the true maximum swimming capabilities of fish (Dockery et al., 2017; Farrell, 2008; Haro et al., 2004; Peake & Farrell, 2006), especially for benthic species that employ station holding techniques (Aedo et al., 2021; Underwood et al., 2014). Additionally, the relatively small size of swim chambers commonly used in forced tests can inhibit natural swimming behaviors, further contributing to underestimated swimming performance (Dockery et al., 2017).

Volitional swim tests, typically conducted in open-channel environments, allow fish to choose whether to participate, simulating more natural conditions. Unlike forced tests, fish enter a test flume or channel voluntarily from a staging area, enabling the measurement of metrics like burst speeds, endurance times, maximum distance of ascent, and passage success rates at varying water velocities. The larger size of these testing facilities does not restrict natural swimming behavior, thereby providing more accurate assessments of true swimming capabilities (Dockery et al., 2017). These tests provide valuable behavioral insights, such as species-specific responses to flow conditions and participation variability influenced by water velocity (Haro et al., 2004).

However, participation rates can be low, potentially underrepresenting the capabilities of less motivated individuals, and results often reflect behavioral choices rather than maximum physiological limits. Despite these limitations, volitional tests complement forced methods by capturing more natural swimming behaviors.

Field observational studies provide critical insights into fish passage behavior and success under real-world conditions, such as in culverts or fishways. These studies capture how fish interact with complex, variable flow environments, offering valuable data on species preferences, diel activity patterns, and passage efficiency. However, predicting swimming velocities from field studies can be challenging due to the natural variation in flow velocities, turbulence, temperature, and structural features that influence fish performance. Unlike controlled laboratory tests, field conditions introduce environmental variability that may obscure precise measurements of swimming capabilities, making it difficult to isolate individual performance from environmental effects. Despite these limitations, field studies are essential for confirming laboratory findings and assessing the effectiveness of fish passage designs.

White Sucker Swimming Studies

Research on the swimming capabilities of white suckers has provided insights into their critical swimming velocities, burst transition speeds, endurance, and swimming behaviors, using various test methodologies to inform fish passage design. These studies, employing both forced swim tests and open-channel volitional tests, highlight the influence of fish length, temperature, and experimental conditions on swimming performance.

The critical swimming velocity (U_{crit}) of white suckers has been a central focus of forced swim tests, providing a standardized measure of the maximum speed fish can sustain over a

defined period. Across studies, U_{crit} consistently increased with fish length, indicating that larger individuals have greater absolute swimming capacities (Jones et al., 1974; Underwood et al., 2014). Jones et al. (1974) first reported a mean U_{crit} of 61.6 cm/s (range: 47.6–74.2 cm/s) for white suckers with a mean length of 27.5 cm at 12°C. Underwood et al. (2014) confirmed this size-velocity relationship but observed a slightly lower U_{crit} of 52.25 cm/s for similarly sized fish tested at a cooler temperature of 7.6°C. These U_{crit} values represent estimates of swim speeds that white sucker can maintain for a 10-minute period. This difference could suggest a temperature effect; however, other studies have shown relatively insignificant influence of temperature on sucker swimming performance (Castro-Santos, 2004; Gardunio et al., 2014; Haro et al., 2004; Myrick & Cech, 2000; Peake, 2008), indicating that the variation in U_{crit} may instead be due to differences in test conditions or individual variation among fish. Notably, Underwood et al. (2014) also highlighted that U_{crit} values vary significantly among sucker species, with white suckers exhibiting the lowest relative U_{crit} compared to other species, such as longnose suckers (*C. catostomus*) and mountain suckers (*C. platyrhynchus*).

Constant acceleration tests (CAT) have provided additional insights into white sucker swimming performance by capturing burst transition speeds (B_t), the velocity at which fish switch from aerobic to anaerobic swimming. The transition between the short, high-speed burst and the long-duration, sustained swimming, using both aerobic and anaerobic metabolism for energy allows fish to efficiently swim through changing environments. Gardunio et al. (2014) demonstrated that white suckers transitioned to burst swimming at velocities ranging from 1.4 to 5.8 body lengths per second (BL/s), with larger fish transitioning at slightly higher water velocities, consistent with the observations of Underwood et al. (2014). Temperature influenced

B_t , with the lowest observed transition speed of approximately 35 cm/s occurring at 5°C, while the highest observed B_t reached 100 cm/s at 14°C (Gardunio et al., 2014). CAT results also revealed that maximum relative swimming velocities (U_{max}) were consistently higher than U_{crit} values obtained from increasing velocity tests, reflecting the anaerobic capacity of white suckers for short bursts of high-speed swimming (Gardunio et al., 2014; Underwood et al., 2014).

Fixed velocity tests (FVT) conducted by Gardunio et al. (2014) examined white sucker endurance at various speeds near their average burst transition threshold across different temperatures. Most individuals could not sustain swimming for more than 50 seconds at velocities exceeding 100 cm/s at all temperatures tested. Conversely, some fish demonstrated endurance exceeding 120 seconds at lower velocities (below 75 cm/s). These FVTs showed that endurance was influenced by both velocity and fish length but appeared largely unaffected by temperature, particularly at higher velocities, suggesting that white sucker anaerobic swimming abilities may be relatively temperature independent.

Ficke et al. (2012) examined juvenile white suckers (mean total length 122 ± 19.2 mm) and reported significantly lower critical swimming speeds (2.1–2.5 BL/s) compared to larger fish in other studies (Jones et al., 1974; Underwood et al., 2014). These findings emphasize the scaling of swimming performance with body size (Aedo et al., 2021), underscoring the importance of considering developmental stages to align fish passage designs with specific project goals and ecological needs.

Distinct behavioral patterns observed during forced swim tests further inform fish passage design. For example, Underwood et al. (2014) noted that white suckers were the only sucker species tested that did not employ station-holding strategies, such as using their mouths or

body shape to maintain position in flowing water. In contrast, Ficke et al. (2012) observed juvenile white sucker predominantly using station-holding behaviors until they could no longer maintain their position. This discrepancy is likely due to differences in fish size and the hydrodynamic advantages available to smaller individuals. Juvenile white suckers may be better able to utilize lower-velocity zones, turbulence-induced refugia, or edge effects within the flow, allowing them to hold position more effectively than larger fish (Bunt et al., 1999). In contrast, larger individuals may rely more on burst swimming to navigate high velocity flows, potentially explaining why station-holding behavior was not observed in adult fish.

This variation in station-holding behavior may influence swimming efficiency and highlights the adaptability of rock ramps as fish passage structures for suckers. These designs provide diverse hydraulic conditions, accommodating species and individuals that use station-holding strategies while also offering low-velocity resting eddies that allow non-station-holding species, such as adult white suckers, to recover and navigate passage more effectively.

In addition to forced swim tests, two open-channel volitional swim studies have provided valuable insights into the endurance and passage performance of white suckers, often demonstrating greater endurance than fixed velocity tests suggest (Gardunio et al., 2014). Haro et al. (2004) observed that mature white suckers could swim up to 18 meters against velocities of 150 cm/s, with a median distance of 3 meters ascended against flows of 450 cm/s. Similarly, Peake (2008) found that 62.5% of white suckers successfully ascended a 50-meter open-channel flume at 120 cm/s, while 92.3% succeeded at 100 cm/s. These findings reinforce the strong anaerobic swimming ability of white suckers, demonstrating their capacity to sustain high

velocities over short distances and successfully navigate challenging flow conditions in open-channel environments.

Peake's study revealed that passage performance was unaffected by fish length, despite the wide range of sizes tested (27.0–64.0 cm), further suggesting that smaller fish may exploit lower-velocity regions within the flume. Castro-Santos (2005) observed white sucker consistently swimming in the corners of the flume for hydraulic conditions with water velocities below 2.5 m/s, providing further evidence that they actively seek out and effectively utilize lower-velocity regions. Additionally, while attempt probability decreased significantly with increasing water temperature, passage success itself did not vary across the broad temperature range tested (5–22°C) (Peake, 2008). Other volitional studies have also found no significant effect of temperature on passage performance, further supporting Peake's findings that white sucker passage success remains largely unaffected by temperature when relying on burst swimming (Castro-Santos, 2004; Haro et al., 2004). These results contrast with the commonly observed temperature dependence of aerobic swimming in some species (eg. Brett, 1964) but align with findings from Myrick and Cech (2000), who reported that the critical swimming velocities of Sacramento suckers (*C. occidentalis*) remained consistent across temperatures of 10, 15, and 20°C. They suggested that species inhabiting broad elevational and latitudinal ranges, such as Sacramento suckers, may have a wider thermal tolerance where swimming performance is optimized, a pattern that appears consistent with white suckers as well.

While Garduino et al. (2014) found a slight temperature effect on burst transition speed in constant acceleration tests, this does not necessarily indicate a meaningful effect on passage efficiency or the ability to traverse velocity barriers. The relationship between B_t and temperature

in forced swim tests suggests that warmer temperatures could influence when white suckers transition from sustained to burst swimming. However, the absence of a significant temperature effect in volitional studies indicates that, under real-world conditions, fish may adjust their swimming behaviors in ways that minimize temperature-related limitations. Taken together, these findings suggest that temperature has little influence on anaerobic swimming performance or passage success in white suckers, underscoring the importance of considering behavioral flexibility and environmental context when evaluating fishway effectiveness.

Field Studies of White Sucker Passage Performance in Conventional Fishways

Field studies provide critical insights into the passage performance of white suckers under real-world conditions, where environmental variability and fish behavior interact with fishway design. These studies reveal important patterns of fishway utilization, including preferences for certain structures, passage efficiency, and the effects of hydraulic and environmental factors.

Observational studies have demonstrated that white suckers can successfully ascend various fishways, though passage efficiency is influenced by fishway design, length, and slope. Slatick and Basham (1985) observed suckers navigating Denil fishways with slopes of 24–28.7% and lengths up to 50 feet but found no successful passage through a 66-foot fishway with a 27.3% slope. While the observations do not utilize standardized methods to assess passage efficiency metrics these findings purported that fishway length, rather than slope alone, may limit passage success, as the longer structure likely exceeds the endurance of the fish. Additionally, the study provides limited details on the specific sucker species, water velocities, temperature, or

fish size, it demonstrates that Denil fishways up to 50 feet at these steep slopes are passable by some suckers.

In a more thorough analysis, Bunt et al. (1999, 2001) reported successful but relatively low to moderate passage efficiency for white suckers in two Denil fishways: a 27 m fishway with a 10% slope that doubled back on itself twice (55% passage efficiency) and an 11 m fishway with a 20% slope (38% passage efficiency). The highest reported water velocity passed by white sucker was 0.96 m/s (Bunt et al., 1999). Notably, debris accumulation on upstream blocking screens altered water depths and velocities, with the highest passage success occurring under intermediate flow conditions created by moderate debris, suggesting that the added hydraulic complexity enhanced fishway effectiveness beyond the natural Denil hydraulics.

Further supporting the effectiveness of Denil fishways for sucker passage, Triano et al. (2022) found nearly 100% passage success for white and longnose suckers (*C. catostomus*) through six Denil fishways ranging from 2.77 to 3.66 meters in length and slopes between 0.6% and 15.7%. These structures also exhibited moderately high attraction and entrance efficiencies (~70%), reinforcing the effectiveness of Denil fishways as a viable passage solution for these species at appropriately scaled lengths.

Schwalme et al. (1985) evaluated the effectiveness of a vertical slot fishway and two Denil fishways incorporated into a weir, using traps at the fishway exits to monitor passage. White and longnose suckers preferentially ascended the vertical slot over the Denil fishways, suggesting they may actively seek the lower-velocity flows of the vertical slot or avoid the higher velocities in the Denils. This behavior aligns with the observations from Bunt et al. (1999, 2001), where suckers preferentially selected the 10% Denil over the steeper alternative. Also similar to

the study by Bunt et al. (1999, 2001), fluctuating river water levels created variable conditions in the fishways, making precise assessments of velocities challenging. Despite this, the study showed that suckers successfully navigated two slots of high velocity flow in the vertical slot fishway (equating to 100 cm), 8.3 m in the 10% Denil, and 9.3 m in the 20% Denil.

The effects of turbulence on fish swimming performance are even more challenging to study due to its spatial and temporal complexity. Lewandoski et al. (2021) examined how turbulence influences white sucker passage through a modified vertical slot fishway by adjusting weir heights to create different hydraulic conditions. Using 3D computational fluid dynamics modeling, they quantified turbulence in terms of turbulent kinetic energy (TKE), turbulence intensity (TI), turbulent length scale, and vorticity. Their results showed that a 0.1 m²/s increase in TKE corresponded to a 19% decrease in upstream movement; however, the overall impact on passage efficiency was minimal, declining only from 55% to 44% between the least and most extreme turbulence conditions. The study demonstrated that white suckers (13–42 cm in length) can still navigate TKE levels between 0.02–0.08 m²/s and turbulent length scales between 0.42–2.3, highlighting their ability to tolerate moderate turbulence when ascending fishways.

These field studies reveal important behavioral patterns in white sucker utilization of fish passage structures, highlighting the influence of size, seasonal migration, and diel activity on passage performance.

Fish size may influence the type of fishway selected and the strategies used to navigate velocity barriers. Bunt et al. (1999, 2001) found that smaller white suckers were more likely to ascend the steeper 20% Denil fishway compared to larger individuals. This size selectivity may reflect hydrodynamic differences, as smaller fish can exploit lower-velocity regions within

turbulent flows more effectively than larger fish. Laboratory studies have also demonstrated that smaller white suckers are capable of swimming against high-velocity flows by utilizing boundary layers, low-velocity refugia, or employing different behavioral strategies such as station holding swimming to maintain position or advance through challenging flow conditions (Ficke et al., 2012; Peake, 2008).

Seasonal patterns of fishway use were also observed, reflecting both spawning and non-spawning migrations. Bunt et al. (1999, 2001) noted that white suckers began using their Denil fishways in early May when water temperatures consistently exceeded 8°C, coinciding with the onset of their spawning migration. Maximum use of the fishways occurred when water temperatures ranged between 10°C and 15°C, aligning with known spawning preferences for this species (Curry & Spacie, 1984; Manny et al., 2010; Olson, 1963). In contrast, Slatick and Basham (1985) and Schwalme et al. (1985) observed suckers utilizing fishways throughout the summer, indicating non-spawning migratory behavior. This extended period of fishway use suggests that white suckers migrate seasonally not only for spawning but also to access feeding or refuge habitats during the open-water season (Brown et al., 2001).

Multiple studies reported diel patterns in fishway utilization, with white suckers primarily using passage structures during daylight hours. Bunt et al. (1999) observed twice as many attempts to use their Denil fishways during the day compared to nighttime hours. Similarly, Schwalme et al. (1985) found that sucker passage through their vertical slot and Denil fishways was highest during the evening, with activity diminishing during nighttime hours. These findings suggest that white suckers may rely on visual cues or experience increased motivation to migrate during daylight or twilight periods in technical fishways. However, recent studies on rock ramp

fishways have observed predominantly nocturnal passage (Fitzpatrick et al., 2023; Jones, 2022; Steffensen et al., 2013), indicating that passage behavior may be influenced by differences in fishway hydraulics, sensory cues, or migration urgency across different passage structures.

Longnose Dace and Small Bodied Fish Swimming Capabilities

While this literature review does not provide a comprehensive history of longnose dace swim studies, it presents the most relevant findings that also include the swimming performance of other small-bodied species. These comparisons are useful for evaluating the effectiveness of fishways for longnose dace and inferring performance for similar species of interest.

Dockery et al. (2017) assessed longnose dace passage success, maximum ascent distances, and maximum sprint speeds in an open-channel flume across a range of velocities and temperatures (10.7°C, 15.3°C, and 19.3°C). Passage success was high (95%) in a 9.2 m section at mean velocities of 39–64 cm/s but declined to 66% at 78 cm/s. At higher velocities (122 cm/s), only 20% of fish successfully ascended a 2.7 m section. Longnose dace actively selected low-velocity pathways along the bottom and corners of the flume, similar to white sucker (Peake, 2008). The mean volitional sprint speed was 174 cm/s. The assessment suggested fishways with mean velocities $<64 \text{ cm s}^{-1}$ should allow passage of most longnose dace, while velocities $>100 \text{ cm s}^{-1}$ within structures should be limited to short distance ($<1\text{m}$), and velocities $\geq 158 \text{ cm s}^{-1}$ would probably represent barriers.

Aedo et al. (2021) examined the swimming performance of several small-bodied species in the Great Basin, estimating prolonged swimming speed for longnose dace at 0.68 m/s and sprint speed at 1.10 m/s. These estimates were slightly lower than those reported by Dockery et al. (2017), but differences in burst testing methodologies may have contributed to the variation.

Both studies noted a positive relationship between fish length and swimming ability, consistent with findings for other small-bodied species (Ficke, 2015).

Ficke (2015) conducted an extensive study and literature review on small-bodied fish, estimating the aerobic swim speed of longnose dace at 44 cm/s and sprint speed at 78 cm/s, values significantly lower than those reported by Dockery et al. (2017) and Aedo et al (2021). The disparity is likely due to differences in testing methodology, as the Ficke (2015) estimates were derived from forced swim chamber tests rather than volitional trials.

Ficke (2015) further reviewed swimming capabilities of small-bodied fish and found that most species under 150 mm total length (TL) could achieve sprint speeds of approximately 50 cm/s. Across 72 species, the median sprinting ability was 62 cm/s, with the 25th percentile at 44 cm/s. These values provide conservative estimates for fish passage design in cases where species-specific data are unavailable. However, given the higher sprint speeds reported for longnose dace by Dockery et al. (2017) and Aedo et al. (2021), these values may underestimate the true capabilities of some small-bodied fish.

The relationship between fish length, temperature, and swimming performance observed in longnose dace is consistent across many small-bodied species. Both Aedo et al. (2021) and Dockery et al. (2017) reported a positive relationship between total length and swimming performance. Additionally, aerobic and anaerobic swimming performance increased between 5°C and 30°C for most tested species (Ficke, 2015), with Dockery et al. (2017) specifically observing improved dace swimming ability at higher water temperatures.

Collectively, these studies highlight the variability in longnose dace swimming performance across different experimental conditions and emphasize the importance of

considering body size, temperature, and testing methodologies when designing fish passage structures for small-bodied fish. While forced swim tests provide conservative estimates of fish capabilities, volitional swim studies offer a more realistic representation of how fish navigate high-velocity environments. These findings reinforce the need for species-specific data when optimizing fish passage designs for weak-swimming species.

Rock Ramps Field Studies

Nature-Like Fishways (NLFs) have been implemented worldwide, most commonly as bypass channels and step-pool designs. They are especially popular in Europe and Australia, where they have been shown to effectively facilitate passage for non-salmonid species. European studies have demonstrated that rock ramps can provide suitable passage conditions for a diverse range of fish species (Calles & Greenberg, 2007; Pander et al., 2013; Santos et al., 2005; Tamario et al., 2018). In Australia, rock ramps have been used successfully to facilitate passage for various native fish, including species with weaker swimming abilities (Stuart et al., 2024; Thorncraft & Marsden, 2000).

In North America, research on rock ramp fishways remains limited, particularly regarding their effectiveness for suckers and small-bodied fish. The few available studies suggest that while rock ramps can support passage for a variety of species, passage success varies widely depending on species-specific swimming abilities and key design elements such as slope, length, and flow rate (Anderson, 2022; Ficke, 2015; Jones, 2022; Paik et al., 2024). These studies underscore the complexity of rock ramp performance by highlighting differences in passage efficiency, species-specific responses, hydraulic conditions, and behavioral patterns, contributing to the growing understanding of how nature-like fishways function in real-world settings.

Field studies demonstrate that rock ramps facilitate passage for various fish species, but passage efficiency varies considerably across species and structures. Steffensen et al. (2013) evaluated a 116-m long pool-and-riffle nature-like bypass channel with a 1.25% slope, finding a moderate attraction efficiency (65.6%) but a lower passage efficiency (25%) for white sucker. While the structure facilitated moderate passage of creek chub (*Semotilus atromaculatus*), it provided poor passage for common shiner (*Luxilus cornutus*), highlighting species-specific variability in fishway performance.

Similarly, Landsman et al. (2018) compared a 60.6-m long, 2.4% slope NLF bypass channel to a traditional pool-and-weir fishway and found a stark contrast in passage success. Rainbow smelt (*Osmerus mordax*) had a 28.6% passage efficiency through the NLF but failed to pass the pool-and-weir structure, while brook trout (*Salvelinus fontinalis*) exhibited nearly 100% passage success in both structures. This study reinforces the ability of NLFs to accommodate a broader range of species compared to traditional technical fishways. Additionally, smelt were observed spawning within the bypass channel, indicating its potential to serve as compensatory lotic habitat rather than just a passage structure.

Anderson (2022) conducted a multi-year evaluation of a 125-m long, 1.22% slope NLF bypass channel built around the Huntley Diversion Dam on the Yellowstone River in Montana. Over 3,500 fish from 14 species were PIT-tagged, and stationary antennas monitored fish movement through the structure. All species exhibited some successful passage, including longnose and white sucker. However, as is common for non-channel-spanning bypass channels, attraction efficiency was low (<50%), while entrance and passage efficiencies were generally high but varied by species. Seasonal fishway use coincided strongly with pre-spawning

migrations from April to August, and diel movement patterns reflected species-specific behaviors. These results highlight a common pitfall of bypass channels, where low attraction efficiency can limit overall passage success (Bunt et al., 2012).

Fitzpatrick et al. (2023) further demonstrated the effectiveness of long, low-slope rock ramps by evaluating a 123-m prefabricated fishway at a 2% slope designed to pass small-bodied Great Plains fish species. The study confirmed successful passage of flathead chub (*Platygobio gracilis*), central stoneroller (*Campostoma anomalum*), creek chub, and white sucker, with high passage success (99%) for fish that entered the structure. However, entrance probability was extremely low (3%), reinforcing the limitation of non-channel-spanning fishways. These findings suggest that while long, low-gradient rock ramps can be effective for small-bodied species, their success is contingent on adequate attraction flow to ensure fish locate and enter the structure.

Richer et al. (2020) evaluated the Fossil Creek Reservoir Inlet Diversion (FCRID) roughened channel rock ramp in Colorado (3 m long, 5% slope, roughness elements arranged in a chevron pattern) which successfully passed brown trout (*Salmo trutta*), white sucker, longnose sucker, longnose dace, and brassy minnow (*Hybognathus hankinsoni*) during the enclosure study. However, passage success was low for the brassy minnow, a weak-swimming, small-bodied fish (Ficke, 2015), suggesting that the slope of this ramp may represent the upper limit for species with limited swimming capabilities.

Extended monitoring studies revealed lower passage success for longnose dace, lower entrance probabilities for all species (Richer et al., 2020), and no passage for Stonecats (*Noturus flavus*), fathead minnows (*Pimephales promelas*), and Central Stonerollers (Jones, 2022) while higher flow rates were present than during the initial enclosure study. This highlights flow rate as

a key design consideration, as increased discharge may create hydraulic conditions that limit passage success, particularly for weaker-swimming species.

Additionally, during high flows, a hydraulic jump formed at the entrance, creating an entrance barrier for small-bodied fish (Richer et al., 2020). This underscores the need to establish tailwater depth criteria across different flow conditions to ensure favorable entrance conditions for all species. To address this issue, the rock ramp was extended an additional 6 m downstream. Following this modification, Jones (2022) conducted extended monitoring and found 55% passage efficiency, with 71% of the 13 species present successfully navigating the fishway, demonstrating that structural adjustments can improve rock ramp effectiveness.

Another key factor influencing passage success is the presence of hydraulic diversity and velocity refugia within the fishway. Jones (2022) monitored a second rock ramp, the Dickens Farm rock ramp (15 m long, 2% slope, grouted boulders ~1.15 m in diameter), which had a slightly higher passage success rate (61%) than the FCRID site. Longnose sucker, white sucker, and longnose dace all passed at rates above 50%.

Compared to the FCRID site, the Dickens Farm ramp featured much larger boulders, creating greater hydraulic diversity and more velocity refugia. These conditions provided additional resting areas during passage and likely contributed to the higher passage success of weaker-swimming species, such as stonecats. Extended monitoring also revealed long residence times for fish within the ramp, suggesting that some individuals were using the structure as habitat, a pattern consistent with Landsman et al. (2018).

Slope is an important factor influencing passage success, as shown by a monitoring study of two rock ramp fishways on the same stream (Ficke, 2015). One fishway, the McGinn fishway,

was a 21.3-m long sculpted concrete structure with a 1.5-m wide confined low-flow notch and a 4.5% slope. The other, the South Boulder fishway, was a 10.4-m long rock ramp spanning the full 9.1-m width of the stream, featuring an unconfined low-flow notch and an 11.2% slope. Brown trout, rainbow trout (*Oncorhynchus mykiss*), and longnose sucker successfully navigated both fishways, but passage was notably reduced in the steeper ramp compared to the lower-sloped ramp and a control section. Notably, one longnose dace successfully ascended the 11.2% ramp, highlighting the species' ability to utilize microhabitats and exploit low-velocity swim paths even under steep slopes and high-velocity conditions, although overall passage efficiency under such conditions remains very low.

These results demonstrate that while stronger-swimming species can ascend steeper ramps, passage success declines significantly, likely excluding weaker-swimming species entirely. This reinforces the importance of establishing slope thresholds based on the weakest-swimming species present, ensuring that rock ramp designs accommodate all target species.

Extended monitoring studies have also revealed notable diel and seasonal patterns in fish behavior. Steffensen et al. (2013) found that white suckers primarily used the pool-and-riffle bypass fishway at night, suggesting that some species exhibit nocturnal passage preferences. Similarly, Jones (2022) observed that white suckers moved more frequently at night at both the FCRID and Dickens Farm rock ramp sites, while longnose dace and longnose sucker did not display a clear diel pattern. Fitzpatrick et al. (2023) further reinforced nocturnal passage tendencies, documenting between 80-100% of movement detected at nighttime for white sucker and longnose dace.

This nocturnal passage trend observed in rock ramp fishways contrasts with findings from technical fishway studies, where white suckers were documented using the structures more frequently during the day (Bunt et al., 1999; Schwalme et al., 1985). The reason for this discrepancy remains unclear, but it may be related to differences in hydraulic complexity and the sensory cues fish rely on for navigation. One possibility is that white suckers depend more heavily on vision to navigate the higher-velocity, more turbulent environments of technical fishways, making daytime movement more advantageous. Alternately, the turbulent flows in technical fishways may act as cover that promote daytime movement. Anderson (2022) observed that longnose and white suckers passed the Huntley Diversion NLF predominantly at night during early spring but shifted to daytime passage during peak flows in June, supporting the idea that diel movement patterns may be influenced by changes in water velocity, turbulence, or turbidity affecting visibility. Alternatively, since technical fishways often present greater physical challenges, suckers may alter their natural migratory behavior, delaying passage attempts until movement is essential for spawning or habitat access. Further research is needed to understand whether these behavioral differences stem from hydraulic conditions, species-specific passage strategies, or other ecological factors influencing fishway use.

Seasonally, Jones (2022) found that fish movement was most frequent before peak runoff in April and May and least frequent in winter, though some movement occurred year-round. Similarly, Anderson (2022) observed the majority of fishway use occurring from April through August, noting that passage was rare after peak water temperatures and during high-discharge periods associated with annual runoff. Anderson also suggested that their delayed monitoring start in late April during the first year likely resulted in missed observations of early-season

white sucker movements, potentially underestimating their passage success. These findings highlight the importance of considering seasonal hydrology when designing fishways to ensure they remain functional across a range of flow conditions. Additionally, they underscore the need to account for species-specific passage timing in fishway monitoring programs to avoid underestimating passage success due to sampling biases.

Beyond improving fish passage, several studies suggest that rock ramps can provide additional ecological benefits by enhancing habitat connectivity. Landsman et al. (2018) observed rainbow smelt spawning within the bypass channel, highlighting the potential for NLFs to serve as compensatory lotic habitat. Similarly, Jones (2022) found long residence times for fish in the Dickens Farm rock ramp, indicating that some species actively use these structures as habitat rather than merely as migration corridors.

Additionally, Stroller (2013) found that a step-pool fishway (82 m long, 58 m wide) maintained ecosystem connectivity, with no significant population impact on 13 of the 20 most abundant species, including minnows and suckers. These findings suggest that well-designed rock ramps can integrate seamlessly into their surroundings, improving both fish passage and overall ecosystem function.

Rock Ramp Lab Tests

Controlled laboratory experiments at Colorado State University (CSU) have played a critical role in advancing the understanding of fish passage performance in rock ramp fishways. Through a series of systematic experiments, researchers at CSU have demonstrated that passage success in rock ramps is highly dependent on slope, substrate type, and hydraulic conditions,

particularly for small-bodied and weak-swimming species, helping to inform design recommendations for improving fishway effectiveness.

The first lab-based investigation into rock ramp hydraulics and fish passage was conducted by Ficke (2015), who examined the effects of substrate arrangement on passage success for three species: longnose sucker, longnose dace, and Johnny darter (*Etheostoma nigrum*). The experimental ramp was 10.1 m long with a 3% slope and had a trapezoidal cross-section with 42-degree side slopes. Roughness elements were arranged in a chevron formation based on perturbation boulder designs, with cobbles measuring 10–15 cm in diameter (Mooney et al., 2007). Two substrate configurations were tested: a closely spaced configuration, where cobbles were arranged one diameter apart, and a widely spaced configuration, where half of the cobbles were removed.

Results showed high passage success for longnose suckers (88–92%), moderate success for longnose dace (31–38%), and extremely low passage for Johnny darters (5% or less). Notably, longnose dace exhibited a negative size-passage relationship, with larger individuals struggling more in the closely spaced roughness elements, likely due to reduced ability to exploit low-velocity microhabitats. These findings suggested that gradual slopes (<3%) and appropriately spaced roughness elements are key to optimizing passage for small-bodied species. Building on Ficke (2015), Swarr (2018) expanded the study to investigate how slope influences passage success for other small-bodied fish species with varying swimming abilities. A similar trapezoidal rock ramp design was used with the closely spaced boulder configuration; however, the side slopes were reduced to 30 degrees, and the total ramp length was 6.1 m. Slopes of 2%, 4%, 6%, 8%, and 10% were tested. The flowrate for each slope was set to maintain an average

water depth of 51-mm. The study focused on three species: flathead chub (strong swimmer), stonecat (moderate swimmer), and Arkansas darter (*Etheostoma cragini*) (weak swimmer).

Results confirmed that passage success declines as slope increases, particularly for weaker-swimming species. Flathead chub successfully passed at all slopes up to 6%, while stonecats passed at slopes to 4%. Arkansas darters exhibited significantly lower passage probabilities, with only 54% successfully ascending 4.06-m at a 2% slope and 43% successfully ascending 2.03-m up the ramp at a 4% slope. At steeper slopes ($\geq 6\%$), passage success dropped for all species, reinforcing the recommendation that rock ramps intended for small-bodied fish should maintain slopes below 4% to maximize passage efficiency.

Brittain et al. (2022) expanded on previous research by testing the same rock ramp used by Swarr (2018), examining how different substrate sizes placed between the perturbation boulders affected passage success at a 6% slope. The study tested four surface textures, varying from smooth PVC to 19-31 mm small cobbles. Results revealed substantial improvements in passage success with the addition of small cobble roughening:

- Arkansas darter passage increased from 0% (smooth substrate) to 32.2% (small cobble).
- Stonecat passage increased from 31.1% (smooth) to 86.7% (small cobble).
- Flathead chub maintained high passage success (>90%) regardless of substrate type.

These findings aligned with Rodgers et al. (2017) and Song & Xie (2024), who found that substrate roughening improved critical and burst swimming speeds by 12.9–15% for small-bodied species. The increase in hydraulic complexity and lower-velocity refugia created by roughening appeared to provide critical resting areas, making passage more feasible for weaker swimmers.

Most recently, Paik et al. (2024) applied these substrate improvements to study passage success for five small-bodied species of special conservation concern in Colorado: Topeka shiner (*Notropis topeka*), suckermouth minnow (*Phenacobius mirabilis*), Rio Grande chub (*Gila pandora*), Rio Grande sucker (*C. plebeius*), and mottled sculpin (*Cottus bairdii*). Using the small cobble roughening recommended by Brittain et al. (2022), this study tested passage success at slopes ranging from 2–10%.

Findings reinforced earlier studies, showing high passage success (>90%) at slopes of 2–4% for all species except Topeka shiner, which exhibited slightly lower success. However, at 8% and 10% slopes, passage success dropped drastically (<31%), reinforcing the evidence that steep ramps are unsuitable for weaker-swimming species unless resting areas are incorporated at frequent intervals (~2.03 m apart).

Application of 3D CFD Modeling in Rock Ramp Design and Fish Passage Assessment

The complex and highly variable hydraulics produced by rock ramps present a significant challenge for traditional 1D and 2D hydraulic modeling techniques, which often fail to capture the intricate flow patterns that influence fish passage. As a result, the growing field of three-dimensional computational fluid dynamics (3D CFD) modeling offers a promising tool for improving both the design of new rock ramp structures and the assessment of existing fish passage solutions. By simulating detailed hydrodynamic conditions, CFD modeling allows researchers to evaluate key parameters such as velocity distributions, turbulence intensity, shear stress, and coherent flow structures (CFS), all of which play a crucial role in fish movement through roughened channels.

Rock ramps offer considerable design flexibility, with variations in boulder size, shape, spacing, and configuration significantly altering flow conditions. Testing every possible variation in a lab or field setting is impractical, as modifying one design element impacts multiple hydraulic factors, such as depth, velocity, eddy structures, and turbulence intensity (Fang et al., 2017). Therefore, CFD modeling provides a cost-effective means of optimizing designs before construction.

A key design principle in roughened channel rock ramps is the use of staggered boulder arrangements, which enhance energy dissipation and create more favorable hydraulic conditions for fish passage. Ahmad et al. (2009) demonstrated that staggered boulders generate higher form drag, wake vortices, hydraulic jumps, and jetting flows, leading to greater velocity reduction and turbulent energy dissipation. Similarly, Magaju et al. (2021) found that staggered arrangements increase resting areas, flow heterogeneity, and low-drag zones, making them more suitable for a wide range of fish species with different swimming abilities. Experimental studies further validate these findings, with Franklin and Bartels (2012) showing that staggered roughness elements improve passage efficiency for weak-swimming fish in culverts.

Extensive research by Baki et al. (2014, 2015, 2016) has refined optimal boulder spacing for roughened channels. Using laboratory experiments and CFD modeling, Baki evaluated the effects of flow rate, slopes, boulder size, and spacing patterns on rock ramp hydraulics. Their modeling results recommend longitudinal boulder spacing between 2.0–3.8 diameters, aligning with FAO/DVWK fish passage guidelines, which suggest 2–3 diameters for optimal hydraulic performance. Golpira (2022) further demonstrated that closer boulder spacing (2 diameters) results in lower turbulence compared to a spacing of 4 diameters.

For lateral spacing, Baki et al. (2016) recommends 2.7–3.5 diameters, which creates the optimal blockage for increasing water height and decreasing velocities. This configuration produces a wake-interference flow regime, where roughness elements are spaced closely enough that the wake from one boulder interacts with the next before fully dissipating. However, wake-interference flow regimes generate greater turbulence and higher bed shear stress, which may negatively impact small-bodied fish that rely on wake zones for resting (Baki et al., 2015; Golpira, 2022). This highlights the trade-offs between maximizing depth and velocity reduction while minimizing turbulence impacts for different species.

CFD modeling has also revealed critical relationships between boulder density and the hydraulic conditions they create, emphasizing the complexity of rock ramp design. Boulder density, determined by size and spacing, plays a key role in modifying flow characteristics. Golpira et al. (2022) found that increasing boulder density from 3.4% to 8.3% enhanced flow heterogeneity and habitat complexity metrics, potentially benefiting a wider range of aquatic species. Similarly, Baki et al. (2016) demonstrated that increasing boulder density from 6% to 20% reduced both average and maximum velocities, improving hydraulic conditions for fish passage.

However, the effectiveness of increased boulder density depends on flow conditions. While emergent boulders strongly influence water depth, once they become submerged the effect is much smaller. Cassan et al. (2014) found that maximum flow resistance occurs just before boulder submergence, suggesting this could be an optimal flow condition for fish passage. However, Golpira (2022) showed that different submergence ratios affect turbulence distribution, with lower submergence ratios intensifying turbulence (TKE and Reynolds shear stress) near the

bed and in recirculation zones. This increased turbulence may raise swimming costs, potentially hindering small-bodied fish that rely on wake regions for resting between bursts.

These findings emphasize the complex interactions between boulder size, spacing, slope, and flow rate in determining hydraulic conditions. Given this complexity, CFD studies paired with empirical fish passage data are needed to refine rock ramp designs to accommodate species with varying swimming capabilities.

CFD modeling is a powerful tool for assessing how turbulence influences fish movement, particularly given the challenges of directly measuring turbulent flow in field conditions. Lewandoski et al. (2021) provided a framework for integrating CFD simulations with fish passage studies, demonstrating how turbulence metrics can be effectively paired with empirical passage data to inform fishway design. Their approach highlights the potential of CFD modeling to refine our understanding of hydraulic conditions that influence fish passage and improve future design strategies.

Integrating CFD modeling with empirical fish passage studies provides a powerful tool for refining rock ramp designs and optimizing hydraulic conditions for diverse species. By systematically linking 3D flow simulations with observed passage data, researchers can establish precise turbulence thresholds that different fish can tolerate, particularly benefiting small-bodied and weaker-swimming species. This data-driven approach will be essential for improving fish passage efficiency, supporting species conservation, and enhancing the overall effectiveness of nature-like fishways.

Conclusion

This literature review examined white sucker and longnose dace swimming abilities, performance of conventional and nature-like fishways, rock ramp studies from both field and laboratory settings, and the potential of 3D CFD modeling to enhance fish passage design. Key findings include:

- Swimming capabilities of benthic and small-bodied species vary widely, and different species utilize distinct behavioral strategies when navigating challenging hydraulic environments.
- Conventional fishways can effectively support passage for white suckers when appropriately designed; however, they are less successful for weaker-swimming, small-bodied fishes.
- Rock ramp fishways have been shown to be effective in facilitating passage of a broad range of fish species, but passage efficiency is significantly influenced by design parameters such as slope, length, substrate size, and boulder arrangement.
- Field studies often indicate low entrance probabilities for rock ramps, making accurate assessments of their true passage efficiency difficult.
- While some laboratory studies have evaluated slope, boulder configuration, and substrate size, no research has specifically investigated how varying flow rates impact passage success for both large and small-bodied fish in a roughened channel rock ramp.
- The complex hydraulics of rock ramps complicate comparisons and identification of key design elements necessary for optimal effectiveness.

- Pairing laboratory experiments with CFD simulations offers a promising approach to better understand how hydraulic conditions, particularly turbulence, impact fish passage success and could significantly inform future design guidance.

This review highlights the need for continued research on rock ramp designs capable of accommodating a wide range of species. Specifically, further laboratory studies evaluating various configurations and flow rate thresholds can refine design guidelines tailored to different fish species. Integrating CFD modeling with laboratory studies could deepen our understanding of fish swimming behaviors in relation to hydraulic conditions, ultimately advancing the effectiveness and inclusivity of future fish passage designs.

CHAPTER TWO

DESIGN, CONSTRUCTION, AND INSTALLATION OF A
MODEL ROCK RAMP FISHWAY IN AN OPEN CHANNEL
FLUMEIntroduction

The Bozeman Fish Technology Center (BFTC) houses an experimental open-channel flume, which provides a controlled environment for evaluating fish passage structures under varied hydraulic conditions. A rock ramp fishway was designed and constructed for installation within this flume to investigate the passage efficiency of small-bodied and benthic fish species. The structure was built to allow for adjustable slopes, enabling both hydraulic assessments and volitional swim trials to determine slope and flow thresholds for different species.

Unlike other models installed directly on the flume, this rock ramp was engineered for modularity, allowing it to be set at multiple inclines within a flume of constant slope. The design incorporates perturbation boulders and a graded gravel substrate, mirroring real-world roughened channel rock ramps used for fish passage. This approach represents a novel method for constructing a model rock ramp adaptable to flume-based fish passage research.

This chapter outlines the design considerations, construction process, and structural components of the rock ramp, providing a framework for its application in both experimental and field-based fish passage studies.

Methods

Experimental Flume

The study took place in an indoor open-channel flume (0.91 m wide x 1.37 m deep x 17.46 m long) at the BFTC. The flume consists of seven fiberglass sections, featuring concrete headwater and tailwater boxes. To ensure a near-flat incline while allowing water to drain, the flume was constructed on a slope of 0.83%. The flume is housed in an enclosed facility, with a garage door positioned near its midsection. This setup allows for the use of a jib-hoist mounted on a forklift to install and remove research structures. This controlled environment allowed for testing the rock ramp fishway under various conditions.

Rock Ramp Design

The roughened channel rock ramp was designed following the guidance of USFWS, DVWK, and USBR nature-like fishway design guidelines (DVWK, 2002; Mooney et al., 2007; USFWS, 2019). Sediment transport calculations were used to size the perturbation boulders, resulting in a boulder diameter (D) of 13.97 cm (5.5 in) for the design flow rate of 0.1262 m³/s (2,000 GPM) at a 3% slope (USFWS, 2019). These elements are referred to as perturbation boulders to align with common NLF terminology, though under USBR classifications, they are technically categorized as cobbles.

The gravel substrate size was informed by Brittain et al. (2022) and commercial availability. River rock, visually classified as sub-rounded, was sourced from local hardware stores and sieved to retain only gravel particles between 3.81 cm (1.5 in) and 2.54 cm (1 in), which were used as the primary substrate placed between the perturbation boulders. Finer gravel,

with a minimum size of 0.635 cm (0.25 in), was used to fill gaps between larger particles, mimicking a well-graded gravel mix typical of natural stream channels or rock ramp designs.

The perturbation boulders were arranged in a typical staggered pattern as recommended by Ahmad et al. (2009), Baki et al. (2014, 2015, 2016), and Magaju et al. (2021). This common configuration allows for scalability and ease of construction. Boulder spacing was 30.48 cm (12 in) longitudinally and 35.56 cm (14 in) laterally, equating to 2.18 D and 2.55 D, respectively. These values fall within DVWK's (2002) recommended range of 2–3D and Baki et al.'s (2016) range of 2–3.8D for longitudinal spacing. The lateral spacing, though slightly below DVWK's 2.7–3.5D recommendation, was the maximum spacing feasible within the flume.

The resulting boulder configuration closely resembles one of the models by Baki et al. (2016) recommended for optimal fish passage. This results in an areal boulder density of 12.83%, which is sufficient to achieve the desired effects of reducing velocities and increasing water depth while maintaining adequate space for larger-bodied fish species (400+ mm suckers) to navigate between boulders (Baki et al., 2016; Golpira, 2022).

Boulders were sourced from the lower Gallatin River and selected based on the following criteria:

- Primary axis: ≥ 13.97 cm, not exceeding 16.51 cm
- Secondary axis: $13.97 \text{ cm} \pm 2.54 \text{ cm}$
- Tertiary axis: ≥ 10.16 cm
- The boulder should stand upright independently, ensuring that the secondary axis is oriented perpendicular to flow.

Fishway Construction

A model rock ramp was designed and constructed to be placed in the flume at various slopes. The ramp consisted of two primary components: modular ramp panels containing the perturbation boulders and substrate, and the ramp frame, which supported the panels at the desired slope. A transition panel, made from a graded gravel mixture, was installed between the most downstream ramp panel and the flume floor to provide a smooth hydraulic transition and improve entrance conditions for benthic fishes.

Rock Ramp Panel Construction

The 18-ft (5.49-m) ramp consisted of six 3-ft-long (91.44 cm) panels, which are a manageable weight for transport and ease of installation in the flume. Each panel was constructed using:

1. A marine plywood base
2. A mortar layer embedding the perturbation boulders and substrate
3. Hardware for fastening and transportation

The base of each ramp panel was constructed using $\frac{3}{4}$ inch marine plywood, cut into 36-inch (91.44 cm) by 35.5-inch (90.17 cm) panels. This sizing allowed for a 0.5-inch (1.27 cm) tolerance between the ramp panels and the flume walls. Each panel contained eight pre-drilled holes near the corners (Figure 1). These holes were counterbore to accommodate steel spacers, which provided unobstructed openings through the panels after the mortar was laid.

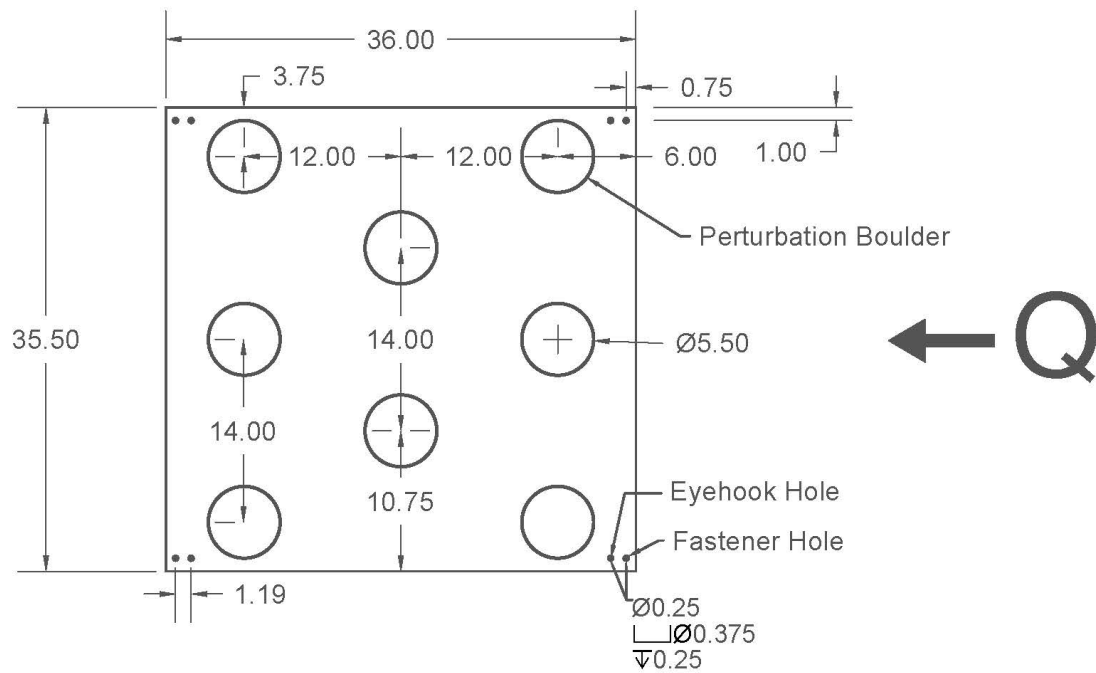


Figure 1: Rock ramp panel dimensions (inches).

Four of these holes were used to insert wood screws, securing the panels to the ramp frame. This design allowed the ramp panels to be interchangeable across multiple frame setups by utilizing the same fastening points. The remaining four holes contained threaded spacers that permitted installation of eyehooks for transport. These eyehooks and securing nuts were installed after the panels had fully cured, allowing the panels to sit flush on the curing surface and preventing any warping caused by resting on protruding hardware (Figure 2).



Figure 2: Corner of finished ramp panel showing fastening spacer and eyehook.

To create mechanical bonding points between the mortar and plywood, approximately 20 evenly spaced 1.25-inch wood screws were inserted through the bottom of each panel. A 6.5-inch diameter buffer was marked around the center point of each boulder to prevent interference with boulder placement. 2x2-inch wooden forms were cut to length and framed around each panel, creating a 0.75-inch-deep mold for the mortar layer.

A 2:1 mortar mix of cement and sand was prepared, with water added until a fluid, workable consistency was achieved. The mortar was poured over each panel and leveled to the top of the wooden forms using a trowel, ensuring a uniform depth for embedding the perturbation boulders and substrate.

Each boulder was placed at its designated location, marked with a nail lightly embedded in the plywood and protruding above the mortar surface. The boulders were carefully set on their stable edge, and the secondary axis was oriented perpendicular to the flow direction. Each boulder was embedded into the mortar while maintaining a thin mortar layer beneath the boulder for additional stability. Once the boulders were set in place, the primary substrate (2.5-3.8 cm gravel) was embedded between them. The smaller gravel particles (0.64 cm minimum) were added to fill gaps and create a stable, interlocking substrate. Additional mortar was applied around the base of each boulder to enhance structural integrity and prevent excessive water infiltration beneath the boulders (Figure 3).



Figure 3: Rock ramp panel post construction including hardware, forms, perturbation boulders, and gravel substrate.

To achieve a natural streambed finish, a concrete retardant (Coca-Cola; Coca-Cola company, Atlanta Georgia) was applied to the mortar surface. Bottles were shaken and evenly sprayed over the panels to slow the setting time of the top mortar layer. Excess mortar was poured into a waste bin to compare its set time against the treated mortar. After about two hours, the ramp panels were lightly hosed off to remove the top layer of mortar from the embedded gravel, exposing a clean, textured surface similar to a natural stream channel.

To allow for proper curing, moist towels were placed over each panel, and they were left undisturbed for two weeks before transportation. For transport, stainless steel eyehooks were installed into the pre-threaded steel spacers using 2-inch washers and lock nuts to securely anchor them to the panels. These eyehooks were then attached to carabiners and chains, allowing the panels to be lifted using custom-made handles or the jib hoist for safe transportation and installation into the flume.

Rock Ramp Frame

The ramp frame was constructed from wood, with individual frames built for each panel. These frames were then securely bolted together to form a single, cohesive structural support system. This approach allowed each frame to be constructed to the exact height required for each panel and for easy installation and removal from the flume.

Lateral supports were made from nominal lumber, cut to 35.5 inches in length. Each panel was supported at its upstream, midspan, and downstream edges by a support. The width of each support was planed down to the nearest 1/32 of an inch using a planer (DeWALT DW735 13" Three Knife Two-Speed Thickness Planer). The top edges of these supports were then sanded with a corner sander to match the designated slope of the ramp.

These lateral supports were connected by 2x4 cross beams, which were cut to length and directly screwed into the supports (Figure 4). Elbow braces were added to provide additional stability, ensuring a square connection and simplifying construction.



Figure 4: Single rock ramp frame shown supporting a ramp panel.

Rock Ramp Transition Panel

The transition panel was constructed from 5 mm hardwood plywood, extending 1 foot downstream beyond the last ramp panel to create a smooth transition. For durability, it was coated with marine-grade epoxy on both sides and along the edges.

River gravel, ranging from 37.5 mm to 4.75 mm, was separated using ASTM E11 sieves. A layer of epoxy was applied to the top surface, and gravel was placed in descending size order to ensure a gradual hydraulic transition between the ramp and the flume floor (Figure 5).

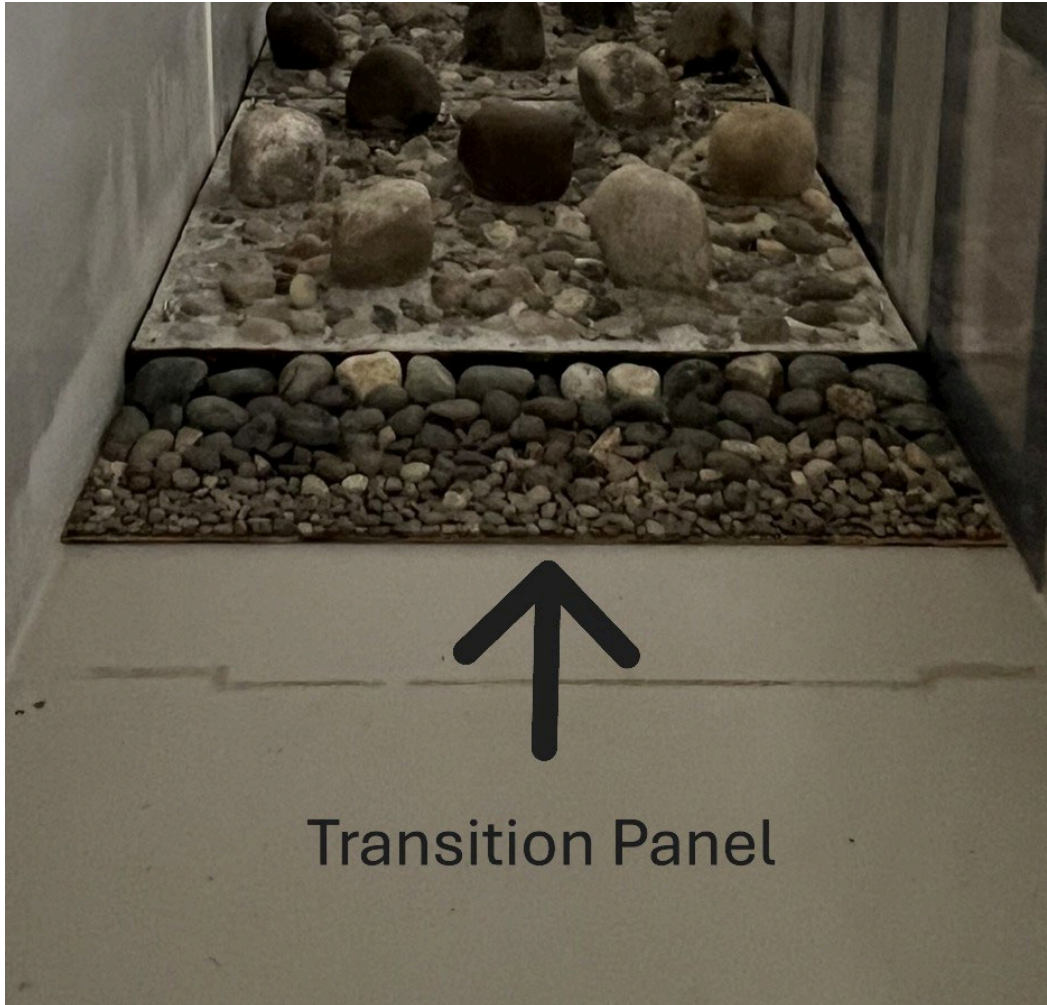


Figure 5: Transition panel installed in the flume with rock ramp.

Installation

The ramp frames were positioned in the flume and fastened together using partially threaded bolts, washers, and lock nuts. Wooden shims ensured the frame remained centered and secure against water forces. To protect the flume walls, tarps were draped over them and clamped in place (Figure 6).



Figure 6: Ramp frame installed in flume looking downstream.

The ramp panels were lowered into the flume using a jib hoist on a forklift, with guide ropes attached to each eyehook for precise placement. Once positioned, each panel was secured by driving 2.5-inch screws through the corner spacers into the frame.

The transition panel was placed downstream, with the last ramp panel resting on it (Figure 7). To seal the $\frac{1}{4}$ -inch gaps between the ramp panels and the flume walls, a $\frac{3}{8}$ -inch OD

vinyl tube was packed into the gaps and secured at both ends with screws. Silicone caulk was applied between the downstream panel and the transition piece to improve adhesion and prevent small fish from getting under the ramp.



Figure 7: 3% slope rock ramp installed in flume looking upstream.

Results and Discussion

Each ramp panel weighed approximately 225 lbs (102.06 kg) and withstood hoisting via eye hooks without deforming, cracking, or breaking. The panels remained structurally intact when submerged for extended periods under high-velocity flows, with only minimal fine substrate loss. Installation and removal using the jib hoist were efficient, demonstrating the feasibility of this design for controlled hydraulic testing.

The modular ramp design effectively simulated a roughened channel rock ramp, incorporating key structural elements of perturbation boulders and gravel substrate while allowing for adjustable slopes in a fixed-slope flume. The flat-bottom channel configuration, rather than a trapezoidal cross-section, was intentionally chosen to isolate and study the internal hydraulics of the rock arrangement (Baki et al., 2014, 2016). This approach enables hydraulic conditions to be scaled for wider streams by proportionally increasing boulder placement. However, edge effects from the flume walls may have influenced flow conditions and are discussed further in Chapter 3 (Hydraulic Evaluation).

This construction method could be adapted for precast concrete panels, allowing for real-world implementation as a bypass or partial-width spanning structure at low-head dams. Similar precast rock ramps have demonstrated effectiveness in facilitating passage for a variety of fish species (Fitzpatrick et al., 2023; Jones, 2022; Richer et al., 2020). The modular nature of the design also allows for scaling to accommodate longer or wider installations, depending on site conditions and target species.

In theory, a ramp of this design could be installed in a small stream with a maximum flow of $0.1386 \text{ m}^3/\text{s}$ per meter width and a maximum slope of 3% using a rock-only construction

approach without mortaring the roughness elements. However, the perturbation boulders were embedded at a shallower depth than the 20–30% recommended by USBR design guidelines (Mooney et al., 2007). Increasing the embedment depth may alter hydraulic conditions and impact fish passage efficiency, requiring additional research and modeling to fully assess its implications. Future studies should explore how different embedment depths influence passage performance and hydraulic conditions, ensuring optimal rock ramp designs for diverse fish species and flow regimes.

CHAPTER THREE

HYDRAULIC EVALUATION OF A MODEL ROCK RAMP

FISHWAY

Introduction

Understanding the hydraulics of roughened channel rock ramps is critical for evaluating their effectiveness as fish passage structures. At the Bozeman Fish Technology Center (BFTC), an experimental flume was used to test an experimental rock ramp under varying flow and slope conditions. While volitional swim trials with white sucker and longnose dace will provide direct data on passage efficiency, detailed hydraulic measurements can be used to characterize the conditions fish experience and relate specific hydraulic metrics to passage performance.

A structured hydraulic data collection plan was developed to assess key parameters, including velocity distributions, depth variations, entrance conditions, and turbulence. Rock ramps create highly heterogeneous hydraulic environments, making it challenging to collect representative data and interpret how different species navigate these conditions. This is particularly important for small-bodied fish, which may exploit different swim paths than larger species.

Hydraulic data collection approaches in previous laboratory studies have varied widely. Some studies have conducted extensive, high-resolution measurements (Baki et al., 2014, 2015; Golpira, 2022), while others have relied on more simplified approaches that assume general flow conditions from a limited number of measurements. This study aimed to strike a balance by

developing a rigorous but efficient methodology to accurately capture hydraulics relevant to fish passage while maintaining feasibility within a reasonable timeframe.

By comparing different hydraulic metrics to fish passage data from the swim trials, this study aims to provide valuable insights into the effectiveness of rock ramps under different flow conditions. Identifying key hydraulic variables that influence passage will help improve future fishway designs and develop more effective assessment techniques.

Methods

Experimental Flume

The study took place in an indoor open-channel flume (0.91 m wide x 1.37 m deep x 17.46 m long) at the BFTC (Figure 8). The flume consists of seven fiberglass sections, featuring concrete headwater and tailwater boxes. To ensure a near-flat incline while allowing water to drain, the flume was constructed on a slope of 0.83%. Water circulation in the flume was maintained by two non-submersible Prime Vertical Axial Pumps: a 40-horsepower and a 20-horsepower pump. Both pumps can operate simultaneously, providing a flow rate from 0.032 to 0.32 m³·s⁻¹. Water was stored in a 34.07 m³ sump at the downstream end of the tailwater box and was recirculated to the headwater box through a 25.4 cm diameter schedule 40 polymerized vinyl chloride (PVC) pipe.

The hydraulic conditions in the flume were controlled by adjusting the pump outflow and by manipulating the height of the steel tailwater gate (Fresno Downward Opening Weir Gate, Selma, CA). A Signet 2540 paddle wheel flow meter (GF Piping Systems, Schlaffhausen, Switzerland) was installed into the recirculation pipe and recorded instantaneous flow rates. The elevation of the steel tailwater gate, functioning as a downstream weir, was adjusted to set the

water depth in the flume. Fresh water lines that were piped into the flume from nearby warm and cool springs were used to supply the water and flow rate from each was adjusted to control the water temperature.

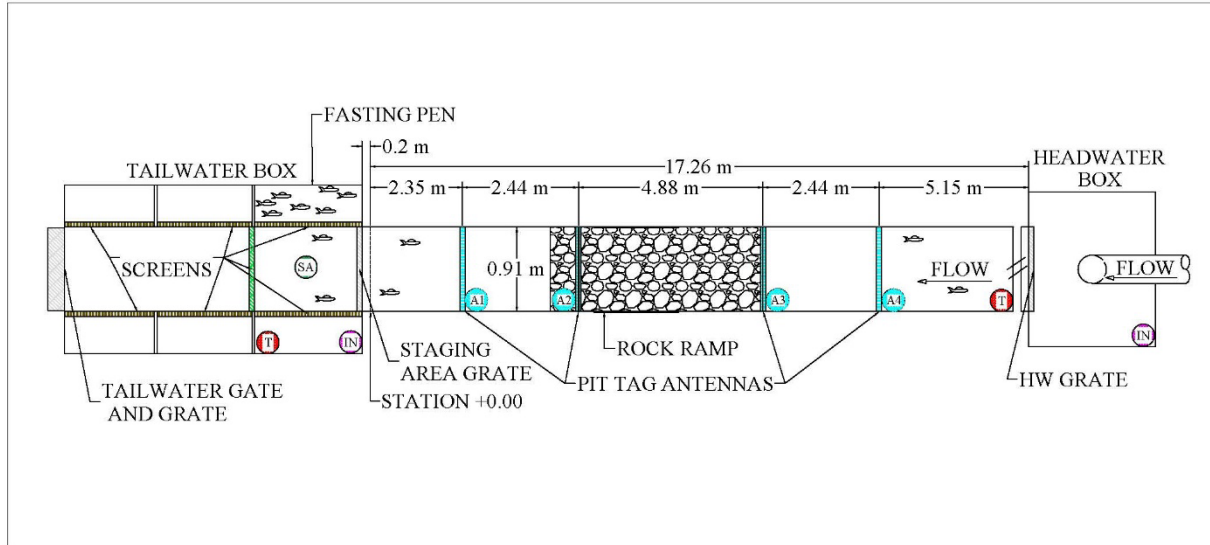


Figure 8: Flume layout schematic. The PIT antenna system is highlighted in light blue, all gates are light gray. IN denotes well inflow locations. T denotes the location of HOBOT water level and temperature sensors. SA denotes the staging area where fish were placed prior to the start of trials. The stationing for antennas starts 0.2 m upstream from the tailwater box.

Hydraulic Data Collection

The ramp was tested at four nominal flow rates at both 3% and 5% slopes (Table 1). Each unique combination of slope and flow rate is referred to as a hydraulic condition (HC). Pump settings for each nominal flow rate were determined after allowing the system to stabilize. The flow rate was adjusted as close to the target value as possible by fine-tuning the pump frequency (Hz). Observations indicated that flow fluctuated approximately $\pm 0.0019 \text{ m}^3/\text{s}$ ($\pm 15 \text{ gpm}$) around the nominal flow rate.

Table 1: Summary of slope and flow rate combinations for each hydraulic condition tested for the hydraulic study and swim trials.

Hydraulic Condition	Slope	Flow Rate (m ³ /s)
HC1	3%	0.0315
HC2	3%	0.0631
HC3	3%	0.0946
HC4	3%	0.1262
HC5	5%	0.0315
HC6	5%	0.0631
HC7	5%	0.0946
HC8	5%	0.1262

Extensive velocity and water depth measurements were collected for HC1-HC8 to gain insight into the hydraulics produced by the rock ramp. However, the scope of data collection for HC5–HC8 was reduced based on insights from HC1–HC4 to ensure the study could be completed within a reasonable timeframe.

The data collected in this study serve several key objectives:

1. Characterize the velocity distributions at each hydraulic condition.
2. Identify the location and magnitude of the maximum velocity within the rock ramp configuration.
3. Determine the distribution and intensity of low-velocity eddies and resting areas.
4. Estimate hydraulic parameters such as Froude Number, Reynolds Number, and Energy Dissipation Factor.
5. Develop rating curves for headwater depth and water depth over the ramp.
6. Establish a standardized, quantitative approach for setting tailwater depths.

7. Define boundary conditions and provide calibration data for 3D hydraulic models in future studies.

Velocity Measurement

Detailed/Reduced Measurement Grid Velocity measurements were collected to characterize the hydraulic conditions within the rock ramp under each test condition. The measurement grid was designed to capture all flow conditions occurring within the ramp. The grid location was selected to ensure fully developed flow within the ramp while avoiding potential tailwater or backwatering effects (Baki et al., 2014). Measurement locations were selected to represent key hydraulic regions, ensuring a comprehensive assessment of the velocity distributions produced by the ramp (Figure 9).

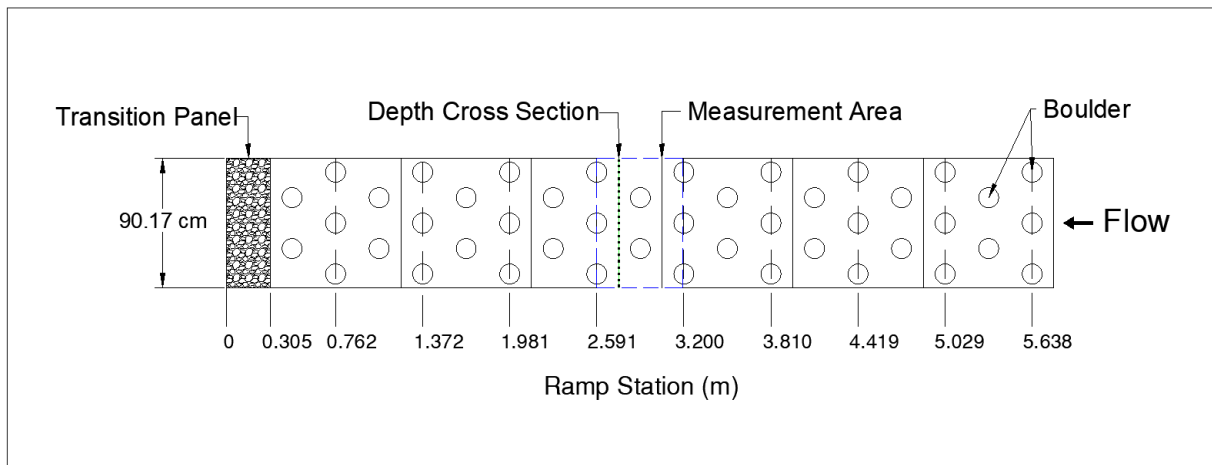


Figure 9: Rock ramp schematic showing hydraulic measurement grid location for velocity and lateral depth measurements.

Velocity was measured at two depths for all locations: the bed of the ramp and at 40% of the total depth from the bed of the ramp (0.4 depth). Bottom velocity measurements were taken

to capture the effects of the gravel substrate, which influences flow resistance, and because benthic and small-bodied fish species often rely on these lower-velocity zones for passage. The 0.4 depth measurements were collected because the velocity at this depth generally approximates the average velocity in open-channel flow (Chow, 1959).

For the 3% ramp, the detailed measurement grid consisted of 107 locations, totaling 214 velocity measurements per hydraulic condition (Figure 10). For the 5% ramp (HC5–HC9), a reduced measurement grid was used to streamline data collection while maintaining coverage of hydraulically significant regions. The number of measurement locations was reduced to 28, with measurements taken at the same two depths, resulting in 56 total velocity measurements per hydraulic condition (Figure 11). Locations for the reduced grid focused on areas where maximum velocities and eddies were expected, such as flow constrictions between boulders and recirculation zones behind boulders.

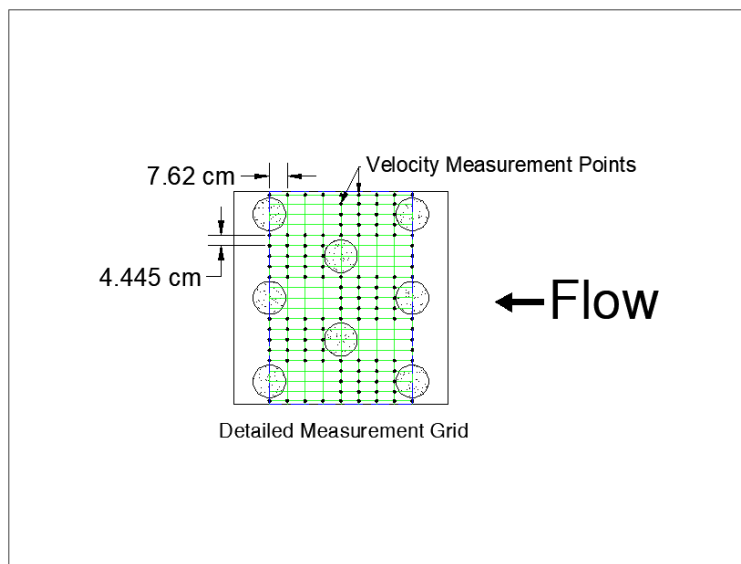


Figure 10: Detailed velocity measurement grid for 3% slope rock ramp.

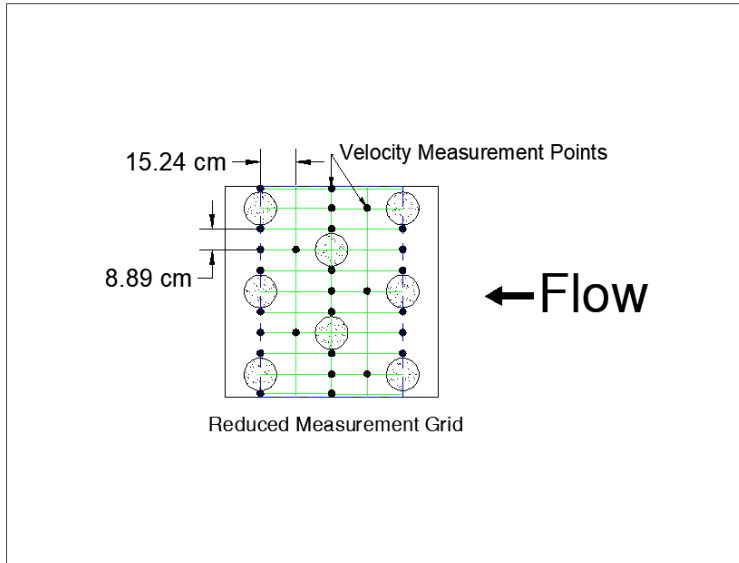


Figure 11: Reduced velocity measurement grid for 5% slope rock ramp.

Measurements were collected using a Hach Flo-Mate velocimeter (Hach Corp., Loveland, CO), with velocity time-averaged over 30 seconds at each location. Water depth was estimated by observing instantaneous fluctuations during the recording period and approximating the average. Due to the size of the velocity probe, velocity could not be measured directly in front of the boulders, limiting insight into localized flow conditions at those points.

Velocity Gradient Maps

Velocity gradient maps were generated using the Detailed and Reduced velocity grid data to visualize the spatial variability of velocities within a representative section of the ramp. For each hydraulic condition, separate maps were created for the bottom and at 0.4 the depth velocity measurements. The maps were produced in R version 4.4.2 using the *akima* and *fields* libraries (R Core team, 2025). Measured velocity data were interpolated onto a 400×400 grid using Kriging, a geostatistical method that estimates values at unsampled locations by weighting

nearby observations based on spatial correlation. A no-slip, zero-velocity boundary condition was applied at all walls, as well as the center, leading and trailing edges, and sides of each perturbation boulder, ensuring that velocities at these interfaces were zero. While direct measurements immediately in front of boulders were limited by probe size, this interpolation method provided a good visual approximation of the complex flow patterns within the roughened channel rock ramp.

Water Depth Measurement

Water depth within the rock ramp was measured using three different methods to obtain a comprehensive understanding of average depth and depth distribution. These methods included depth data from the flow meter, centerline depth measurements, and lateral depth cross-section measurements. While flow meter depth readings provided a general estimate, centerline and lateral depth measurements using a point gauge ensured greater accuracy and were used for hydraulic calculations.

Flow Meter Depth Measurements

Water depth was recorded at each velocity measurement location using the Hach Flo-Mate velocity probe (Figure 10 and Figure 11), which estimates depth based on pressure under the assumption of hydrostatic conditions. However, in the turbulent flow environment of the rock ramp, this assumption may not hold, potentially reducing accuracy. Additionally, the probe rested on top of the gravel substrate and could not measure directly in front of boulders, limiting its ability to capture true depth variations. To obtain more precise depth data, centerline and lateral depth measurements were conducted using a point probe for comparison.

Centerline Depth Measurements

A point gauge was used to measure depth along the centerline (CL) of the rock ramp, ensuring a more accurate representation of depth variation. For the 3% slope ramp, depth was recorded at 72 locations from the upstream to the downstream end at 7.62 cm (3-inch) intervals. Depth was calculated as the difference between the ramp bed elevation and the water surface elevation, with the water surface estimated as the average of the fluctuating levels.

Baki et al. (2014) demonstrated that centerline depth approximates area-averaged depth within 1% error, validating this method for estimating overall ramp depth. Additionally, a comparison of average centerline depth across the full ramp versus depths measured within the detailed measurement grid showed a difference of less than 0.254 cm (0.1 in) for all flow rates. Given this minimal difference, for the 5% slope ramp, centerline depth was measured only within the detailed measurement grid, from one central perturbation boulder to the next downstream boulder.

Lateral Depth Cross-Section Measurements

To validate centerline depth estimates and further characterize depth variability, a lateral depth cross-section was recorded perpendicular to flow across an unobstructed section of the ramp within the measurement area. Depths were measured at the flume edges and then at 4.45 cm (1.75-inch) intervals from 6.35 cm to 85.73 cm (2.5 inches to 33.75 inches) across the width of the ramp (Figure 9).

These measurements allowed for the calculation of bulk velocity, which was used to derive hydraulic parameters such as Reynolds number, Froude number, and energy dissipation factor.

Tailwater Depth Selection Method

Existing rock ramp design guidelines provide little to no guidance on setting tailwater (TW) depth using equations or rating curves. Instead, they offer general recommendations and qualitative criteria, such as ensuring entrance velocities remain below the burst speed of the weakest-swimming species, avoiding high turbulence and aeration zones, maintaining a flow depth at least twice the body depth of the largest target species, and ensuring the transition operates in the streaming flow regime (USFWS, 2019). While these guidelines provide a framework, they lack a standardized, quantitative method for determining TW depth that satisfies these criteria.

If the TW depth is too low, the transition from the steep sloped rock ramp with large roughness elements to the smooth flume floor can create a drawdown effect, accelerating flow and reducing depth (plunging). This can also lead to a hydraulic jump downstream of the ramp entrance, where the supercritical flow abruptly transitions back to subcritical flow, generating high turbulence and aeration that may act as a barrier to fish passage.

Increasing the TW depth applies backpressure, smoothing the transition from the ramp to the pool, and allowing for a more gradual velocity reduction (streaming flow). However, excessive TW depth can backwater up the ramp, altering its internal hydraulics and complicating inferences about fish passage across its full length.

The goal was to establish a TW depth that ensured a streaming flow transition while minimizing backwatering effects, allowing the swim trials to accurately represent passage conditions throughout the entire ramp. The selected TW depths from this method can serve as a minimum depth requirement for similar applications and ramp designs. To achieve this, a

standardized procedure was developed for determining the TW depth for each experimental condition:

1. Lower the TW gate until visible plunging flow occurs at the transition between the ramp and the flume. This ensures that backwatering of the ramp is eliminated.
2. Measure depth and velocity (at 40% of total depth) between the boulders at ramp station 0.762 m (2.5 ft) (teal Xs in Figure 12).
3. Measure depth and velocity between the boulders at ramp station 1.372 m (4.5 ft) (orange squares in Figure 12).
4. Compare the average depth and velocity at these two stations with the corresponding measurements from the detailed measurement grid (grey dots in Figure 12), which characterize the internal hydraulics of the ramp under steady conditions and hereafter are referred to as the “reference depths and velocities”.
5. If the depth at station 0.762 m is lower than the reference depths or if velocity is higher than the reference velocities, raise the TW gate by 0.635 cm (0.25 in) and repeat steps 2–4.

Once the depth at station 0.762 m exceeds the reference depths and velocity is lower than the reference velocities, TW depth is considered sufficient to prevent an entry barrier more challenging than the internal ramp hydraulics. Finally, the water surface at the downstream end of the ramp was visually inspected to ensure a streaming flow transition and that no backwatering extends beyond ramp station 1.372 m.

The measurement locations at stations 0.762 m and 1.372 m were chosen because they represent the highest velocity regions within the rock ramp. Additionally, station 0.762 m

aligns with the entry pit antennae, allowing for direct assessment of entry conditions relative to fish movement data, discussed in Chapter 4.

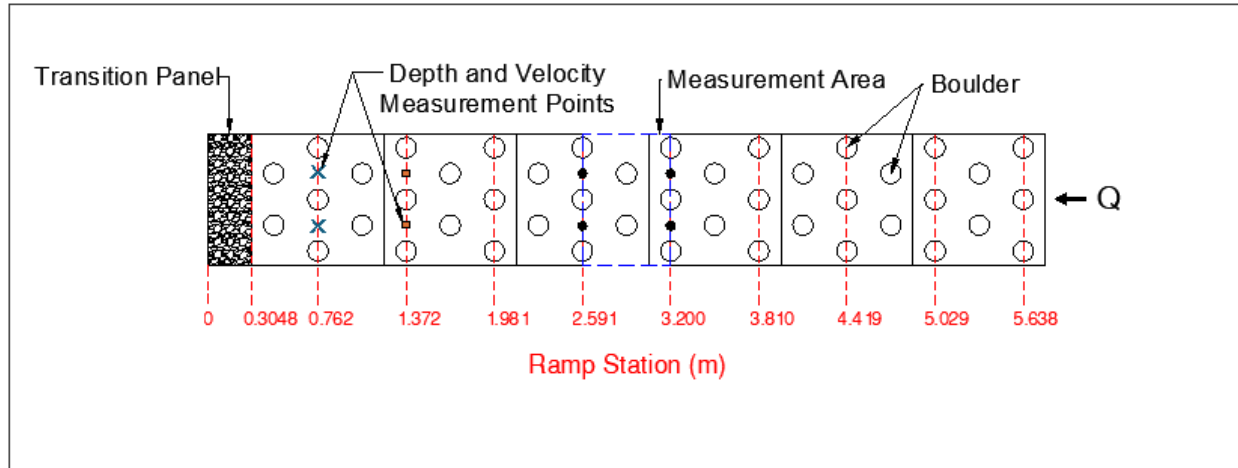


Figure 12: Tailwater depth selection measurement points.

Fishway Entrance Velocity Cross-Section

At ramp station 0.3048 m (where the transition panel meets the first rock ramp panel), a velocity cross-section was measured to characterize the entrance velocity conditions of the ramp. Measurements were taken at 21 locations across the width of the flume, at the flume edges, as well as at 7.62 cm intervals from 5.7 cm to 85.7 cm, at both the bottom and 40% of the total depth. Additionally, velocity was measured 0.75 m downstream of the ramp centerline at both depths to characterize the entrance pool velocities, and the pool depth was recorded using the flowmeter.

Additional three-dimensional velocity measurements were collected using an Acoustic Doppler Velocimeter (ADV) (FlowTracker 2; SonTek, San Diego, California) at five strategically selected locations along the cross-section. Measurements were taken at lateral stations 0.102 m, 0.279 m, 0.457 m, 0.635 m, and 0.768 m, corresponding to the middle of the gaps between or

behind the final row of boulders. ADV measurements were recorded at both the bottom and at 0.4 of the total depth to assess turbulence conditions at the ramp entrance. For HC5 and HC6, the 0.4 depth measurements were not recorded because the depths were too shallow for the probe to be fully submerged. Sampling periods of 120 seconds were used for ADV measurements, following the recommendations of Baki et al. (2014) to ensure reliable turbulence estimates. The collected 3D velocity data were used to calculate turbulence metrics, serving as estimates of entrance turbulence for each hydraulic condition.

Results and Discussion

Velocity Measurement

Velocity distributions generally increase with flow rate, and average velocities were higher on the 5% ramp than on the 3% ramp for the same flow rate. However, a wide range of velocities were present within the ramp for all hydraulic conditions (Table 4 and Figure 13).

Table 4: Summary statistics of velocity measurements within the experimental rock ramp for HC1-HC8. Mean velocity is presented as the average $\pm$ one standard deviation (cm/s). Data for HC1–HC4 include all 214 measurements from the detailed velocity grid, while HC5–HC8 include all 54 measurements from the reduced velocity grid.

HC	Mean Velocity (cm/s)	Median Velocity (cm/s)	Min Velocity (cm/s)	Max Velocity (cm/s)
1	35 $\pm$ 18	36	-13	70
2	51 $\pm$ 20	53	-12	94
3	65 $\pm$ 26	66	-21	116
4	75 $\pm$ 33	73	-20	129
5	54 $\pm$ 21	61	-2	90
6	67 $\pm$ 22	70	15	108
7	83 $\pm$ 25	82	35	134
8	93 $\pm$ 32	90	5	146

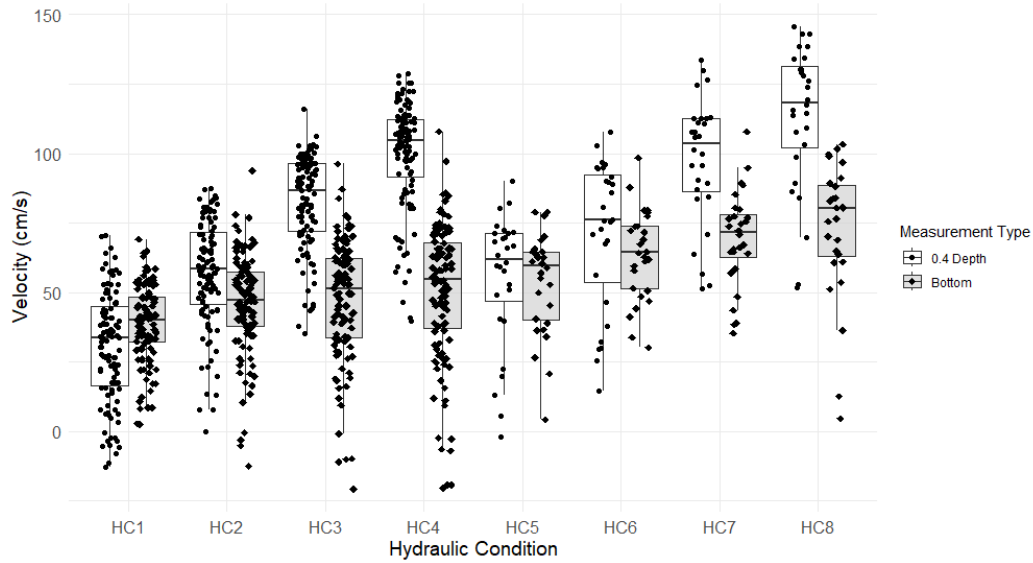


Figure 13: Distributions of streamwise velocities measured within the rock ramp for each hydraulic condition. The 3% ramp velocity distributions contain all 214 measurements taken from the detailed measurement grid. The 5% ramp velocity distributions contain all 56 measurements taken from the reduced measurement grid. Each measurement point is symbolized by its depth location overlayed on box-and-whisker plots depicting summary statistics.

All hydraulic conditions on the 3% ramp included velocities below 0 cm/s, indicating the presence of resting refugia. While some low-velocity measurements were still recorded on the 5% ramp, their frequency decreased as flow rate increased. However, the reduced measurement grid for the 5% slope, particularly the lack of data points directly behind perturbation boulders, may have contributed to the absence of near-zero velocity recordings. These low-velocity areas may still exist but were not captured by the reduced measurement grid dataset.

For both slopes, lower flow rates exhibited a more even distribution of high and low velocities at both the bottom and 0.4 depth. As flow increased, velocities measured at 0.4 depth rose more noticeably, while bottom velocities remained relatively consistent across flow rates. Although 0.4 depth is typically used to represent the same relative position in the water column, the hydraulic environment within the rock ramp changes with depth. At higher flows, increased

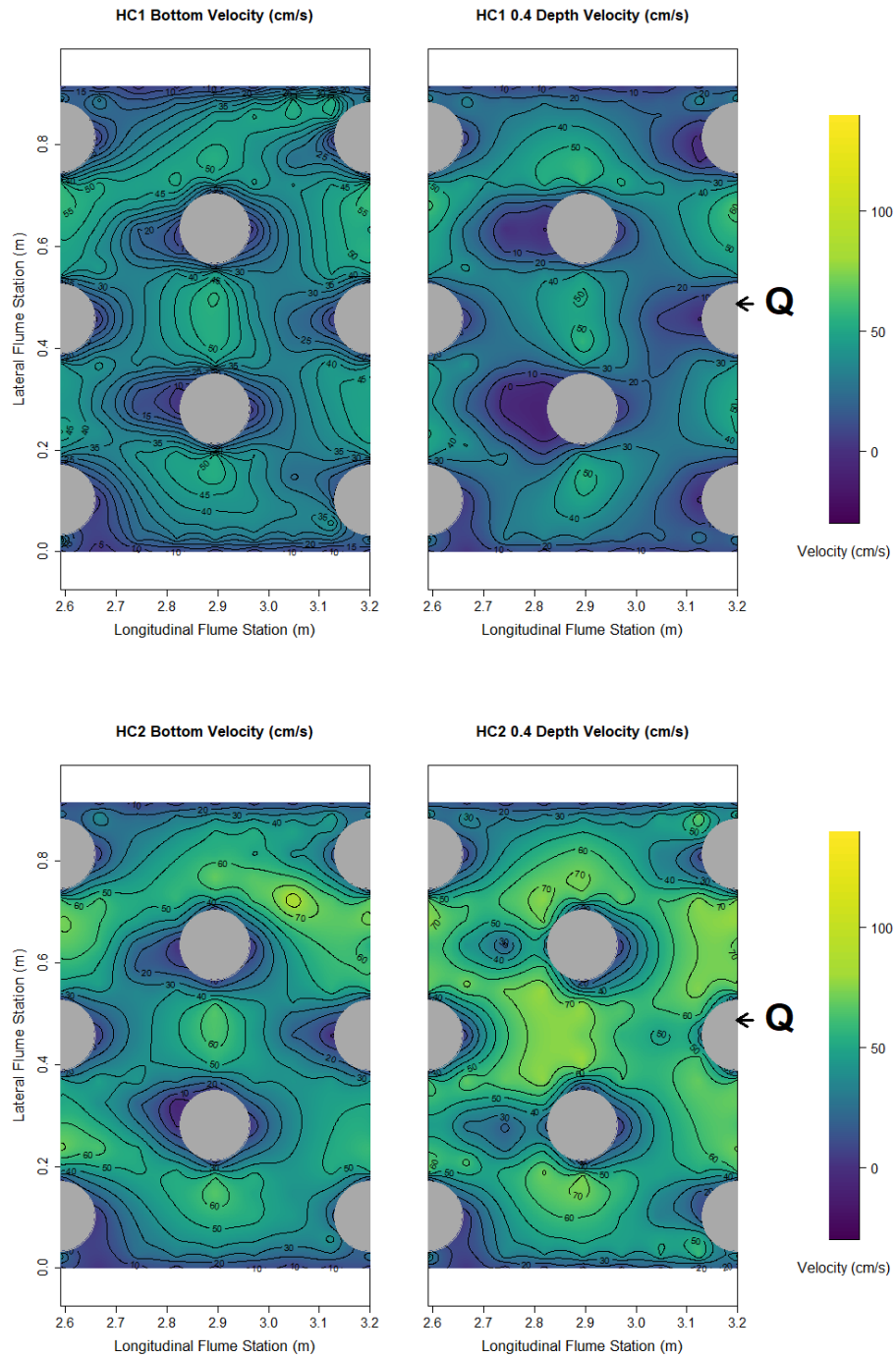
water depth causes flow to transition from a wake interference regime to a more uniform streaming flow over the boulders. As a result, 0.4 depth measurements increasingly capture the faster skimming flow above the boulders, leading to higher recorded velocities despite maintaining the same relative depth.

The similarity between mean and median velocities across all HCs suggests velocities were roughly normally distributed. However, Figure 15 reveals that a substantial proportion of velocity measurements fall outside the interquartile range (IQR), indicating significant variability. This variability highlights the limitations and potential pitfalls of using only average velocity metrics, even when accompanied by standard deviation or IQR, to draw conclusions about fish passage. Unlike conventional swim studies, which typically feature uniform or gradually changing velocities, fish navigating this ramp encounter highly heterogeneous flow conditions. Consequently, fish likely utilize different swimming strategies and behaviors, making assumptions based solely on average velocities potentially misleading.

To evaluate the accuracy of the reduced measurement grid, velocity estimates from the detailed grid used for the 3% ramp were compared to a subset of the same dataset, containing only the points selected for the reduced grid. On average, the reduced grid produced average velocity estimates 6.9 ± 1.1 cm/s higher than the detailed grid, corresponding to an 11% overestimation. This suggests that the reduced grid is a viable method for reducing sampling effort, but some caution should be taken when interpreting velocity data, as it may slightly overestimate flow conditions. This overestimation is likely due to the limited number of measurements taken in low-velocity regions directly in front of and behind the perturbation boulders.

Velocity Gradient maps

The velocity gradient maps illustrate potential swim paths, resting areas, and the maximum velocities fish must overcome (Figure 14 and Figure 15). While not exact due to interpolation between discrete measurement points, some closely spaced and others with larger gaps, these maps provide a useful visual representation of the diverse velocities produced by a roughened channel rock ramp.



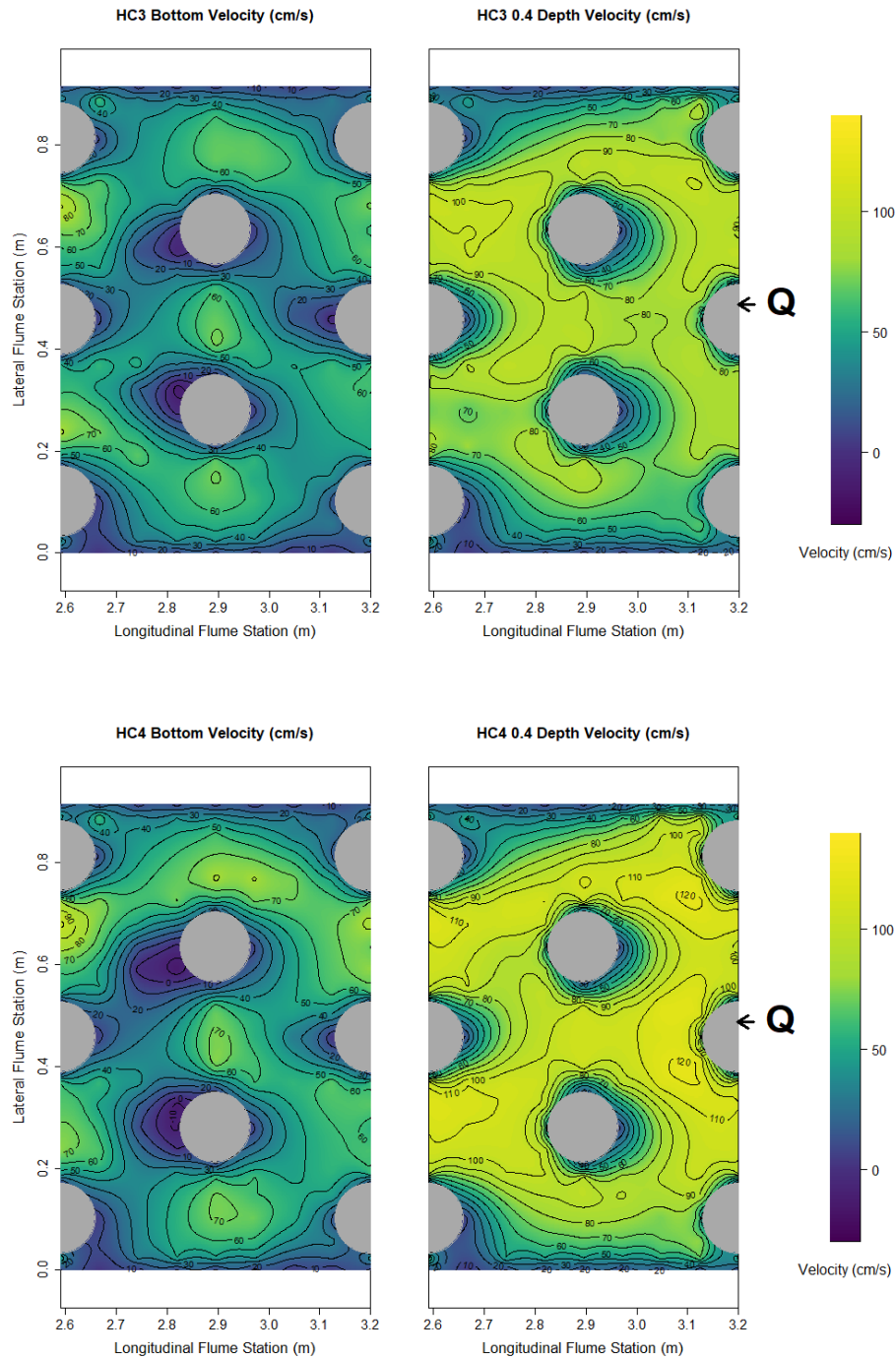
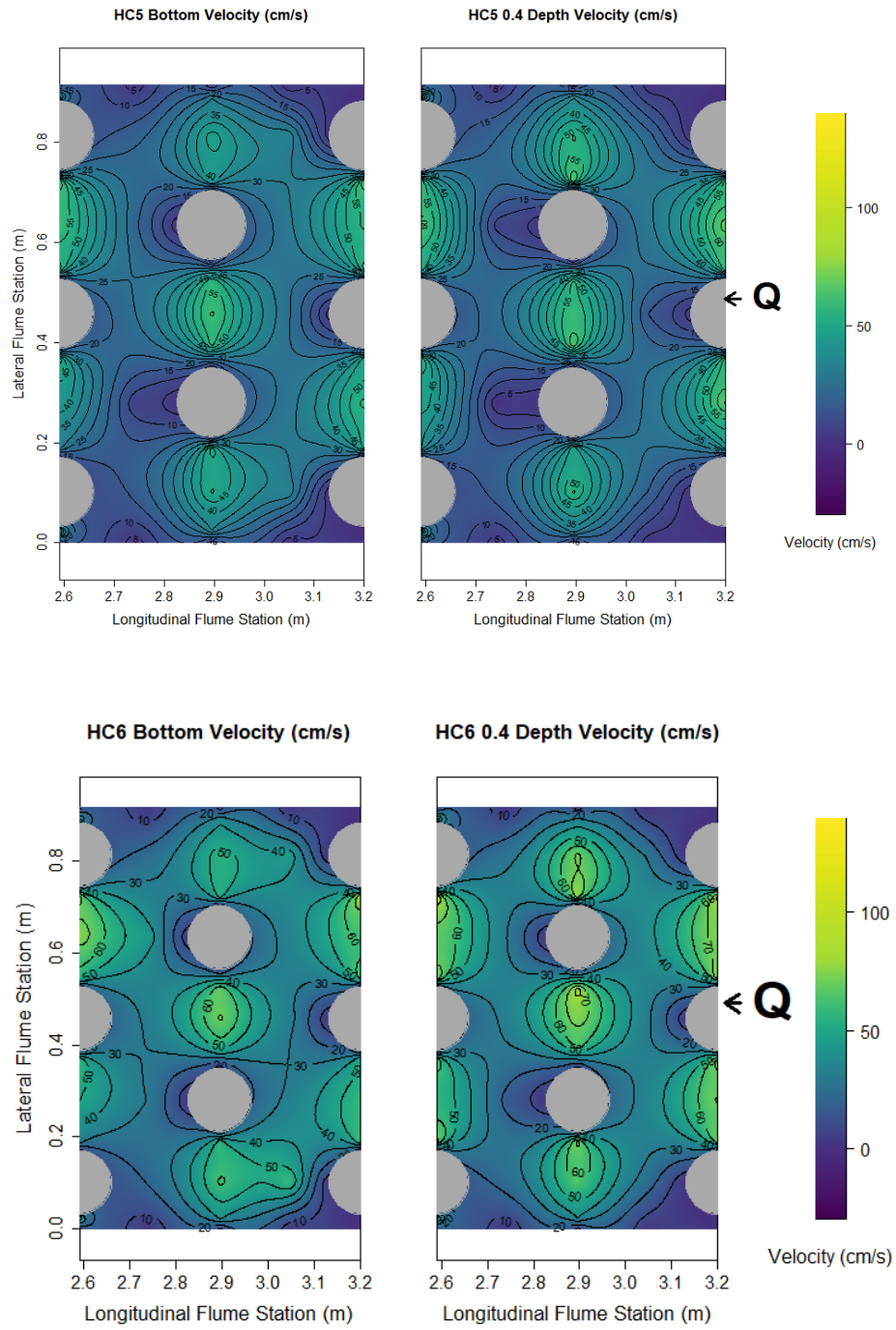


Figure 14: Velocity gradient maps for the 3% slope rock ramp using the detailed measurement grid data. Each row represents a different flow rate. The left column displays interpolated velocities on the bed of the ramp, while the right column shows interpolated velocities at 0.4 of the total depth. Gray circles indicate the approximate size and location of the perturbation boulders. Flow direction is from right to left.



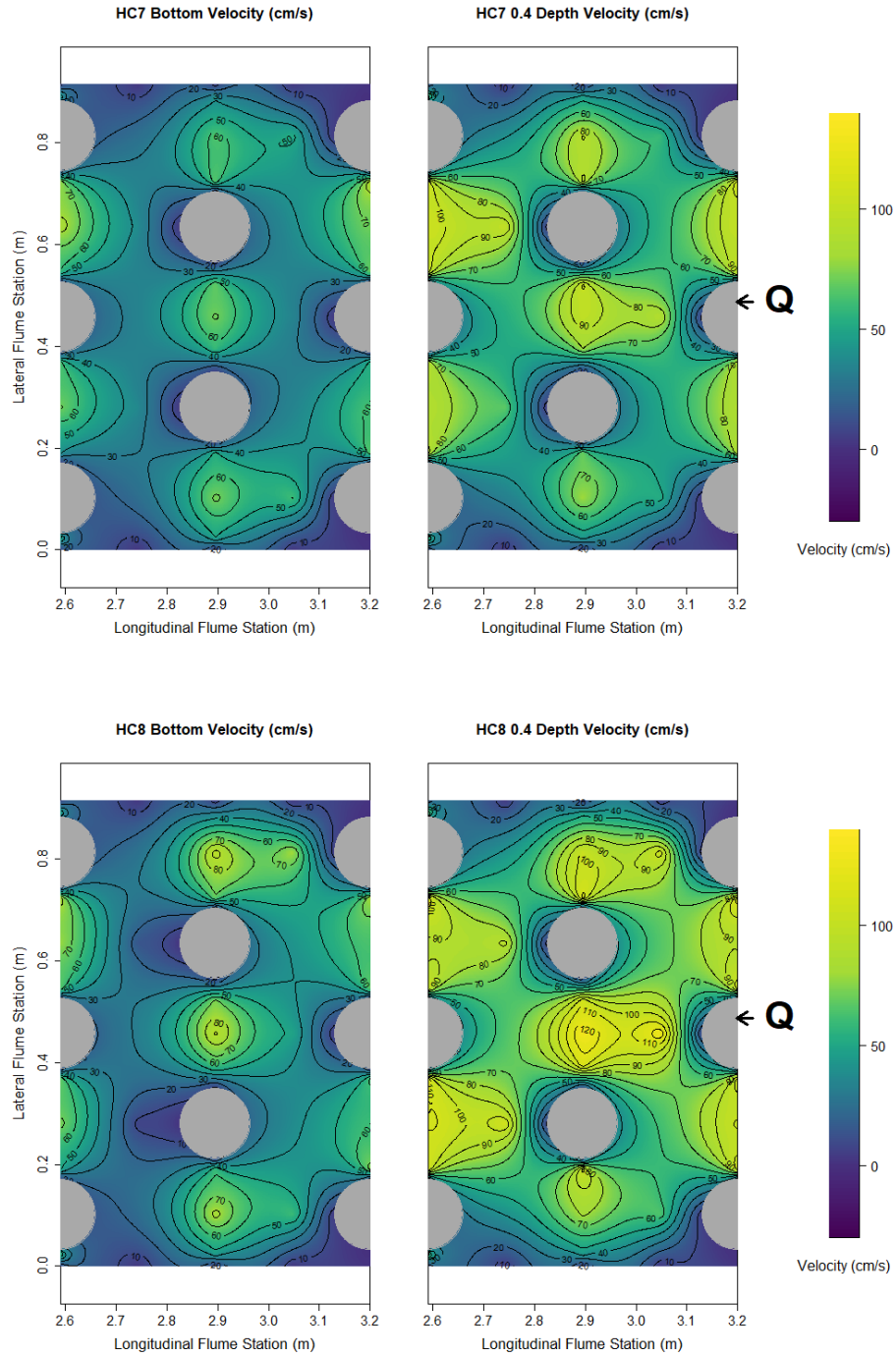


Figure 15: Velocity gradient maps for the 5% slope rock ramp using the reduced measurement grid data. Each row represents a different flow rate. The left column displays interpolated velocities on the bed of the ramp, while the right column shows interpolated velocities at 0.4 of the total depth. Gray circles indicate the approximate size and location of the perturbation boulders. Flow direction is from right to left.

The coarser sampling grid reduced resolution for the 5% slope plots (Figure 15), but the maps still illustrate the location and magnitude of maximum velocities and eddy structures and offer a detailed picture of the flow environment.

Bottom velocities were lower than 0.4 depth velocities for all hydraulic conditions except HC1. Additionally, velocities at 0.4 of the total depth increased more with higher flow rates than the bottom velocities, as also shown in Figure 13. This indicates that as flow rate increases, the rock ramp continues to provide lower velocity conditions near the bottom, which small-bodied and benthic fishes can use for passage, demonstrating its effectiveness across a broad range of flow rates. However, larger-bodied fish may be less able to take advantage of these lower velocity zones and will need to navigate higher velocity regions to ascend the ramp. The highest velocities occurred between perturbation boulders where the flow area is minimized. These regions likely represent the most significant areas for fish passage and should be analyzed in comparison to target species sprint swimming capabilities to determine if passage issues may exist.

The velocity gradient maps also verified the presence of eddies behind the perturbation boulders, which create low velocity and recirculating flow areas. These low-velocity zones were most prevalent near the bed and persisted across all hydraulic conditions tested. However, most eddies still contained positive velocities and were relatively small in scale, ranging from ten to twenty centimeters in length. Small-bodied fish may be able to use these areas for refuge, but they are too small to provide effective resting zones for larger fish. Additionally, these maps only represent streamwise velocity and do not account for potential downward or lateral velocity components, which could further impact their suitability as resting areas. The area directly

downstream of the boulders is highly turbulent, meaning that even though streamwise velocity appears low, these zones may not function as true velocity refuges, particularly for small-bodied fish (Golpira, 2022).

These plots illustrate the edge effects caused by the flume walls, as evidenced by significantly lower velocities near the lateral boundaries. These edge effects result from the frictional resistance at the water-wall interface, creating hydraulics that differ from those produced solely by the rock ramp configuration. Consequently, hydraulic conditions near the flume edges are not fully representative of natural rock ramp conditions without wall interference. These edge-effect regions could have implications for the swim trial results, particularly for the small-bodied longnose dace, which may utilize these areas for resting or passage (further discussed in Chapter 4). However, the rectangular or trapezoidal cross-section of any roughened channel rock ramp will have an edge region where small-bodied fish could similarly benefit from lower velocity zones and have been observed doing so (Brittain et al., 2022). Nonetheless, velocities observed in the center of the flume are less affected by these boundary effects and therefore provide a more representative depiction of hydraulics generated by the ramp configuration. Additionally, variations in velocities between gaps among the perturbation boulders indicate the natural heterogeneity inherent to the rock ramp design and gravel substrate, underscoring the realistic complexity of the hydraulic environment created by the experimental ramp.

The average depth and velocity from the detailed measurement grid were used to calculate flow rates using continuity (Equation 1). The estimated flow rate from the measured data could then be compared to the nominal flow rate to assess its accuracy in capturing all the flow

conditions within the ramp. For HC2-HC4, average bottom velocities underestimated the flow rate in the ramp, while average velocities at 0.4 total depth overestimated it. However, when using only the reduced grid measurements, bottom velocities also overestimated the flow rate obtained from Equation 1. In this equation, Q represents flow rate ($\text{m}^3 \cdot \text{s}^{-1}$), V is the average measured velocity ($\text{m} \cdot \text{s}^{-1}$), and A is the cross-sectional flow area, calculated as the product of average measured depth and flume width.

Equation 1: $Q=VA$

For the 5% ramp, velocities at 0.4 total depth also overestimated the flowrate, similar to the 3% ramp. Additionally, for HC5 and HC6, bottom velocities overestimate the flow rate in the ramp. However, for HC7 and HC8, bottom velocities underestimated the actual flow rate, despite using the reduced sampling method. This further demonstrates that using 0.4 total depth velocity as a proxy for average velocity, as is common in uniform open-channel flow, does not accurately estimate flow conditions in a roughened channel rock ramp. This is likely due to the large roughness elements, where the perturbation boulders are similar in scale to the total flow depth, significantly disrupting uniform velocity distributions. Combining both depth measurements and weighting them evenly or using a 25/75 bottom-to-top ratio did not consistently improve flow rate estimates. These results emphasize the challenge of accurately characterizing velocities in a rock ramp fishway, as capturing the full range of hydraulic conditions requires many measurements across different locations and depths.

Water Depth Measurements

Average depth estimates were consistent between centerline (CL) and lateral depth measurement techniques, with minimal variation between the two methods. However, depth measurements taken with the velocimeter were consistently lower than those recorded using a point probe. This discrepancy is likely due to the velocimeter resting on top of the gravel substrate, whereas the point probe was able to measure water depth within the gaps between the bed substrate.

Centerline Depth

The average difference between the lateral cross-section depth and the centerline depth was 1% for the 3% slope and 5% for the 5% slope, indicating the reliability of both methods for estimating the water depth within the rock ramp. To further refine the depth estimate, the two measurements were averaged for each hydraulic condition, assuming this approach minimizes individual measurement errors. Figure 16 shows the relationship between the averaged depth (H cm) and flow rate ($Q \text{ m}^3/\text{s}$) for both ramp slopes, with power functions fitted to the data.

- 3% slope: $H = 37.292Q^{0.3283}$ ($R^2 = 0.9837$)
- 5% slope: $H = 32.383Q^{0.3345}$ ($R^2 = 0.9899$)

While these regression models provide a useful predictive tool for estimating depth under varying flow conditions, caution should be exercised when applying them beyond the tested measurement range.

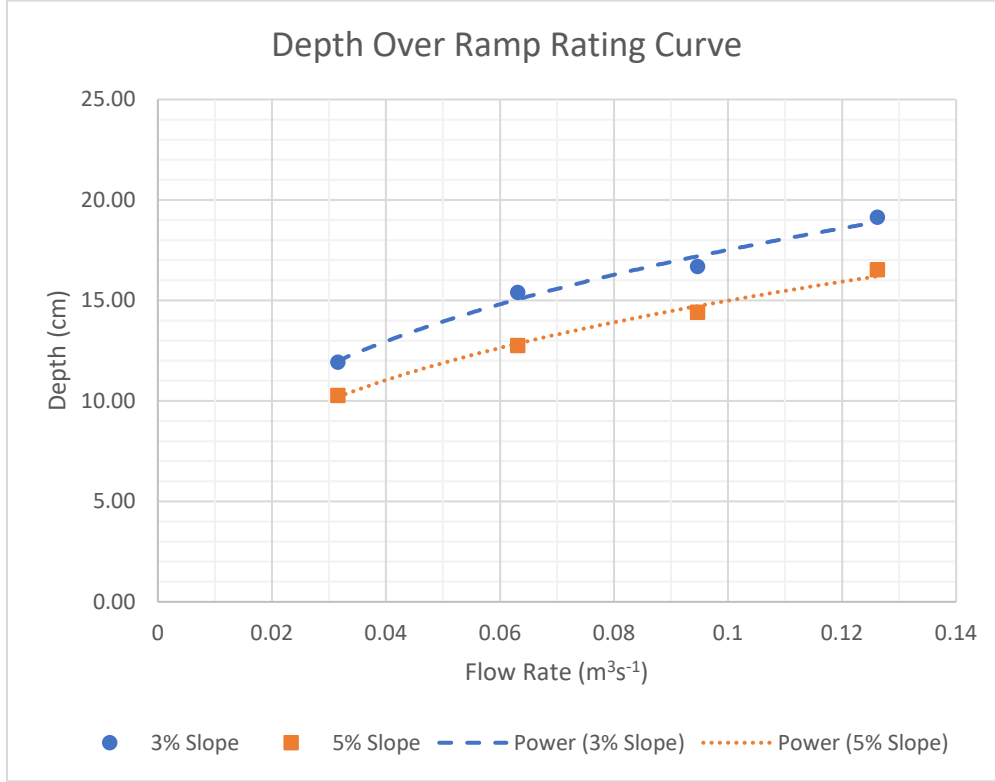


Figure 16: Depth rating curves for the 3% and 5% slope rock ramps, showing the relationship between flow rate and depth. Depths are averages from the lateral depth and centerline depth measurements. Points were fitted with power functions shown.

Lateral Depth

Average depth estimates from the lateral depth cross-section were used to calculate bulk velocity (V_{bulk}) by rearranging the continuity equation (Equation 1). These bulk velocity estimates were then used to compute hydraulic metrics, including the Froude number

($Fr = V_{bulk} / \sqrt{g \cdot H_{avg}}$), Reynolds number ($Re = V_{bulk} \cdot R / \nu$), and energy dissipation factor

($EDF = \gamma \cdot V_{bulk} \cdot S_0$) (Table 2). Here g is gravitational acceleration, H_{avg} is the mean depth from the lateral cross section, R is hydraulic radius, ν is the kinematic viscosity of water at 10°C, γ is the specific weight of water, and S_0 is the ramp slope.

Table 2: Summary of hydraulic variables calculated for each hydraulic condition, using V_{bulk} calculated from the lateral depth cross-section.

HC	Flow Rate (m ³ /s)	Mean Depth (cm)	V_{bulk} (cm/s)	Fr	Re	EDF (kg·m/m ³ ·s)
3% Slope						
1	0.0315	12.0 (10.4-13.5, 0.8)	28.7	0.27	20,890	8.6
2	0.0631	15.3 (12.3-17.3, 1.1)	45.1	0.37	39,517	13.5
3	0.0946	16.5 (14.3-18.2, 1.1)	62.8	0.49	58,154	18.8
4	0.1262	19.1(16.3-21.3, 1.4)	72.2	0.53	74,378	21.6
5% Slope						
5	0.0315	10.3 (8.1-11.6, 0.8)	33.5	0.33	21,519	16.7
6	0.0631	12.4 (10.7-14.6, 1.1)	55.8	0.51	41,506	27.9
7	0.0946	13.5 (9.1-16.5, 2.0)	76.5	0.67	61,075	38.3
8	0.1262	16.3 (12.7-19.3, 1.8)	84.4	0.67	77,733	42.2

Note: The Reynolds number (Re) and the Froude number (Fr) are dimensionless. Mean Depth is presented as the mean (range, ± 1 standard deviation).

Differences between estimated V_{bulk} and average measured velocities ranged from 3.3 to 20.9 cm/s across all hydraulic conditions, translating to errors of 5% to 38%, with the average measured velocity consistently higher. The greatest discrepancies between these two velocities occurred at the lowest tested flow rates on both slopes. Despite this, using average measured depths and velocities to calculate flow rates through continuity ($Q = VA$) consistently resulted in significant overestimations (between 5% and 63%). Therefore, V_{bulk} was selected for calculating hydraulic metrics since it provided a consistent, continuity-based estimation across all experimental conditions.

The Froude number provides insight into flow regime. For all hydraulic conditions, Fr remained below 1, indicating subcritical flow. Subcritical flow is the lower energy state of flow in an open channel and is generally favorable for fish passage, as it minimizes excessive turbulence and extreme velocity gradients.

All HCs were in the turbulent regime ($Re > 2,500$) as expected. Re increased with flow rate and showed a slight increase at the higher slope for the same flow rate, though the difference was minimal. However, using Re calculated from bulk velocity may not be a particularly useful metric for assessing fish passage in a roughened channel rock ramp, especially for small-bodied fish. While it provides a general indication of turbulence within a cross-section, it does not offer insight into the location, scale, or structure of turbulence—all of which influence how fish of different sizes experience and respond to hydraulic conditions. For example, small fish may be more affected by localized high-energy vortices, while larger fish may be able to navigate through them with less difficulty. Consequently, additional turbulence metrics, such as turbulent kinetic energy (TKE), turbulent length scale, vorticity, or Reynolds shear stress, may provide a more detailed understanding of the turbulent structure and its impact on fish movement.

Compared to the rock ramp tested by Baki et al. (2014) with similar-sized boulders but slightly different spacing, the ramp in this study produced lower Reynolds number (Re) and Froude number (Fr) values for comparable slope and flow rate conditions. However, these differences could be attributed to variations in flow rates and the methods used to estimate depth and velocity. A key distinction between the two studies is that this model included a gravel substrate, which may have contributed to lower Re and Fr values by increasing boundary roughness and reducing overall velocities near the bed.

The energy dissipation factor (EDF) is a metric commonly used to assess meso-scale turbulence and air entrainment in fishways, most used for sizing resting pools in conventional designs (Towler et al., 2015; USFWS, 2019). Towler et al. 2015 introduced a modified version of the equation for baffled chute fishways, emphasizing the dissipation rate produced by a fishway,

the calculation of which is conceptually similar to stream power. While EDF has been widely applied in traditional fishway designs, its use in characterizing turbulence in rock ramps is largely unexplored. Maximum recommended values exist for salmonids ($<20 \text{ kg}\cdot\text{m}/\text{m}^3\cdot\text{sec}$) and American Shad (*Alosa sapidissima*, $<15.68 \text{ kg}\cdot\text{m}/\text{m}^3\cdot\text{sec}$); however, specific criteria for other taxa have not yet been established (Ficke, 2015; Haro et al., 2008). In this study, EDF increased with both flow rate and slope, with higher values recorded for the 5% ramp, indicating greater turbulence and energy dissipation at steeper slopes.

Fishway Entrance Conditions

The tailwater depth determination method, which compared entrance velocities and depths to those within the ramp, effectively ensured a streaming flow transition into the tailwater pool. This method kept entrance velocities and depths within the range of hydraulic conditions present in the ramp, avoiding extreme entrance conditions that could hinder fish passage. As a result of the selected tailwater depths, entrance velocities remained below the prolonged swim speed of longnose dace and white sucker for all hydraulic conditions (Jones et al., 1974; Richer et al., 2020).

The resulting entrance conditions contributed to high entrance efficiencies for both species, discussed in Chapter 4, highlighting the effectiveness of the tailwater pool depths used. Additionally, this method ensured that the ramp was minimally backwatered, meaning flow conditions within the ramp were representative of its entire 5.49-m length. This validation allows the results of the swim trials to be reasonably inferred across the full ramp, providing reliable insights into fish passage performance.

Table 3: Tailwater pool depths 0.75 m downstream from the ramp entrance selected for each hydraulic condition to ensure a streaming flow transition from the rock ramp while minimizing backwatering.

HC	TW Pool Depth (cm)
1	20.0
2	23.0
3	26.0
4	28.0
5	18.5
6	22.0
7	24.0
8	30.5
9	31.5

HW Rating Curve

The depth of the upstream pool (H_{HW}) increased with flow rate (Q) in an approximately linear relationship (Figure 17). The relationship for each ramp slope was described by the following linear regression models:

- 3% slope: $H_{HW} = 101.92Q + 27.458$ ($R^2 = 0.994$)
- 5% slope: $H_{HW} = 106.67Q + 34.545$ ($R^2 = 0.9939$)

These equations provide practical estimates for headwater depth under varying flow conditions. However, caution should be exercised when applying them beyond the tested measurement range.

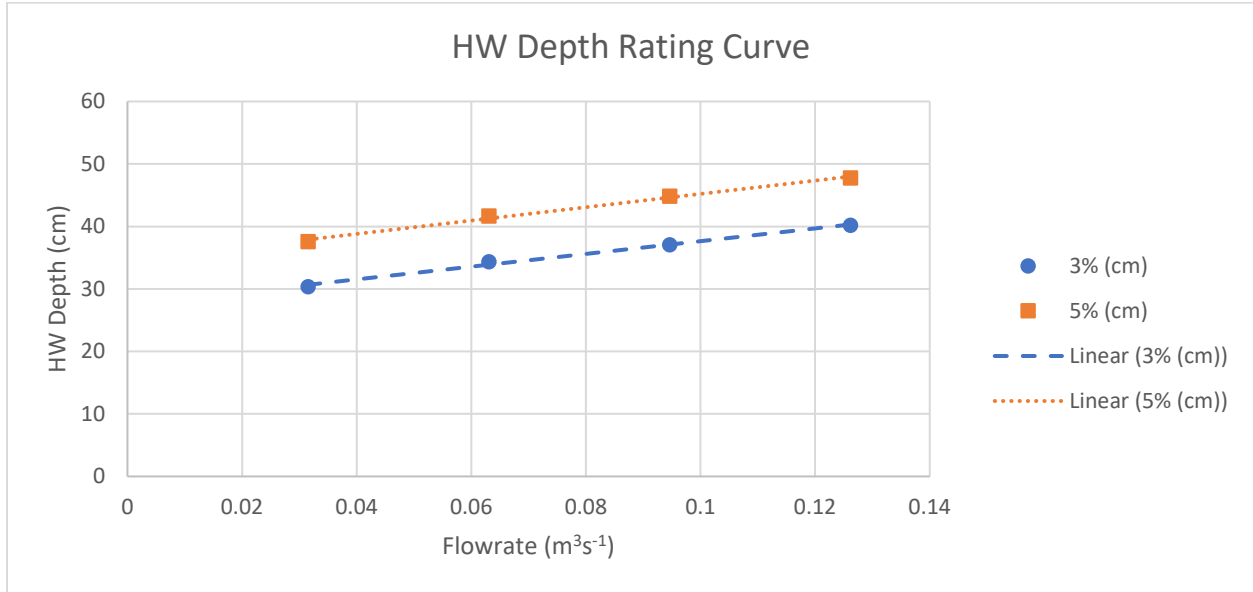


Figure 17: Headwater depth rating curve showing the relationship between flow rate and headwater pool depth for the 3% and 5% ramp slopes. Linear trendlines are fitted to the data for both slopes.

Turbulence

Turbulence kinetic energy (TKE) at the fishway entrance generally increased with flow rate (Figure 18). However, the values measured at the entrance represent an average of the sampled points rather than a complete characterization of turbulence at the entrance of the ramp. Given the variability in flow conditions, these discrete measurements provide only a limited snapshot of turbulence levels rather than a comprehensive assessment of the hydraulic environment experienced by fish. Flow conditions vary significantly at fine spatial scales, with turbulence intensity, eddy structures, and shear layers fluctuating dramatically around perturbation boulders and velocity refuges (Golpira, 2022). Because turbulence is inherently three-dimensional and highly dynamic, localized measurements at a few discrete points fail to capture the full range of hydraulic conditions present in the ramp.

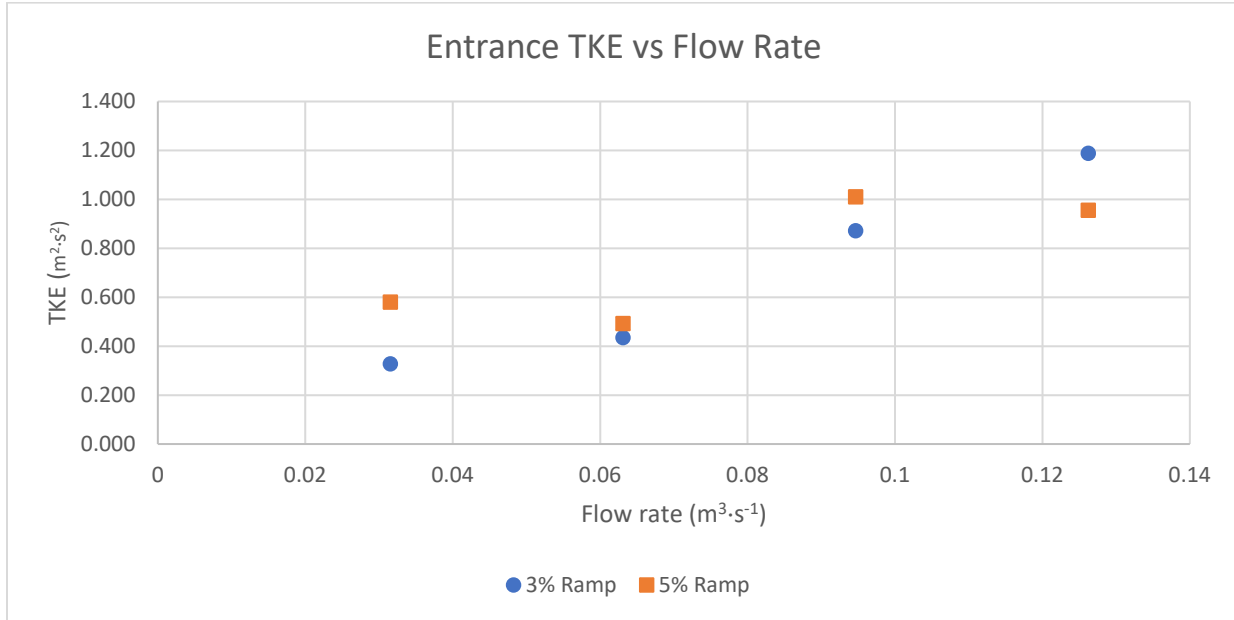


Figure 18: Average TKE measured at the entrance of the rock ramp for each flow rate. Data points represent the average of ten discrete measurement locations.

This limitation suggests that direct turbulence measurements in roughened channel fishways may not provide meaningful insights into fish passage conditions, particularly when trying to relate hydraulic features to fish movement. The highly variable nature of turbulence in these systems means that individual measurement points may not accurately reflect the conditions fish experience. More comprehensive approaches, such as CFD modeling or dense measurement grids, may be necessary to better understand turbulence dynamics and their effects on fish passage. These findings reinforce the need for more robust methodologies when assessing turbulence in nature-like fishways.

Conclusion

The hydraulics within a roughened channel rock ramp are highly complex and dynamic. A comprehensive hydraulic data collection plan was developed to characterize the flow

conditions at each hydraulic condition (HC) tested during volitional swim trials. This data provides insights into the entrance conditions and inter-ramp hydraulics experienced by fish. The velocity measurements and gradient maps revealed the significant variability in flow velocities within the ramp across all flow rates and locations. These maps identify the high-velocity areas that fish must navigate as well as the low-velocity refugia behind boulders. Key findings include the presence of consistently lower velocities near the bed, which could serve as important passage corridors for small-bodied benthic fish. Additionally, low-velocity zones behind the perturbation boulders remained below 30 cm/s across all conditions, providing potential resting areas. At 40% of the total depth, velocities were higher but remained within a range (≤ 120 cm/s) that may still be passable for larger-bodied, strong-swimming riverine fish.

Efforts to determine an accurate estimate of average velocity within the ramp proved difficult, even with the detailed measurement grid containing 214 velocity measurements. Using averages of the depth and velocity measurements to estimate flow rate resulted in high error. This highlights the inaccuracy of using sparse discrete velocity sampling to characterize velocities within a roughened channel rock ramp.

Depth measurements demonstrated that both lateral and centerline depth measurement techniques produced similar estimates of ramp depth, though lateral depth measurements conceptually provide a more appropriate basis for calculating a bulk velocity (V_{bulk}). Using these depth measurements, hydraulic parameters such as Reynolds number (Re), Froude number (Fr), and energy dissipation factor (EDF) were computed to better understand ramp hydraulics and provide potential indicators of fish passage conditions.

Tailwater (TW) depth selection was found to be a critical factor influencing entrance conditions. Through a systematic approach, TW depths were set and quantitatively verified to produce less challenging conditions at the entrance than within the ramp while minimizing backwatering effects. The TW depths established in this study can serve as a baseline for future laboratory studies and real-world rock ramp installations to optimize entry conditions.

Rating curves for headwater depth, depth over the ramp, and TW pool depth were developed, offering a useful predictive tool for understanding the hydraulic conditions produced by this rock ramp configuration.

Turbulence measurements at the ramp entrance confirmed a general increase in turbulence with both slope and flow rate. However, quantifying turbulence through discrete point measurements was beyond the scope of this hydraulic evaluation. The limitations of this approach emphasize the potential value of computational fluid dynamics (CFD) modeling for a more comprehensive assessment of turbulence effects on fish passage.

Overall, the hydraulic data collected in this study provide valuable insights into how this rock ramp design functions across a range of flow conditions. When paired with passage results, these data will help identify which hydraulic parameters most influence fish movement and passage success. This information can serve as a predictive tool for evaluating passage efficiency in other species and similar rock ramp designs. Additionally, these data can be used to calibrate and validate CFD models, which can further enhance our understanding of roughened channel fishways and improve future design and implementation. CFD modeling holds significant potential for better understanding how turbulence affects fish passage performance, which remains a major challenge in the design of nature-like fishways.

CHAPTER FOUR

EFFECTS OF SLOPE AND FLOW RATE ON WHITE SUCKER
AND LONGNOSE DACE PASSAGE IN A MODEL ROCK
RAMP FISHWAY

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

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Contributions: Provided intellectual contributions, co-authored proposal to secure funding, reviewed manuscript.

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Contributions: Helped form conceptual basis of project, co-authored proposal to secure funding, reviewed manuscript.

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Abstract

Effective fish passage structures are crucial for maintaining connectivity in aquatic ecosystems, improving climate resilience, and supporting fish populations. This study evaluated the passage efficiency of white sucker (*Catostomus commersonii*) and longnose dace (*Rhinichthys cataractae*) over a 5.49-m experimental rock ramp fishway under varying hydraulic conditions. Volitional swim trials were conducted over 21 hours in an open-channel flume at the Bozeman Fish Technology Center. Fish movements and passage efficiencies were tracked using four PIT tag antennas. Nine hydraulic treatments were tested, combining two ramp slopes (3% and 5%) and five flow rates (0.0315, 0.0631, 0.0946, 0.1262, and 0.1893 m³/s). The average participation rate among all trials was 99%. White sucker exhibited consistently high passage success (97%) across all slopes and flow rates. In contrast, longnose dace showed reduced passage success with increased flow, particularly at the steeper 5% slope, where passage rates ranged from 100% at the lowest flow to 0% at the highest flows. Travel-time analysis revealed that white sucker ascended the ramp in a sustained manner, whereas longnose dace ascended using short bursts between velocity refugia. Logistic regression analysis identified fish length, flow rate, and ramp slope as critical predictors of longnose dace passage. Hydraulic measurements provided insight into velocity and depth conditions, reinforcing the importance of designing rock ramps at slopes of 3% or less to accommodate the weakest-swimming species and facilitate passage across diverse flow conditions.

Introduction

Freshwater fishes in North America, are among the most threatened groups of animals due to anthropogenic activities. One of the primary causes of this decline is the loss of longitudinal connectivity in rivers and streams. Aquatic connectivity to diverse habitats is a critical factor for the persistence of many freshwater fish species (Cooke et al., 2005; Ficke, 2015; Perkin & Gido, 2011). Lotic environments are inherently variable across space and time, requiring fish to migrate to access suitable habitat like low-gradient riffles used for spawning and deep pools used for thermal refuge, throughout different seasons and life stages (Bunt et al., 2001; Ficke, 2015). Barriers such as dams, culverts, and water diversions, and associated changes in channel morphology and flow regimes obstruct essential migration pathways and pose a significant threat to the survival of native fish populations if fish cannot access habitats necessary for spawning, feeding, and refugia (Curry & Spacie, 1984; Fausch et al., 2002; Graf, 1999; Larinier, 2000; Perkin & Gido, 2011).

Engineered fishways have emerged as solutions designed to restore fish passage across barriers, reconnect fragmented habitat, and restore the health of ecosystems. Among design alternatives rock ramp fishways have emerged as a newer and increasingly popular type of fish passage structure in part because they use natural materials to mimic stream conditions and are relatively simple to construct (Mooney et al., 2007; USFWS, 2019). Roughened channel rock ramps feature constant, gradual slopes constructed with strategically placed boulders and substrate to create varied hydraulic conditions (Mooney et al., 2007; USFWS, 2019). Such structures offer pathways suitable for diverse fish species, especially those unable to jump or sustain high swimming speeds, while providing cost-effective, durable, and visually appealing

solutions that can also function as grade control or erosion mitigation structures (DVWK, 2002; Mooney et al., 2007; USFWS, 2019). As a result, rock ramps are increasingly common in agricultural landscapes, irrigation infrastructure, and conservation-focused stream management (Anderson, 2022; Ficke, 2015; Jones, 2022; Stuart et al., 2024; Tamario et al., 2018).

The hydraulics of rock ramps are complex and highly dependent on specific design variables such as slope, flow rate, boulder placement, substrate size, and ramp length (Baki et al., 2016; R. Jones, 2022; Paik et al., 2024; Swarr, 2018). While several studies have investigated different rock ramp designs and their hydraulic characteristics, it remains challenging to draw broad conclusions about fish passage because modifications in one design element can significantly alter flow patterns (Baki et al., 2014, 2015, 2016; Cassan & Laurens, 2016; Golpira, 2022; Papanicolaou et al., 2012). Furthermore, accurately characterizing these hydraulic conditions is inherently difficult due to the three-dimensional nature of flow and high turbulence associated with rock ramps (Baki et al., 2015; Golpira, 2022). Additional research is needed to better understand how specific design variables of rock ramps (e.g., slope, flow) interact with the swimming performance of fish, particularly understudied nongame species, across a range of hydraulic conditions. An iterative design process guided by the best available science is essential to optimize fishway performance across diverse species and river systems.

Preserving biodiversity in freshwater ecosystems requires a better understanding of how diverse native fish species interact with fish passage structures, particularly species with weaker swimming abilities. Minnows (Cyprinidae) and suckers (Catostomidae), two widespread but often overlooked North American fish families, play vital ecological roles despite their limited economic recognition (Cooke et al., 2005; Moyle & Cech, 2003). These species represent two

distinct movement ecologies (e.g. physiology, cognition, external drivers and other features described by Cooke et al., 2022 and Nathan et al., 2008) and swimming capabilities. White sucker (*Catostomus commersonii*) and longnose dace (*Rhinichthys cataractae*) are among the most widely distributed species within their respective families, making them useful representatives for studying fish passage. White suckers are benthic, robust-bodied fish capable of strong bursts and are known to undertake seasonal spawning migrations (Bunt et al., 2001; Underwood et al., 2014). Longnose dace, on the other hand, are smaller-bodied, agile fishes that often reside in fast-flowing riffles but have more limited swimming endurance (Dockery et al., 2017; Ficke, 2015).

While the swimming capabilities of these species have been studied, varying testing methodologies significantly affect estimates of swimming performance (Aedo et al., 2021; Dockery et al., 2017; Ficke, 2015; Haro et al., 2004; Jones et al., 1974; Underwood et al., 2014). Forced-swim experiments frequently yield different outcomes than volitional swim trials, suggesting that assumptions based solely on laboratory testing may not reliably represent fish behavior in natural hydraulic environments (Dockery et al., 2017). Additionally, field-based studies on rock ramp fish passage are scarce and often challenging to compare due to differences in rock ramp design, low entry probabilities, seasonal monitoring limitations, and the necessity of tagging or confining fish, which may alter natural behaviors (Anderson, 2022; Ficke, 2015; Fitzpatrick et al., 2023; Stuart et al., 2024). Consequently, conducting controlled, volitional swim tests under realistic hydraulic conditions remains the most accurate approach to evaluating fishway effectiveness across various designs and operational scenarios.

The objective of this study was to test the effects of slope and flow rate in an experimental roughened channel rock ramp fishway for passage of longnose dace and white sucker. The fishway was designed based on established guidelines (DVWK, 2002; Underwood et al., 2014; USFWS, 2019), previous studies (Baki et al., 2014; Brittain et al., 2022; Ficke, 2015; Paik et al., 2024; Swarr, 2018), and CFD modeling (Baki et al., 2016; Golpira, 2022), and installed in the indoor open-channel flume at the Bozeman Fish Technology Center (BFTC). Hydraulic data and passage success was collected for five flow treatments ($0.0315 - 0.1893 \text{ m}^3\text{s}^{-1}$) and two slope treatments (3% and 5%) to allow passage probabilities of longnose dace and white sucker to be estimated over a range of hydraulic conditions and design criteria. Achieving these objectives provided insight into how slope and discharge interact to affect fish passage, the results of which can inform future rock ramp designs, helping to improve passage of target species, restore aquatic connectivity, and support the health of river ecosystems.

Methods and Materials

Fishway layout and Instrumentation

The study took place in an indoor open-channel flume (0.91 m wide x 1.37 m deep x 17.26 m long) at the BFTC (Figure 19). The flume consists of seven fiberglass sections, featuring concrete headwater and tailwater boxes. To ensure a near-flat incline while allowing water to drain, the flume was constructed on a slope of 0.83%.

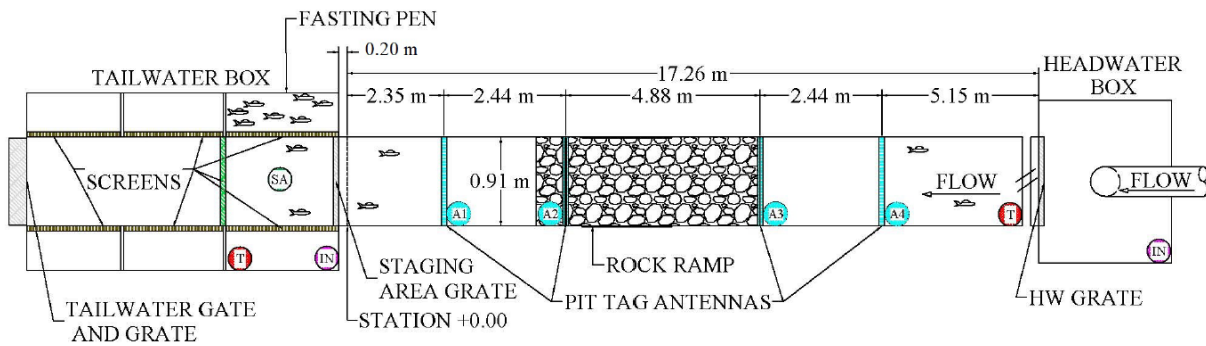


Figure 19: Flume layout schematic. The PIT antenna system is highlighted in light blue, all grates are light gray. IN denotes well inflow locations. T denotes the location of HOBO water level and temperature sensors. SA denotes the staging area where fish were placed prior to the start of trials. The stationing for antennas starts 0.2 m upstream from the tailwater box with a station of +0.00.

The rock ramp was installed in the flume with the downstream end positioned 4.15 m upstream from the staging area. The ramp was 5.49-m long composed of natural boulders and gravel embedded within a 1.9-cm thick layer of mortar. The mortar was supported by a plywood base with protruding screws to enhance mechanical bonding. The ramp consisted of eight precast panels ($91.44 \text{ cm} \times 90.17 \text{ cm}$) to facilitate easy installation and adjustment in the flume. These panels were placed onto wooden frames pre-installed in the flume, enabling the ramp to be set at two distinct slopes (3% and 5%) inclusive of the constant slope of the flume. This allowed the same panel configuration to be used for both ramp slopes. Additionally, a transition panel was placed to abut the downstream ramp panel to mitigate the ledge created by the layer of mortar; the transition panel consisted of graded gravel epoxied onto a thin plywood sheet, creating a smooth, 0.30-m transition from the ramp panels to the flume floor.

The rock-ramp design featured a staggered arrangement of isolated natural boulders sourced from the lower Gallatin River, combined with a sub-rounded gravel substrate. A total of

45 boulders with an approximate diameter (D) of 14.0 cm were placed throughout the ramp in 18 alternating rows of two and three boulders each (Figure 20). Gravel, sieved to retain particles between 3.8 cm and 2.5 cm in diameter, was used to fill the spaces between boulders; substrate of this size can enhance passage efficiency for small-bodied fishes (Brittain et al. 2022). Any remaining gaps were filled with smaller gravel (minimum diameter of 0.64 cm) to simulate natural streambed conditions. We followed guidelines (DVWK2002) that recommend longitudinal (Δx) and lateral (Δy) spacing between boulder centers to be two to three times the boulder diameter. Considering the experimental flume width and boulder diameter, Δx was set at 30.48 cm ($2.18D$), and Δy was set at 35.56 cm ($2.55D$). This configuration resulted in an aerial density of approximately 12.8%, establishing a wake-interference flow condition, wherein roughness elements were sufficiently close that the wake generated by one boulder was disrupted by the subsequent boulder (Baki et al., 2014).

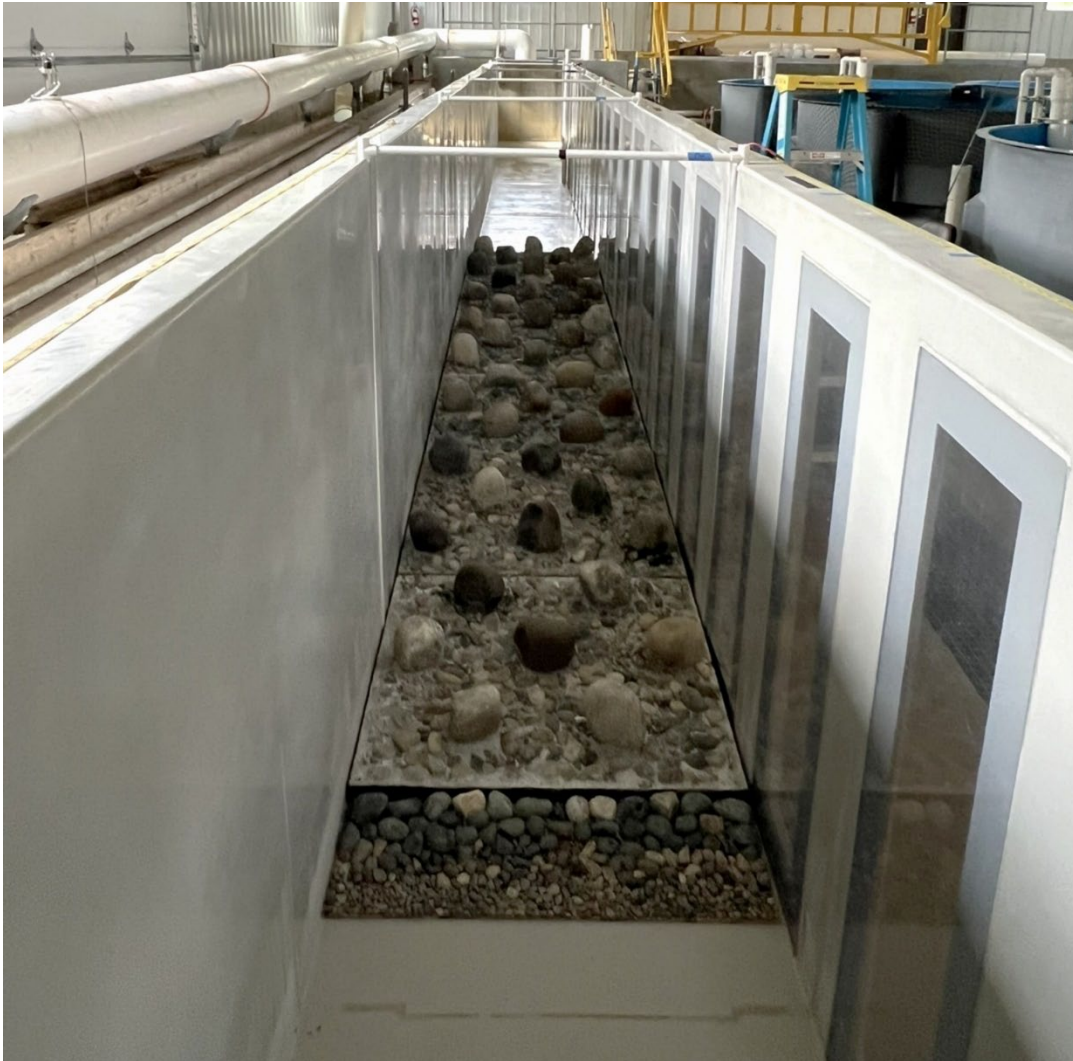


Figure 20: 3% slope rock ramp installed in the flume looking upstream.

Water circulation in the flume was maintained by two non-submersible Prime Vertical Axial Pumps: a 40-horsepower and a 20-horsepower pump. Both pumps can operate simultaneously, providing a flow rate from 0.032 to $0.320 \text{ m}^3 \cdot \text{s}^{-1}$. Water was stored in a 34.1 m^3 sump at the downstream end of the tailwater box and was recirculated to the headwater box through a 25.4 cm diameter schedule 40 polymerized vinyl chloride (PVC) pipe. The headwater

box was designed to provide a low-velocity refuge area for fish that swam the entire length of the open-channel flume.

At the downstream end of the flume a 3.0 x 3.7 m staging area was constructed flush with the flume floor which allowed fish to acclimate before each trial and provided a low velocity resting area for the fish. The staging area was screened off on all sides with 0.5 x 0.5 cm plastic mesh screens to prevent fish from entering the tailwater box. The upstream end of the staging area and the downstream end of the headwater box featured removeable metal grates. All metal grates were constructed out of expanded aluminum metal panels, and 0.5 x 0.5 cm screens were adhered to the grates to contain fish within the respective study area. Downstream of the staging area, water descended over a 0.46 m vertical drop into the tailwater box, and eventually returned to the sump. Within the tailwater box, removable screens were used to create five holding pens.

Water utilized in the flume was sourced from on-site warm and cold-water artesian wells. Inflow water temperatures were controlled using visual float valves. Water from the cold and warm water wells passed through a packed column before entering the flume to thoroughly mix the water. Freshwater inflows were located at both the headwater and tailwater boxes. The hydraulic conditions in the flume were controlled by adjusting the pump outflow and by manipulating the height of the steel tailwater gate (Fresno Downward Opening Weir Gate, Selma, CA). A Signet 2540 paddle wheel flow meter (GF Piping Systems, Schlaffhausen, Switzerland) was installed into the recirculation pipe and recorded instantaneous flow rates. The elevation of the steel tailwater gate, functioning as a downstream weir, was adjusted to set the tail water depth in the flume.

An ORMR Multiple Antenna PIT Tag Reader (OregonRFID, Portland, OR) PIT system was used to track individual fish over the duration of a swimming trial. Four stationary PIT antennas were placed within the flume. The antennas were slid into grooves in the flume to minimize flow disruptions and eliminate resting areas for fish. ATC auto tuners automatically adjusted the capacitance to tune to the antennae loops, and the charge and read rates were calibrated until 100% single tag detection and > 85% multi-tag detection rates were achieved for both 12 mm and 23 mm PIT tags (Triano et al., 2022). The four PIT antennas release an electrical charge for 15 milliseconds and then pause for 35 milliseconds to listen for the response of a PIT tag. The resulting read ranges were 35.6 cm for the 23 mm PIT tags and 7.6 cm for the 12 mm tags. When a PIT tag passes through an antenna the Multi-Antenna reader box will record the PIT tag number and the time of detection.

The first antenna (A1) located at station 2.35 m identified voluntary participants, or fish that left the downstream staging area and approached the rock ramp. A second antenna (A2) was placed 1.07 m upstream of the entrance to the rock ramp at station 4.78 m and identified fish that had successfully entered the rock ramp. The third antenna (A3), at station 9.66 m, was at the upstream end of the rock ramp and identified fish that successfully ascended the fishway. The most upstream antenna (A4), at station 12.11 m, was a redundant passage success antenna in case of missed detections at A3. These antennae were used to analyze participation, entrance, and passage efficiencies and the recorded detection times could then be used to calculate ascent times for fish that successfully ascended the fishway.

Test Fish

Wild fish were used in this study to produce representative results for natural populations. Two species, white sucker and longnose dace, were collected from different locations in Montana and transported to the BFTC for holding and experimentation. A total of 84 white suckers were used in this study and were collected from Ennis Lake, MT on October 4, 2024, using gill nets. To minimize injury, gill net sets were limited to one hour, and fish were carefully removed and placed into a live well for transport. During transport, water temperature was maintained at 14°C ($\pm 2^\circ\text{C}$) to match collection site conditions, and dissolved oxygen was kept at 8 mg/L. Upon arrival at the BFTC, fish were transferred to a 3.60 m diameter circular holding tank.

A total of 168 longnose dace were used in this study and were collected from Ross Fork Creek, MT on September 25, 2024, using a backpack electrofisher (LR-24, Smith-Root Inc., Vancouver, WA). During transport, the live-well temperature was also maintained at 14°C ($\pm 2^\circ\text{C}$) to match collection site conditions, and the oxygen maintained at 8 mg/L. At the BFTC, dace were placed in a 1.83 m diameter circular holding tank.

To control tank temperatures, warm and cold well water was mixed and then entered the tank through a nozzle that was directed at the tank surface. This created circular flow patterns, which exercised the fish. Holding tanks were initially maintained at the temperature of the collection site and gradually reduced to the test temperature of 10°C at a controlled rate of 1°C per day to allow for acclimation. To provide cover and habitat complexity, and reduce stress, each tank contained a combination of boulders, PVC pipe sections, and cinder blocks. Fish were fed daily using a timed belt feeder with Bio trout 2mm (Bio-Oregon, Longview WA).

All fish were acclimated to laboratory conditions for a minimum of 11 days before PIT tagging for individual identification and tracking. Before tagging, fish were anesthetized in 25 mg/L of tricaine methane sulfonate (MS-222) to minimize handling stress. A small incision was made in the peritoneal cavity, just anterior to the pelvic fin, using a sterile scalpel, and a passive integrated transponder (PIT) tag was inserted. White suckers were tagged with 23×3.65 mm half-duplex (HDX) Biomark PIT tags (Biomark, Boise, ID), while longnose dace received 12×2.15 mm HDX Biomark PIT tags. The incision method followed the protocol described by Swarr (2018), and no sutures were required. It was assumed that PIT tagging did not significantly affect the fish's swimming abilities (Ficke et al., 2012; Swarr et al., 2022). Fish were held without food for 24 hours before and after tagging to ensure a post-absorptive state and were given a minimum of two weeks to heal before participating in trials.

Experimental Treatments

A total of 28 trials were conducted, each consisting of three white suckers and six longnose dace (Table 4). The study included three replicates of nine experimental treatments, which were defined by a combination of two slopes (3% and 5%) and five flow rates (0.0315, 0.0631, 0.0946, 0.1262, and $0.1893 \text{ m}^3\text{s}^{-1}$). The highest flow rate ($0.1893 \text{ m}^3\text{s}^{-1}$) was only tested at the 5% slope. Each treatment hereafter is referred to as a Hydraulic Condition (HC). A fourth replicate trial was conducted for HC4 to obtain additional passage data for the longnose dace, as further detailed in the passage results section.

Table 4: Summary of hydraulic conditions tested during volitional swim trials. Trials at the 3% slope were conducted first, with flow rates randomly selected using a number generator. Trials at the 5% slope followed, also using randomly selected flow rates. Trials 13, 26, 27, and 28 were not randomly selected because they were added later to collect additional data.

Hydraulic Condition	Nominal Flow Rate (m ³ /s)	Slope	Trial Numbers
1	0.0315	3%	6, 9, 10
2	0.0631	3%	1, 4, 8
3	0.0946	3%	2, 7, 11
4	0.1262	3%	3, 5, 12, 13
5	0.0315	5%	17, 19, 25
6	0.0631	5%	14, 18, 22
7	0.0946	5%	20, 21, 24
8	0.1262	5%	15, 16, 23
9	0.1893	5%	26, 27, 28

Each trial lasted 21 hours, including an overnight period, allowing fish to volitionally participate during their preferred phase of the photoperiod. The water temperature for all trials was maintained at $10^{\circ}\text{C} \pm 0.1$, as this is the known spawning temperature for white suckers, a period associated with increased upstream movement and a critical time for passage structures to facilitate migration (Anderson, 2022; Bunt et al., 1999, 2001; Curry & Spacie, 1984; Manny et al., 2010; Olson, 1963). Additionally, previous studies have shown that colder temperatures can increase volitional participation rates (Gardunio et al., 2014). Wehrly et al (2003) identified both species as cool-water fishes, with optimal physiological performance occurring around 20.5°C . Because the trials were conducted at 10.0°C , well below the thermal optimum for both test species, successful passage at this temperature suggests that performance would likely be maintained or improved at warmer temperatures (Dockery et al., 2017; Wehrly et al., 2003).

Tailwater (TW) pool depths for each experimental treatment were systematically determined by raising the tailwater gate in 0.635 cm increments until a streaming flow transition was achieved. If the TW depth is too low, the transition from the steep sloped rock ramp to the smooth flume floor can create a drawdown effect, accelerating flow and reducing depth (plunging). This can also lead to a hydraulic jump further downstream, where the supercritical flow abruptly transitions back to subcritical flow (Chow 1959), generating high turbulence and aeration that may act as a barrier to fish passage.

To avoid this, TW depth was gradually increased to apply just enough backpressure to smooth the transition between the ramp and the downstream pool, producing a streaming flow and ensuring that entrance velocities were reduced without raising the pool depth excessively. Velocity measurements between perturbation boulders at the ramp entrance (0.762 m) were compared with velocities farther upstream on the ramp (1.372 m and mid-ramp). The tailwater gate was raised only until entrance velocities were slightly lower than internal velocities, ensuring a hydraulically smooth and enterable ramp condition.

This fine-tuned approach minimized turbulence and air entrainment at the entrance while carefully avoiding excessive backwatering. As a result, hydraulic conditions throughout the 5.49-m ramp were governed solely by the ramp's internal configuration. This allowed swim trial results to be reasonably interpreted as representative of fish performance along the full ramp length.

Trial Process

Twenty-one hours before the start of each trial, three white suckers and six longnose dace were haphazardly netted from their respective holding tanks and placed in a fasting tank. The

white sucker were placed in one of five fasting pens in the tailwater box of the flume, while the longnose dace were placed in a separate 1.83-m tank. During the fasting period, food was withheld to ensure a post-absorptive state during swim trials. These fish were scanned with a hand-held PIT tag reader (Model 601, Biomark, Boise, ID) to ensure a functioning PIT tag.

Before the start of the trial, pump flow rates, inflow well-water ratios, and tailwater gate elevations were manually set for the targeted treatment. While the hydraulics in the flume stabilized, the PIT array was turned on and the detection rate was determined with single and multiple-tag detection tests for both PIT tag sizes (12 and 23 mm HDX tags). Three HOBO Water Level Loggers (U20L, Onset Computer Corporation, Bourne, MA) were activated and installed to record ambient, headwater, and tailwater temperatures and pressures at 15-minute intervals throughout each trial. Once the system reached a steady state, a set of hydraulic and temperature measurements were taken to ensure the test conditions matched those of the targeted treatment conditions. Thirty minutes before the start of the trial, fish from the fasting tanks were netted and placed into the flume staging area. This period allowed fish to acclimatize to the test environment without having to be handled directly preceding the start of the trials.

At the beginning of the trial (13:00 MST), the staging area upstream grate was removed, enabling fish to volitionally swim up the open-channel flume. Trials lasted from 13:00 MST to 10:00 MST the following day, to capture peak movement periods at dusk and dawn. At the end of the trial, the PIT array system was turned off and the staging area grate was inserted. Fish were removed from the flume, their PIT tag numbers were re-scanned, and their final positions in the flume were recorded (headwater or tailwater pools). After being removed from the flume, the fish were lightly anesthetized using the same process as PIT tagging, measured for weight (g)

and total length (mm), and then transferred to recovery tanks. White sucker were measured to the nearest 5 mm and longnose dace were measured to the nearest mm. Test fish were only used in one trial.

Hydraulic Data Collection

Velocity

Velocity measurements were collected to characterize the hydraulic conditions within the rock ramp under each test condition. Detailed hydraulic measurements were collected in a measurement area located in the middle of the rock ramp, from ramp station 2.59 to 3.20 m (Figure 21). The measurement area was selected to ensure fully developed flow within the ramp while avoiding potential tailwater effects (Baki et al., 2014). Due to the symmetry of the boulder configuration, the measurement area captures all flow conditions occurring within the ramp (Baki et al., 2014). Since the measurement area spans the width of the flume (as opposed to from the sidewall to the centerline), it captures two representative sections of the rock ramp configuration, so that the data better accounts for the heterogeneity of the boulders and substrate (Baki et al., 2014). Hydraulic data were not collected for HC9, as this condition was added after the hydraulic sampling period and time constraints prevented further data collection.

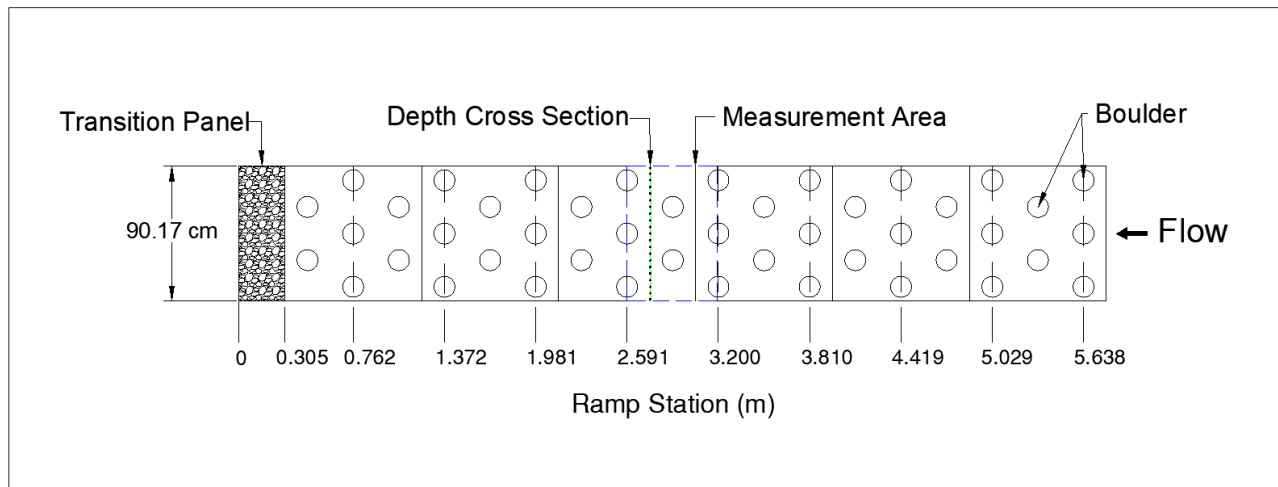


Figure 21: Rock ramp schematic showing velocity measurement area and depth measurement cross section location.

Velocity measurements were taken in a grid pattern, and measurements were taken at two depths for all locations: with the probe resting on the bottom of the ramp (bottom) and at 40% of the total depth from the bottom. Bottom velocity measurements were taken to capture the effects of the gravel substrate, which influences flow resistance, and because benthic and small-bodied fish species often rely on these lower-velocity zones for passage. The 0.4 depth measurements were collected because the velocity at this depth generally approximates the average velocity in a vertical section of open-channel flow (Chow, 1959).

For the 3% ramp, the detailed velocity measurement grid consisted of 107 locations, totaling 214 velocity measurements per hydraulic condition (Figure 22). Velocity measurements within the detailed velocity grid were taken every 7.62 cm longitudinally (in the streamwise direction) and 4.45 cm laterally. For the 5% ramp (HC5–HC9), a reduced velocity measurement grid was used to streamline data collection while maintaining coverage of hydraulically significant regions. The number of measurement locations was reduced to 28, with

measurements taken at the same two depths, resulting in 56 total velocity measurements per hydraulic condition (Figure 22). Locations for the reduced grid focused on areas where maximum velocities and eddies were expected, such as flow constrictions between boulders and recirculation zones behind boulders. The spacing between velocity measurements in the reduced grid was 15.24 cm longitudinally and 8.89 cm laterally. Due to the size of the velocity probe, velocity could not be measured directly in front of the boulders.

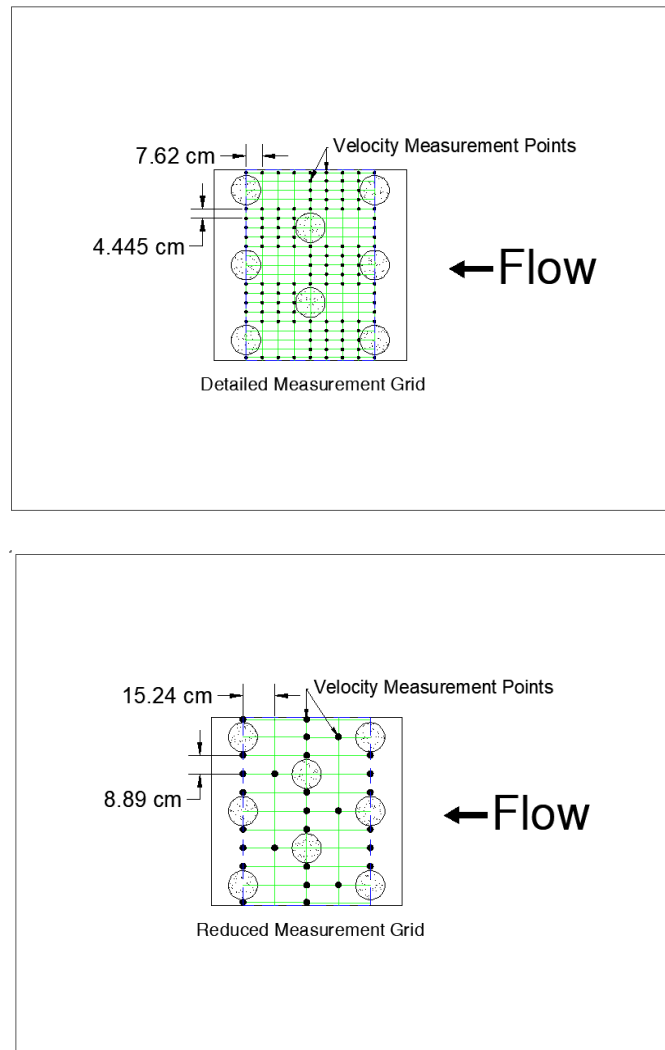


Figure 22: 3% slope rock ramp detailed velocity measurement grid (top) and 5% slope reduced velocity measurement grid (bottom).

Measurements were collected using a Hach Flo-Mate velocimeter (Hach Corp., Loveland, CO), with velocity time-averaged over 30 seconds at each location. Water depth was estimated by observing instantaneous fluctuations during a velocity measurement and approximating the average.

Velocity Check Measurements

Before the start of each trial, 10 velocity measurements were collected (5 measurement locations and two depths: bottom and 0.4 total depth) to ensure the test conditions matched that of the targeted treatment conditions. Three measurements were taken between boulders within the measurement area of the ramp, and two at the headwater and tailwater pool.

Table 5: Location of velocity check measurements taken before the start of each trial to ensure test conditions matched the targeted treatment conditions.

Flume Station (m)	Lateral Station (cm)
3.05	45.72
6.40	27.94
6.40	63.50
6.71	45.72
11.30	45.72

Velocity Gradient Maps

Velocity gradient maps were generated using the detailed (3% slope treatments) and reduced (5% slope treatments) velocity measurement data to visualize the spatial variability of velocities within a representative section of the ramp. For each hydraulic condition, separate maps were created for the bottom and at 0.4 the depth velocity measurements. The maps were produced in R version 4.4.3 using the akima (v0.6-3.4, Akima and Gebhart 2022) and fields

(v16.3, Nychka et al. 2021) packages (R Core team 2025). Measured velocity data were interpolated onto a 400×400 grid using Kriging, a geostatistical method that estimates values at unsampled locations by weighting nearby observations based on spatial correlation. A no-slip, zero-velocity boundary condition was applied at all walls, as well as the center, leading and trailing edges, and sides of each perturbation boulder, ensuring that velocities at these interfaces were zero. While direct measurements immediately in front of boulders were limited by probe size, this interpolation method provided a good visual approximation of the complex flow patterns within the roughened channel rock ramp.

Depth Cross Section

A point probe was used to measure the depth of the water surface elevation for HC1-HC8 across an unobstructed lateral cross section within the measurement area (Figure 21). Depth was calculated as the difference between the ramp bed elevation and the water surface elevation, with the water surface estimated as the average of the fluctuating levels. Twenty-one measurement points were taken along this cross section, 2.54 cm from the flume walls and then at 4.45 cm intervals from 6.35 cm to 85.73 cm across the width of the ramp (Figure 21). The bulk velocity (V_{bulk}) was calculated from the measured depth by rearranging the continuity equation ($Q = VA$), which was used to derive hydraulic parameters such as Reynolds number, Froude number, and energy dissipation factor.

PIT Data Analysis

The PIT data from the Multi-Antenna HDX reader was downloaded at the end of each trial and analyzed on a by fish basis to summarize participation, entrance, and passage results. A fish was considered a participant if it was scanned at antenna A1. If a fish was scanned at A2,

then it was considered to have entered the fishway. A fish was considered to have successfully passed through the fishway if it was scanned at either A3 or A4, since both antennas are upstream of the fishway (Figure 19). The measure of passage success in the trial was the total number of fish that ascended the fishway divided by the number of fish that entered the fishway. A summary of passage and hydraulic results are presented in Table 5 and Table 6 and are presented separately for longnose dace and white sucker. All analyses were performed using R statistical software (v4.3.1, R Core Team 2025).

Travel Time Analysis

The time of travel for the first successful passage attempt for each participant was calculated using PIT data. If a fish's first attempt was missing a detection at A2 (ramp entrance), its travel time was excluded from analysis to maintain consistency. Travel time was defined as the difference between the first detection at A3 and the closest preceding detection at A2.

Longnose Dace Probability of Passage Model

Binary logistic regression was used to analyze how hydraulic conditions affected the probability of longnose dace passage success on a by-fish basis. A logit transformation was applied to the passage rate, and the initial model included flow rate (continuous), slope (discrete), and fish total length (TL; continuous) as explanatory variables. Empirical logits were examined to verify that the assumption of linearity was approximately met. Side-by-side boxplots comparing fish total length for fish that passed versus those that did not pass across hydraulic conditions, in conjunction with the findings of Dockery et al. (2017) indicating that longnose dace swimming speed increases with TL, provided further support for including fish

length and its interactions in the initial model. This analysis was not performed for white suckers because they had high passage rates for all hydraulic conditions.

Results

Test Conditions

Flow rate, headwater depth, tailwater depth, and temperature remained relatively constant throughout the duration of each trial, verified by the HOBO sensor data. The mean observed temperature per trial ranged from 9.8 to 10.6 °C. The overall mean temperature for all trials was 10.2°C and the mean standard deviation per trial was 0.1°C. Given the minimal temperature variation, it was not included as a variable in explanatory models of passage success.

The average standard deviation in HW depth within trials was 0.17 cm, confirming that flow rate remained consistent throughout trials. Among the replicate trials for each hydraulic condition, the average Root Mean Square Error (RMSE) for the 5 velocity check measurement locations was 3.67 cm/s for the bottom and 3.20 cm/s for 0.4 depth measurements, confirming flow rate and ramp conditions were consistent among trials within the same treatments.

The total length (TL) for white sucker ranged from 190 to 480 mm, with a mean TL of 380 ± 50 mm. Total length for longnose dace ranged from 59 to 107 mm, with a mean TL of 74 ± 9 mm. To determine if total length of test fish differed among trials, we used a nonparametric Kruskal-Wallis test to account for unequal variances in length among trials. There was no evidence for TL to differ among trials for white sucker ($p = 0.7896$, $\chi^2 = 20.929$, $df = 27$) or longnose dace ($p = 0.7559$, $\chi^2 = 21.63$, $df = 27$).

Passage Result

A total of 84 white sucker were tested in this study, all of which (100%) participated in experiments. Of the 168 longnose dace intended for use in this study, 166 were included in the analysis. Two fish became stuck in the screen before trials began and were excluded (trials 23 and 24). Of the 166 dace tested, 162 participated in experiments, resulting in a total participation rate of 97.6%. Most trials (25 out of 28) achieved 100% participation. Only participants were considered in further data analysis. During the first five trials, 0.64 cm gaps between the rock ramp and flume walls were not sealed, allowing a total of four dace to enter the ramp, swim through these gaps, and remain under the ramp for the duration of the trial (trials 2, 3, and 5). Since these fish successfully entered the ramp, they were included in entrance analyses but excluded from passage analyses. Participation, entrance, and passage rates, along with average temperature, nominal flow rate, and mean fish total length for each trial, are presented in Table 5 and Table 6.

Table 6: Summary of rock ramp participation, entrance, and passage rates for longnose dace. Trials are grouped by hydraulic conditions. Participation rate is the number of dace detected at the A1 antennae divided by the total number of dace in the trial. Entrance is the number of dace detected at the A2 antennae divided by the dace detected at the A1 antenna. The passage rate is the number of dace that ascended the fishway and were detected at the A3 or A4 antennae divided by the dace detected by the A2 antenna. The average passage rate is the average of the passage rates for each of the three replicates in a hydraulic condition.

Hydraulic Condition	Nominal Flow Rate (m^3s^{-1})	Slope	Trial	Mean Temp ($^{\circ}\text{C}$)	Mean Total Length (mm)	Participation Rate	Entrance Rate	Passage Rate	Average Passage Rate per HC
1	0.0315	3%	6	10.4 $\pm$ 0.1	78 $\pm$ 13	100%	100%	100%	100%
			9	10.3 $\pm$ 0.1	76 $\pm$ 8	100%	100%	100%	
			10	10.0 $\pm$ 0.0	82 $\pm$ 14	100%	100%	100%	
2	0.0631	3%	1	10.0 $\pm$ 0.1	74 $\pm$ 9	100%	100%	100%	100%
			4	10.0 $\pm$ 0.0	77 $\pm$ 10	100%	100%	100%	
			8	10.2 $\pm$ 0.1	75 $\pm$ 8	100%	100%	100%	
3	0.0946	3%	2	10.2 $\pm$ 0.0	72 $\pm$ 9	100%	83%	75%	64%
			7	10.0 $\pm$ 0.1	75 $\pm$ 10	100%	100%	50%	
			11	10.1 $\pm$ 0.0	73 $\pm$ 10	100%	100%	67%	
4	0.1262	3%	3	10.5 $\pm$ 0.1	76 $\pm$ 8	100%	100%	40%	43%
			5	10.1 $\pm$ 0.0	73 $\pm$ 10	100%	83%	33%	
			12	9.9 $\pm$ 0.1	74 $\pm$ 8	100%	100%	50%	
5	0.0316	5%	13	10.1 $\pm$ 0.0	72 $\pm$ 9	100%	100%	50%	83%
			17	9.8 $\pm$ 0.1	78 $\pm$ 17	100%	100%	100%	
			19	9.9 $\pm$ 0.0	74 $\pm$ 14	100%	67%	50%	
6	0.0631	5%	25	10.0 $\pm$ 0.0	79 $\pm$ 14	100%	100%	100%	47%
			14	10.5 $\pm$ 0.1	81 $\pm$ 13	100%	100%	50%	
			18	10.2 $\pm$ 0.1	72 $\pm$ 6	100%	83%	40%	
7	0.0946	5%	22	10.1 $\pm$ 0.0	68 $\pm$ 5	100%	100%	50%	28%
			20	9.9 $\pm$ 0.0	71 $\pm$ 5	100%	100%	17%	
			21	9.9 $\pm$ 0.4	77 $\pm$ 8	100%	100%	67%	
8	0.1262	5%	24	10.2 $\pm$ 0.0	73 $\pm$ 7	100%	60%	0%	7%
			15	10.5 $\pm$ 0.1	72 $\pm$ 10	83%	80%	0%	
			16	10.2 $\pm$ 0.1	71 $\pm$ 8	100%	83%	20%	
9	0.1893	5%	23	10.4 $\pm$ 0.1	72 $\pm$ 6	80%	100%	0%	0%
			26	10.2 $\pm$ 0.0	69 $\pm$ 5	67%	100%	0%	
			27	10.5 $\pm$ 0.1	67 $\pm$ 5	100%	67%	0%	
			28	10.6 $\pm$ 0.1	70 $\pm$ 20	100%	100%	0%	

Table 7: Summary of rock ramp participation, entrance, and passage rates for white sucker. Trials are grouped by hydraulic conditions. Participation rate is the number of sucker detected at the A1 antennae divided by the total number of sucker in the trial. Entrance is the number of sucker detected at the A2 antennae divided by the sucker detected at the A1 antenna. The passage rate is the number of sucker that ascended the fishway and were detected at the A3 or A4 antennae divided by the sucker detected by the A2 antenna. The average passage rate is the average of the passage rates for each of the three replicates in a hydraulic condition.

Hydraulic Condition	Slope	Nominal Flow Rate (m^3s^{-1})	Trial	Mean Temp ($^{\circ}\text{C}$)	Mean Total Length (mm)	Participation Rate	Entrance Rate	Passage Rate	Average Passage Rate per HC
1	3%	0.0315	6	10.4 ± 0.1	435 ± 55	100%	100%	100%	100%
			9	10.3 ± 0.1	390 ± 10	100%	100%	100%	
			10	10.0 ± 0.0	410 ± 45	100%	100%	100%	
2	3%	0.0631	1	10.0 ± 0.1	410 ± 45	100%	100%	100%	89%
			4	10.0 ± 0.0	385 ± 30	100%	100%	100%	
			8	10.2 ± 0.1	370 ± 10	100%	100%	67%	
3	3%	0.0946	2	10.2 ± 0.0	390 ± 10	100%	100%	100%	100%
			7	10.0 ± 0.1	365 ± 50	100%	100%	100%	
			11	10.1 ± 0.0	390 ± 15	100%	100%	100%	
4	3%	0.1262	3	10.5 ± 0.1	380 ± 20	100%	100%	100%	88%
			5	10.1 ± 0.0	395 ± 30	100%	100%	100%	
			12	9.9 ± 0.1	355 ± 55	100%	100%	100%	
			13	10.1 ± 0.0	345 ± 35	100%	67%	50%	
5	5%	0.0316	17	9.8 ± 0.1	390 ± 80	100%	100%	100%	100%
			19	9.9 ± 0.0	400 ± 50	100%	100%	100%	
			25	10.0 ± 0.0	400 ± 50	100%	100%	100%	
6	5%	0.0631	14	10.5 ± 0.1	375 ± 50	100%	100%	100%	100%
			18	10.2 ± 0.1	400 ± 50	100%	100%	100%	
			22	10.1 ± 0.0	360 ± 20	100%	100%	100%	
7	5%	0.0946	20	9.9 ± 0.0	395 ± 20	100%	100%	100%	100%
			21	9.9 ± 0.4	360 ± 80	100%	100%	100%	
			24	10.2 ± 0.0	390 ± 40	100%	33%	100%	
8	5%	0.1262	15	10.5 ± 0.1	335 ± 130	100%	67%	100%	100%
			16	10.2 ± 0.1	405 ± 50	100%	67%	100%	
			23	10.4 ± 0.1	350 ± 50	100%	100%	100%	
9	5%	0.1893	26	10.2 ± 0.0	330 ± 40	100%	67%	100%	100%
			27	10.5 ± 0.1	400 ± 20	100%	100%	100%	
			28	10.6 ± 0.1	380 ± 35	100%	100%	100%	

Entrance rates were consistently high for both species across all trials ($\geq 67\%$ for all trials except trial 24 for white sucker). Longnose dace entrance rates were 100% for 21 of the 28 trials, and white sucker entrance rates were 100% for 23 of the 28 trials. White sucker exhibited very high passage rates across all hydraulic conditions (97%), while longnose dace showed substantial variation. Dace passage was high at the lowest flow rate ($Q = 0.0315 \text{ m}^3\text{s}^{-1}$) for both ramp slopes and declined as flow rate increased. At the same flow rate, passage success was significantly greater on the 3% slope ramp compared to the 5% slope ramp. Notably, at HC8,

only one dace (TL = 96 mm) successfully passed the rock ramp, and no dace successfully passed at HC9.

Travel Time Analysis

Longnose dace median travel times ranged from 1758.7 s to 568.7 s, while white sucker median travel times ranged from 67.9 s to 16.2 s (Figure 23 and Figure 24). For both ramp slopes, longnose dace travel time generally increased with flow rate, whereas white sucker travel time exhibited the opposite trend (Figure 23 and Figure 24). For example, at HC5, white sucker mean and median travel times were 65.5 s and 67.9 s, whereas at HC9, mean and median times decreased to 18.0 s and 16.2 s.

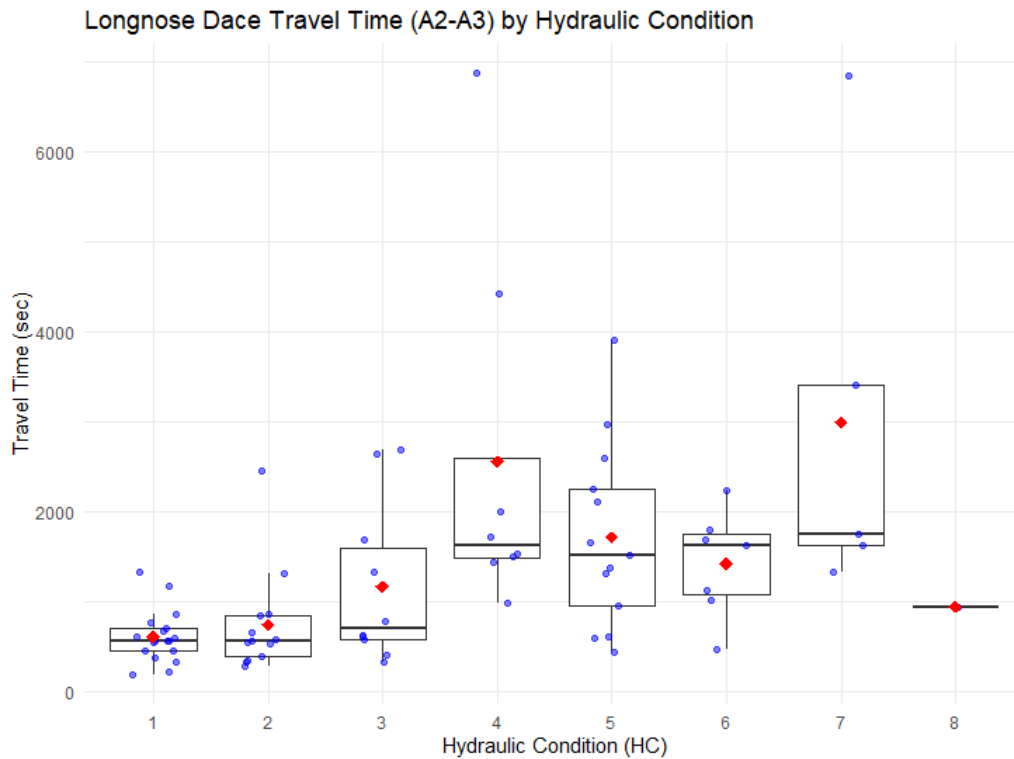


Figure 23: Boxplots of longnose dace travel times (difference between the first detection at A3 and the closest preceding detection at A2) for each HC. Each box shows the interquartile range (IQR), the horizontal line inside the box is the median, and the whiskers extend to $1.5 \times \text{IQR}$. Individual data points are plotted in blue, and the red diamonds represent the mean travel time for each HC. HC9 is not shown because there were no successful passage attempts.

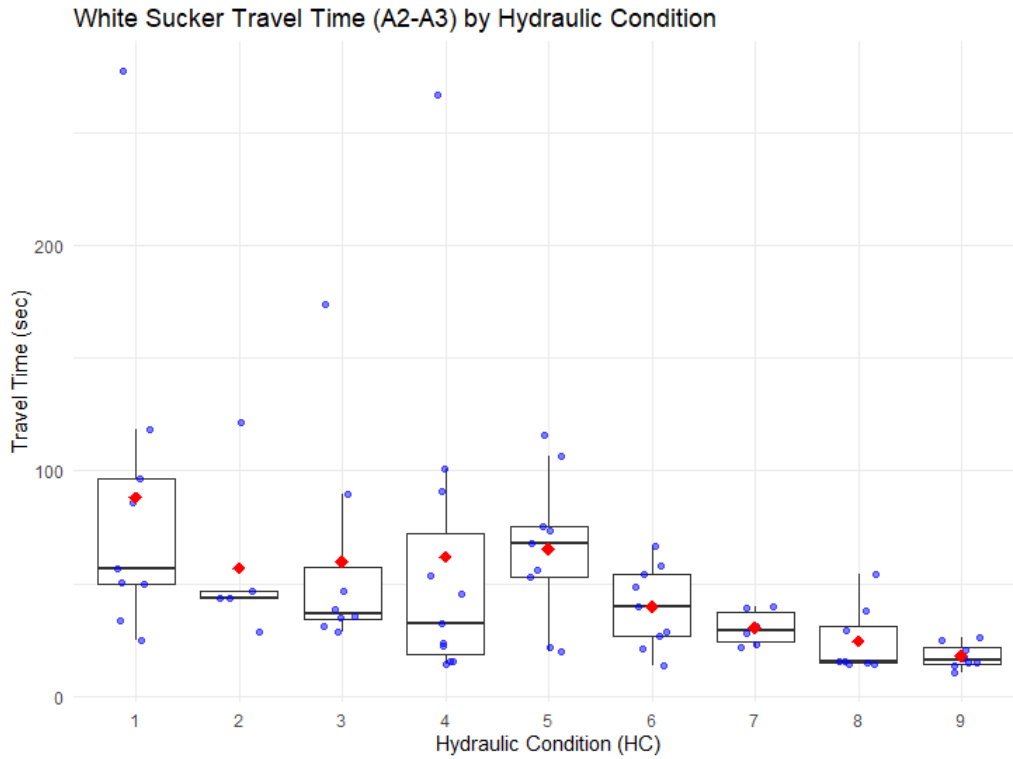


Figure 24: Boxplots of white sucker travel times (difference between the first detection at A3 and the closest preceding detection at A2) for each HC. Each box shows the interquartile range (IQR), the horizontal line inside the box is the median, and the whiskers extend to $1.5 \times \text{IQR}$. Individual data points are plotted in blue, and the red diamonds represent the mean travel time for each HC.

Longnose Dace Probability of Passage Model

A backward elimination method was used to identify the best-fitting logistic regression model predicting passage from slope, flow rate, and total length. The initial, full model included all main effects, all two-way interactions, and the three-way interaction. A likelihood ratio test comparing the full model with a model omitting the three-way interaction showed no significant difference ($\chi^2 = -0.34155$, $df = 2$, $p = 0.5589$), justifying its removal. Next, the slope $\times$ flow rate interaction, which had the highest p-value among the remaining interactions ($p = 0.9023$), was removed; the corresponding likelihood ratio test ($\chi^2 = -0.15063$, $df = 1$, $p = 0.9023$) confirmed

that its exclusion did not significantly affect the model fit. Subsequently, the slope $\times$ total length interaction ($p = 0.1173$) was dropped, with its removal likewise showing no significant change ($\chi^2 = -2.38000$, $df = 1$, $p = 0.1229$). With all remaining explanatory variables demonstrating p -values below the 0.10 threshold, it was concluded that this was the best fitting model (Equation 2). The parameter estimates and corresponding p -values for the final model are presented in Table 7.

$$\text{Equation 2: } \text{logit}(p) = \beta_0 + \beta_1 S + \beta_2 Q + \beta_3 TL + \beta_4 (Q \times TL)$$

Here, S denotes slope (with 5% coded as 1 and 3% as 0), Q denotes flow rate (m^3/s ; continuous), and TL denotes fish total length (mm; continuous).

Table 8: Final Logistic Regression Model for longnose dace passage. The table displays the estimates, standard errors, z -values, and p -values for the predictors in the final model.

Predictor	Estimate	Standard Error	Z value	p-value
(Intercept)	-19.2464	8.1002	-2.376	0.0175
S	-2.8144	0.6025	-4.671	<0.0001
Q	114.7219	73.6171	1.558	0.1192
TL	0.3571	0.1198	2.980	0.0029
Q X TL	-2.3747	1.0630	-2.234	0.0255

Note: S : Slope (%), Q : flow rate (m^3/s), TL : fish total length (mm), $Q \times TL$: flow rate fish length interaction.

Based on these results, the final model retained the main effects of slope, flow rate, fish length, and the flow rate $\times$ total length interaction. Although flow rate did not achieve statistical significance at the $p < 0.10$ level, its significant interaction with fish length justifies its inclusion

and indicates total length had a larger effect on passage probability in the 5% slope treatments than the 3% slope treatments (Figure 25 and Figure 26). Notably, under the 3% slope condition and at the two lowest flow treatments ($Q = 0.0315$ and $0.0631 \text{ m}^3 \text{ s}^{-1}$), passage success was 100%, a ceiling effect that the model does not accurately capture. Probability of passage curves, with 95% confidence intervals, are plotted for both slopes at the 10th, 50th, and 90th percentile fish lengths (Figure 25 and Figure 26).

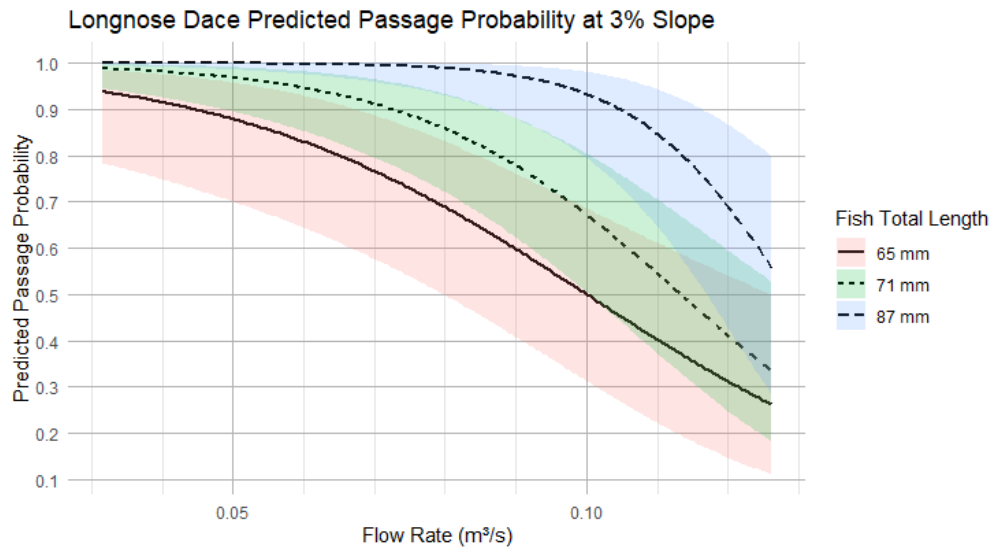


Figure 25: Predicted passage probability of longnose dace at a 3% slope as a function of flow rate, with 95% confidence intervals. Curves are shown for total lengths at the 10th, 50th, and 90th percentiles of fish tested. The model does not account for the ceiling effect observed for flow rates below $0.0631 \text{ m}^3/\text{s}$, where passage success was 1.0. Predictions are only shown for the range of tested flow rates.

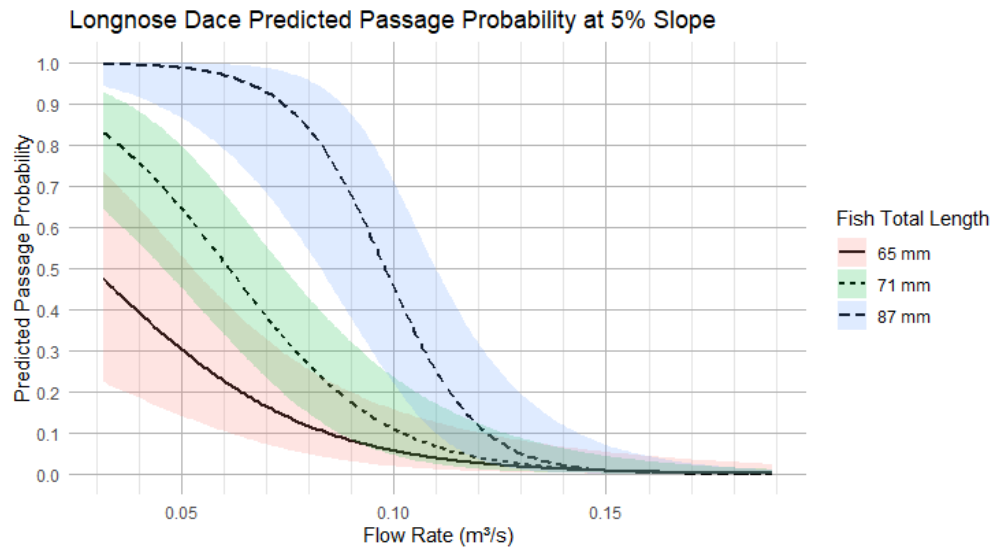


Figure 26: Predicted passage probability of longnose dace at a 5% slope as a function of flow rate, with 95% confidence intervals. Curves are shown for total lengths at the 10th, 50th, and 90th percentiles of fish tested. Predictions are only shown for the range of tested flow rates.

Velocity

Velocity distributions generally increased with flow rate, and average velocities were higher on the 5% ramp than on the 3% ramp for the same flow rate. However, a wide range of velocities were present within the ramp for all hydraulic conditions (Table 8 and Figure 27).

Table 9: Summary statistics of velocity measurements within the experimental rock ramp for HC1-HC8. Median velocities are presented as the median $\pm$ standard deviation (cm/s). Data for HC1–HC4 (3% slope) include all 214 measurements from the detailed velocity grid, while HC5–HC8 (5% slope) include all 54 measurements from the reduced velocity grid.

HC	Median Bottom Velocity (cm/s)	Median 0.4 Total Depth Velocity (cm/s)	Range of Bottom Velocities (cm/s)	Range of 0.4 Total Depth Velocities (cm/s)
1	40.2 $\pm$ 14.2	33.8 $\pm$ 20.1	-2.4 - 69.2	-12.8 - 70.4
2	47.2 $\pm$ 18.2	58.5 $\pm$ 19.4	-12.5 - 93.9	0 - 87.5
3	51.5 $\pm$ 21.8	86.6 $\pm$ 17.2	-20.7 - 96.3	35.4 - 115.8
4	54.6 $\pm$ 25.3	104.9 $\pm$ 19.8	-20.4 - 107.9	39.6 - 128.9
5	59.6 $\pm$ 18.2	62 $\pm$ 23.8	4.3 - 78.9	-1.8 - 90.2
6	64.5 $\pm$ 16	76 $\pm$ 26.8	30.2 - 98.5	14.6 - 107.9
7	71.5 $\pm$ 17.4	103.6 $\pm$ 22.7	35.4 - 107.9	51.5 - 133.5
8	80.3 $\pm$ 24.5	118.4 $\pm$ 26	4.6 - 103.3	51.8 - 145.7

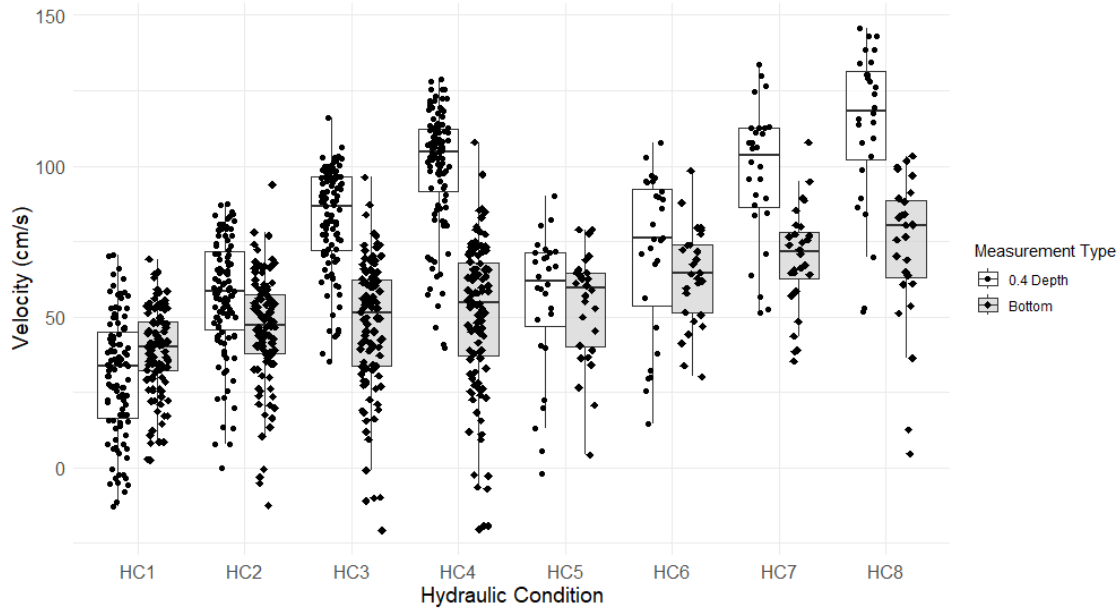


Figure 27: Boxplots of streamwise velocities measured within the rock ramp for each hydraulic condition. The 3% (HC1-HC4) ramp velocity distributions contain all 214 measurements taken from the detailed measurement grid. The 5% (HC5-HC9) ramp velocity distributions contain all 56 measurements taken from the reduced measurement grid. Separate boxplots are shown for the bottom and 0.4 depth measurements.

All hydraulic conditions on the 3% ramp included velocities below 0 cm/s, indicating the presence of eddies that serve as resting refugia. While some low-velocity measurements were still recorded on the 5% ramp, their frequency decreased as flow rate increased (Figure 27). However, the reduced velocity measurement points for the 5% slope, particularly the lack of data points directly behind perturbation boulders, may have contributed to the limited number of near-zero velocity measurements. These low-velocity areas may still exist but were not captured by the coarser sampling method.

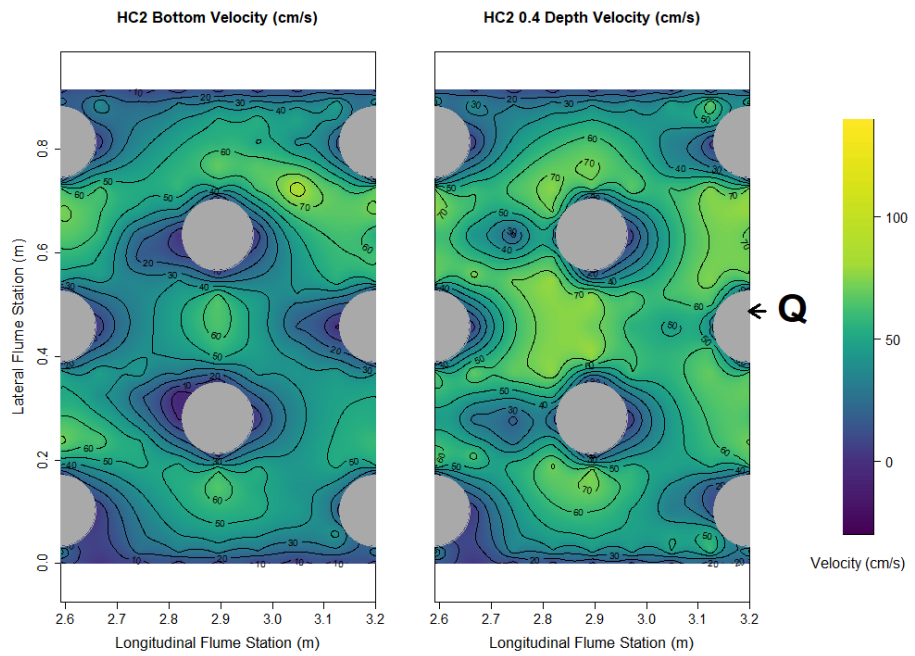
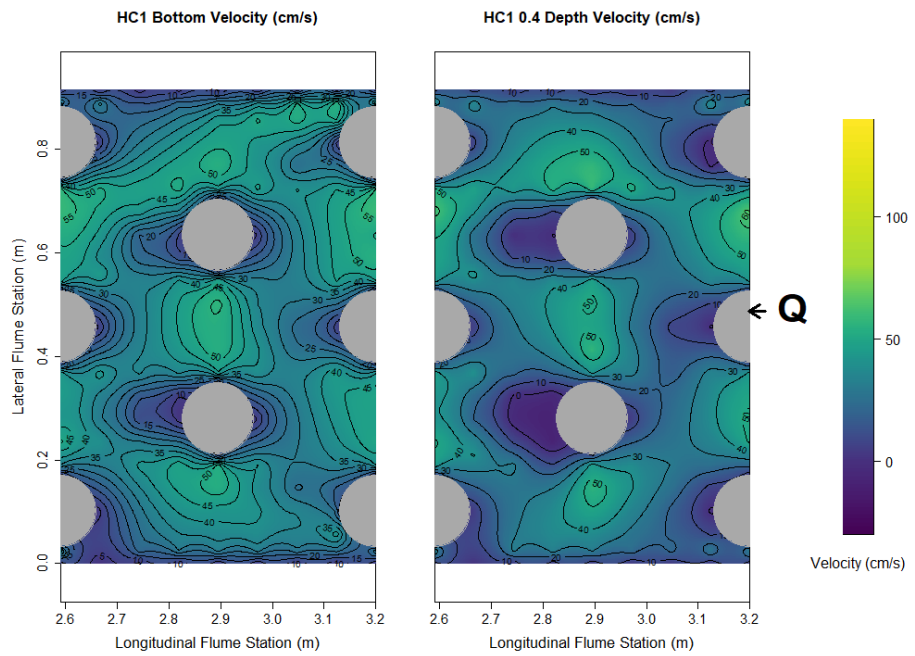
For both slopes, lower flow rates exhibited a more even distribution of high and low velocities at both the bottom and 0.4 depth. As flow increased, velocities measured at 0.4 depth rose more noticeably, while bottom velocities remained relatively consistent across flow rates. Although 0.4 depth is typically used to represent the same relative position in the water column, the hydraulic environment within the rock ramp changes with depth. At higher flows, increased water depth causes flow to transition from a wake interference regime to a more uniform streaming flow over the boulders. As a result, 0.4 depth measurements increasingly capture the faster skimming flow above the boulders, leading to higher recorded velocities despite maintaining the same relative depth.

To evaluate the accuracy of the reduced velocity measurement grid, velocity estimates from the detailed grid used for the 3% ramp were compared to a subset of the same dataset, containing only the points selected for the reduced grid. On average, the reduced grid produced average velocity estimates 6.9 ± 1.1 cm/s higher than the detailed grid, corresponding to an 11% overestimation. This suggests that the reduced grid is a viable method for reducing sampling effort, but some caution should be taken when interpreting velocity data, as it may slightly overestimate velocity conditions. This overestimation is likely due to the limited number of measurements taken in low-velocity regions directly in front of and behind the perturbation boulders.

Velocity Gradient maps

The velocity gradient maps illustrate potential swim paths, resting areas, and the maximum velocities fish must overcome (Figure 28 and Figure 29). While not exact due to interpolation between discrete measurement points, some closely spaced and others with larger

gaps, these maps provide a useful visual representation of the diverse velocities produced by a roughened channel rock ramp.



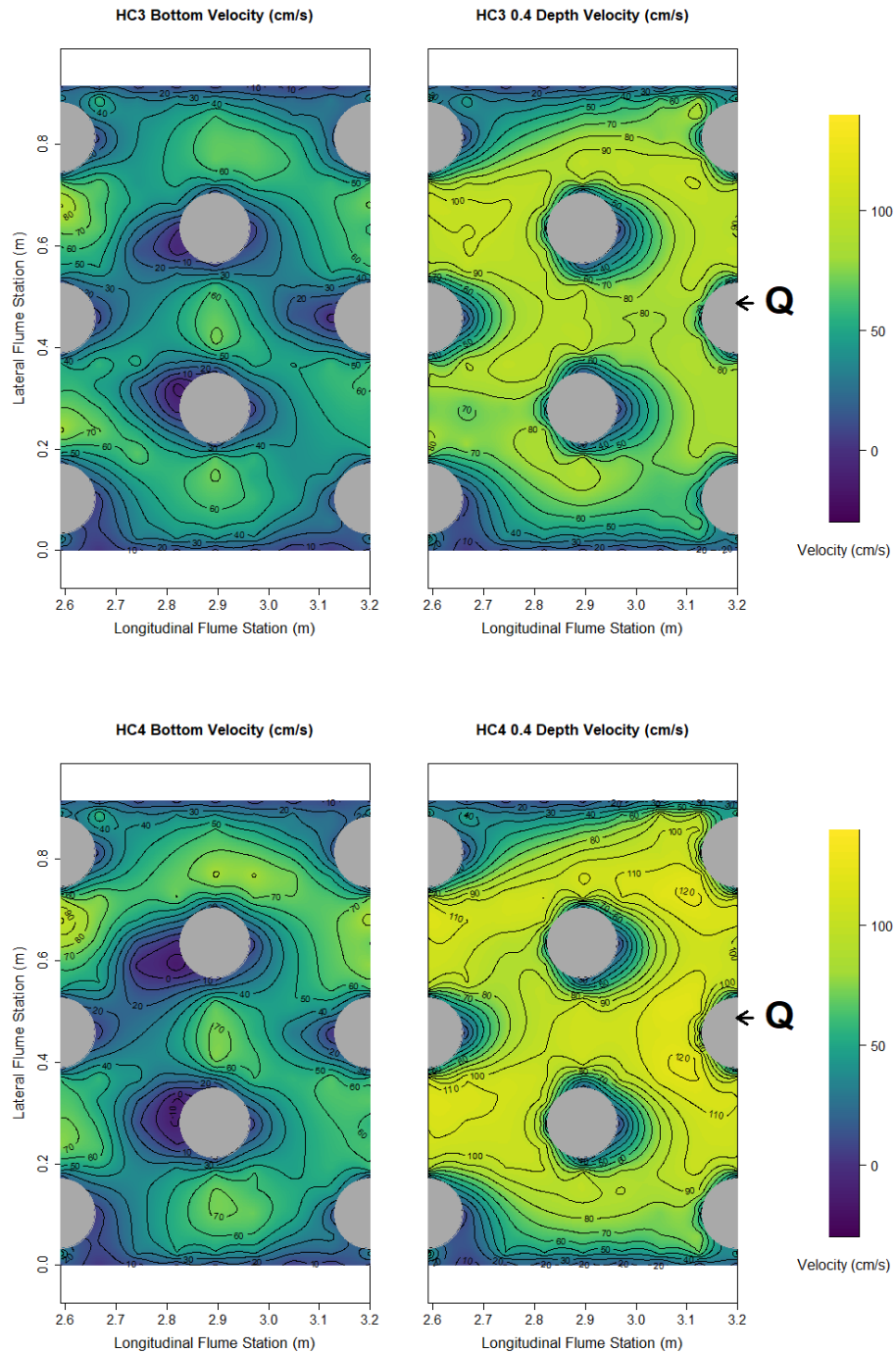
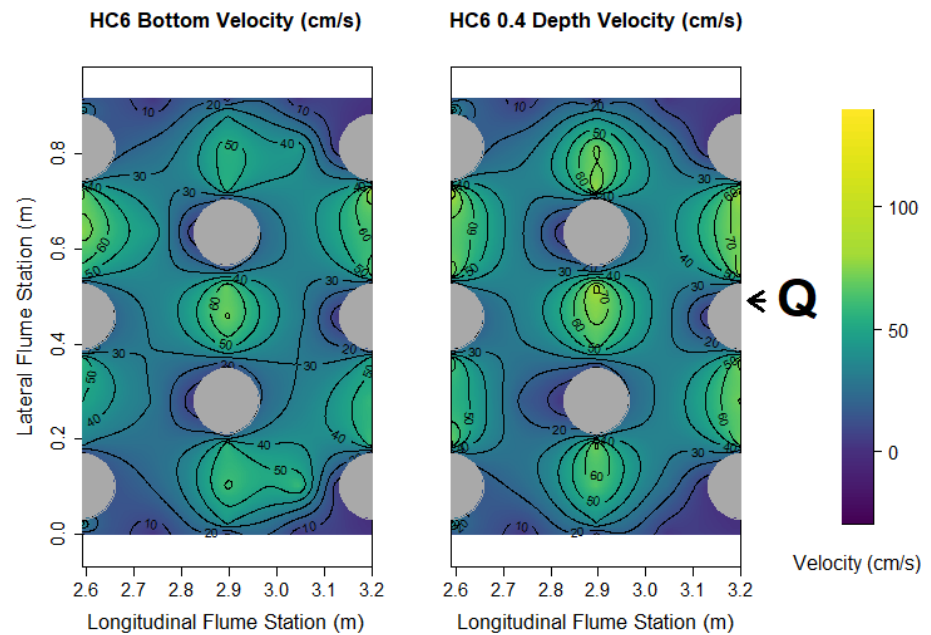
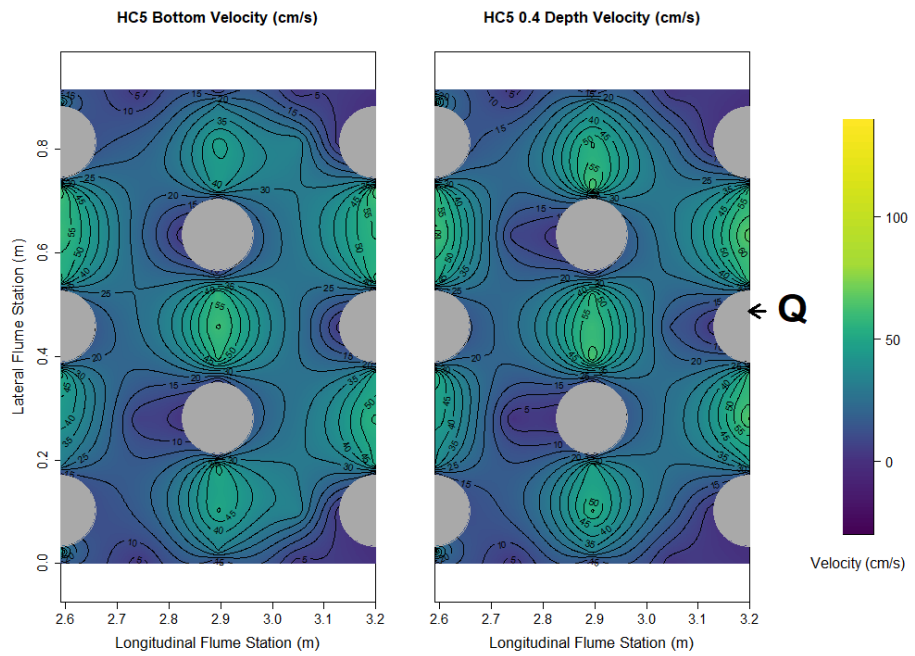


Figure 28: Velocity gradient maps for the 3% slope rock ramp using the detailed measurement grid data. Each row represents a different flow rate. The left column displays interpolated velocities on the bed of the ramp, while the right column shows interpolated velocities at 0.4 of the total depth. Gray circles indicate the approximate size and location of the perturbation boulders. Flow direction is from right to left.



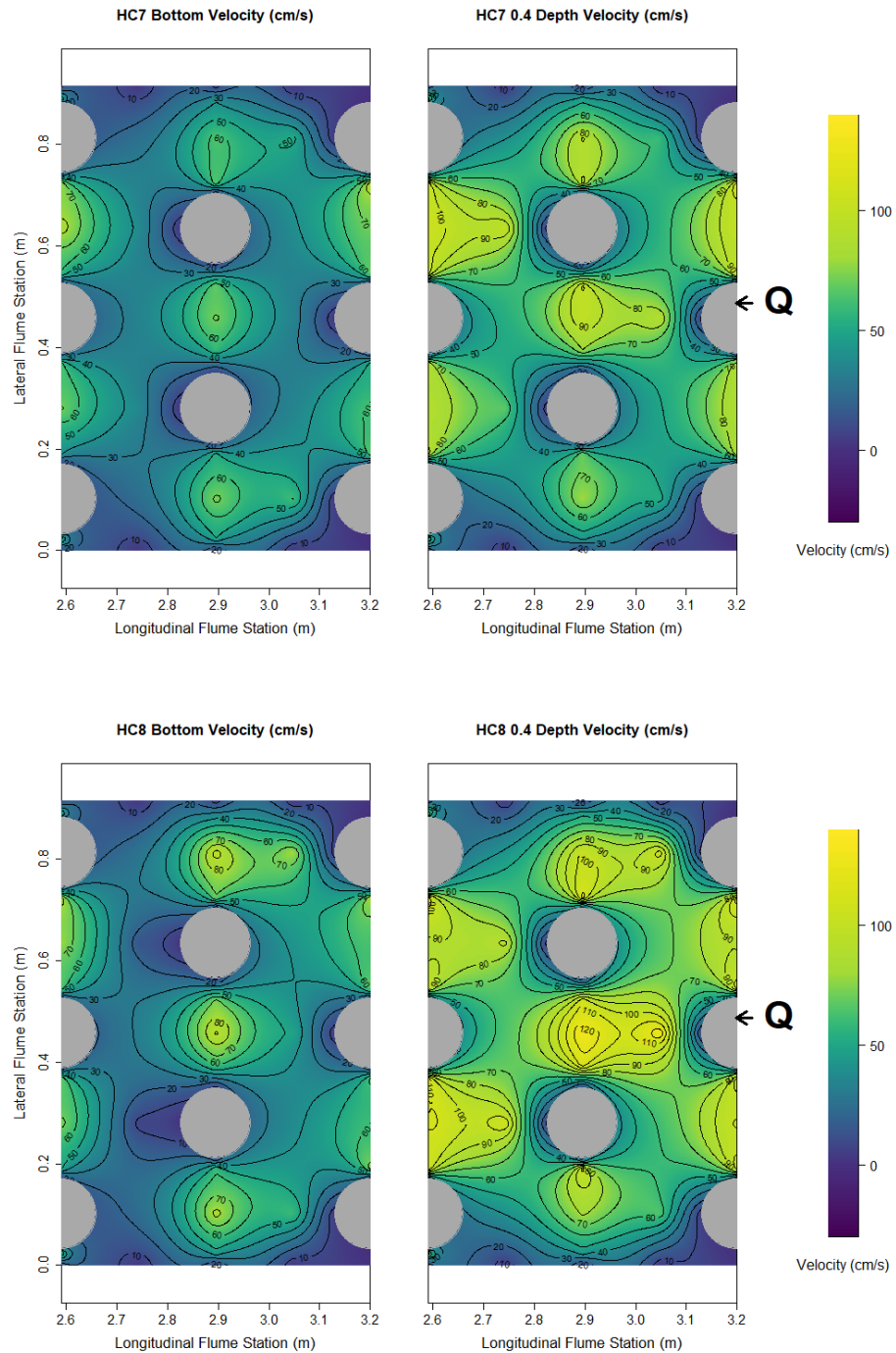


Figure 29: Velocity gradient maps for the 5% slope rock ramp using the reduced measurement grid data. Each row represents a different flow rate. The left column displays interpolated velocities on the ramp bed, while the right column shows interpolated velocities at 0.4 of the total depth. Gray circles indicate the approximate size and location of the perturbation boulders. Flow direction is from right to left.

The velocity gradient maps illustrate the spatial distribution of flow velocities within the rock ramp. The coarser sampling grid used for the 5% slope (Figure 22) reduced resolution (Figure 29), but the maps still capture the location and magnitude of maximum velocities and eddy structures, providing a detailed visualization of flow conditions. For all hydraulic conditions except HC1, bottom velocities were lower than velocities measured at 0.4 of the total depth. As flow rate increased, velocities at 0.4 total depth increased more rapidly than bottom velocities. This suggests that the rock ramp maintains lower velocity conditions near the bottom, which small-bodied and benthic fish may be able to use for passage across a range of flow rates. In contrast, larger-bodied fish are less able to take advantage of these near-bottom low-velocity zones and must navigate higher velocity areas to ascend the ramp.

The highest velocities occurred between perturbation boulders where flow constriction minimize cross-sectional area. These high-velocity regions likely represent the most challenging areas for fish passage and should be compared to the sprint swimming capabilities of the target species to determine if passage issues may exist. The velocity gradient maps also verified the presence of eddies behind the perturbation boulders, which create low-velocity and recirculating flow areas. These low-velocity zones were most prevalent near the bed and persisted across all hydraulic conditions tested. However, most eddies still contained positive velocities and were relatively small in scale, ranging from ten to twenty centimeters in length.

Depth Cross Section

The average depth from the lateral depth cross-section (Figure 21) increased with higher flow rates. At equivalent flow rates, the average depth on the 5% slope ramp were between 1.7 and 3 cm shallower than on the 3% slope ramp. These depth measurements were used to

calculate bulk velocity (V_{bulk}) which in turn was used to compute hydraulic metrics, including the Froude number ($Fr = V_{bulk} \cdot \sqrt{g \cdot H_{avg}}$), Reynolds number ($Re = V_{bulk} \cdot R \cdot \nu$), and energy dissipation factor ($EDF = Y \cdot V_{bulk} \cdot S_0$) (Table 9). Here g is gravitational acceleration, H_{avg} is the mean depth from the lateral cross section, R is hydraulic radius, ν is the kinematic viscosity of water at 10°C, Y is the specific weight of water, and S_0 is the ramp slope in percent.

Table 10: Summary of hydraulic variables calculated for each hydraulic condition, using V_{bulk} calculated from the lateral depth cross-section.

HC	Flow Rate (m ³ ·s ⁻¹)	Mean Depth (cm)	V_{bulk} (cm/s)	Fr	Re	EDF (kg·m/m ³ ·s)
3% Slope						
1	0.0315	12.0 (10.4-13.5, 0.8)	28.7	0.27	20,890	8.6
2	0.0631	15.3 (12.3-17.3, 1.1)	45.1	0.37	39,517	13.5
3	0.0946	16.5 (14.3-18.2, 1.1)	62.8	0.49	58,154	18.8
4	0.1262	19.1(16.3-21.3, 1.4)	72.2	0.53	74,378	21.6
5% Slope						
5	0.0315	10.3 (8.1-11.6, 0.8)	33.5	0.33	21,519	16.7
6	0.0631	12.4 (10.7-14.6, 1.1)	55.8	0.51	41,506	27.9
7	0.0946	13.5 (9.1-16.5, 2.0)	76.5	0.67	61,075	38.3
8	0.1262	16.3 (12.7-19.3, 1.8)	84.4	0.67	77,733	42.2

Note: The Reynolds number (Re) and the Froude number (Fr) are dimensionless. Mean Depth is presented as the mean (range, ± 1 standard deviation).

All hydraulic conditions were deep enough to ensure the largest suckers were fully submerged. Bulk velocity increases with flow rate, and V_{bulk} for the same flow rate at the steeper ramp slope was between 14%-19% higher. V_{bulk} for all hydraulic conditions that were measured was below the published burst swim speeds of both species (Dockery et al., 2017; Haro et al., 2004; Richer et al., 2020).

Differences between estimated V_{bulk} and average measured velocities (from the measurement area located approximately in the middle of the ramp) ranged from 3.3 to 20.9 cm/s across all hydraulic conditions, translating to errors of 5% to 38%, with the average measured velocity consistently higher. The greatest discrepancies between these two velocities occurred at the lowest tested flow rates on both slopes. Despite this, using average measured depths and velocities to calculate flow rates through continuity ($Q = VA$) consistently resulted in significant overestimations (between 5% and 63%) compared to the value obtained from the pipe flowmeter. Therefore, V_{bulk} was selected for calculating hydraulic metrics since it provided a consistent, continuity-based estimation across all experimental conditions.

The Froude number provides insight into flow regime. For all hydraulic conditions, Fr remained below 1, indicating subcritical flow. Subcritical flow is the lower energy state of flow in an open channel and is generally favorable for fish passage, as it minimizes excessive turbulence and extreme velocity gradients. All HCs were in the turbulent regime ($Re > 2,500$) as expected. Re increased with flow rate and showed a slight increase at the higher slope for the same flow rate, though the difference was minimal.

EDF increased with both flow rate and slope, with higher values recorded for the 5% ramp, indicating greater turbulence and energy dissipation at steeper slopes. In comparison to Re , EDF is much higher at the steeper slope for the same flow rate.

Discussion

Passage Results

This study highlights how species-specific swimming capabilities influence passage success in roughened channel rock ramps, revealing key differences between white sucker and longnose dace facing the same hydraulic conditions. The contrasting outcomes between these species offer important insights into how slope and flow rate affect passage performance, underscoring the need for species-specific design criteria. While white suckers consistently achieved successful passage, longnose dace exhibited reduced success at steeper slopes and higher flow rates, emphasizing the importance of both slope and flow as critical design variables. These findings demonstrate the potential for rock ramps to accommodate a range of passage strategies, while also illustrating the importance of these design variables to facilitate high passage for different species.

White suckers achieved consistently high passage success across all hydraulic conditions, indicating that rock ramps up to 5% slopes can support their upstream movement with the appropriate combination of boulder spacing, ramp length, and flow rates. The fish tested were adult white suckers (mean total length 381.5 ± 46.6 mm) with strong burst swimming abilities. Haro et al. (2004) found that white suckers can swim through velocities up to 4.5 meters per second, far exceeding any velocities observed in this study. In that study, even the weaker swimmers (25th percentile) passed a 13-meter section against velocities of 1.5 m/s. This suggests that, for adult white suckers, ramps of this design could be effective at lengths up to 13 meters and flow rates up to $0.1262 \text{ m}^3/\text{s}$. However, Ficke et al. (2012) showed that juvenile suckers (mean TL 122 mm) have much weaker swimming performance. As such, the high passage rates

observed here should not be extended to juveniles outside the tested size range. One fish measuring 175 mm did pass the ramp under HC8, one of the most challenging hydraulic conditions, suggesting that some smaller individuals may still be capable of passage. Nonetheless, juvenile passage may be limited due to both weaker swimming capacity and a greater susceptibility to turbulence. These findings highlight the need to consider not only target species but also life stage and body size when designing passage structures. Still, for adult white suckers in the size range tested here, the ramp proved highly effective across all tested slopes and flow conditions.

In contrast, longnose dace passage was strongly influenced by flow rate. At the lowest flow rate tested, high passage success was observed at both slopes (100% at 5% slope and 83% at 3% slope). As flow increased, passage success declined, particularly on the steeper 5% ramp. While the 3% ramp still achieved moderate passage (43%) at 0.1262 m³/s, the 5% ramp produced very low passage (7%) at the same flow rate. This indicates that a lower slope ramp is passable across a wider range of flows and is more appropriate in situations where flow cannot be regulated. These findings have important implications for design. In systems where discharge cannot be controlled, a 3% slope may offer more consistent performance, particularly for small-bodied species like longnose dace.

Slope is a critical design parameter for roughened channel rock ramps, but its influence on fish passage must be considered alongside flow rate and ramp length to ensure effective performance. The USFWS (2019) guidelines recommend a maximum slope of 3% for roughened channel rock ramps, and the findings of this study support this threshold for longnose dace. Paik et al. (2024) also demonstrated high passage rates for small-bodied species on ramps with slopes

up to 4%, with a marked decline in passage at slopes of 6% and higher. Their results showed that passage at steeper slopes can be improved for shorter ramp lengths. However, that study only tested a single flow condition for each slope. The present study builds on that work by showing that flow rate also strongly affects passage, even at moderate slopes. Together, these findings underscore the importance of considering slope, flow rate, and ramp length as key design parameters.

High participation and entry rates across all hydraulic conditions indicate that the tailwater depths used in this study effectively encouraged entry and did not deter fish. This highlights the importance of providing adequate tailwater depth, which can facilitate participation and entrance even under hydraulic conditions that may ultimately limit full passage. Castro-Santos (2004) described passage success as a continuous, time-dependent process, emphasizing the importance of providing favorable entry conditions to allow fish multiple opportunities to attempt passage, potentially adapting their strategies or awaiting more favorable environmental conditions to succeed. By ensuring a streaming flow transition into the ramp, entrance remained possible for both species across all flow and slope combinations tested.

Travel Time Analysis

Travel time patterns in this study revealed species-specific responses to slope and flow rate, with longnose dace exhibiting slower passage at steeper slopes and higher velocities, while white suckers completed ascents more quickly under the same conditions. The extended travel times recorded for longnose dace indicate they did not maintain a continuous ascent up the ramp under most flow conditions. This may reflect a natural swimming behavior in which dace move in short bursts and seek cover within the substrate, or it may indicate that the combined effects of

slope, flow rate, and ramp length exceeded their burst swimming capacity and fatigue sets in ending upstream progress; since burst swimming is a type of swimming primarily powered by anaerobic metabolism. In either case, median travel times of 568 seconds or more suggest that dace relied on velocity refugia during their ascent. Direct observations and video recordings confirmed that dace frequently paused at the ramp entrance, initiated partial ascents with rapid sprints, and then sought low-velocity zones behind perturbation boulders or within interstitial spaces in the substrate. This observation aligns with Dockery et al. (2017), who also noted that longnose dace used station holding between upstream movements under high-velocity conditions.

Dace were most frequently observed utilizing refugia along the flume edges, where velocities were significantly lower than in the central ramp, consistent with observations by Dockery et al. 2017. Velocity gradient maps (Figure 28 and Figure 29) clearly show that these edge zones consistently offered the lowest velocity swim paths and resting areas. These findings reinforce the importance of incorporating edge regions in rock ramp designs. Similar behaviors were documented by Brittain (2022) and Paik (2024), who observed small-bodied fish resting and ascending along the edges of trapezoidal rock ramps. These results support the guidance from USFWS (2019), which recommends that for larger rivers and systems with variable flow, channel designs should include both a low-flow channel and a roughened bench to maintain passability across a range of flows. Without access to these edge-affected areas, some dace may not have been able to ascend under certain hydraulic conditions. Including edge habitats with reduced velocity conditions may improve passage opportunities for a wider range of species, especially under higher flow conditions.

Travel time data from this study showed that longnose dace exhibited prolonged and variable passage durations, particularly under higher velocities, steeper slopes, and more turbulent conditions, reflecting a stepwise movement strategy. Brittain et al. (2022) reported travel times ranging from 10 to nearly 100,000 seconds across three small-bodied species in a 6.1-meter rock ramp. This broad range suggests that individual species use different behavioral strategies depending on their swimming capabilities and the conditions they faced. These findings are consistent with the present study, where longnose dace exhibited variable travel times and stepwise movement patterns, relying on periodic use of low-velocity refugia to complete passage.

In contrast, white sucker exhibited substantially shorter travel times overall, suggesting that they utilized sustained burst or prolonged speeds to ascend the ramp in a single continuous effort. Median travel times for white sucker ranged from 16 to 68 seconds across all trials. The sustained swimming behavior observed is similar to observations of white suckers in other swim studies, which described that white sucker swam continuously and did not use station holding behaviors (Underwood et al., 2014). As flow rates increased, travel time decreased indicating that the suckers increased their ground speeds against higher velocity flows. At the 3% ramp slope, some suckers had travel times exceeding 100 s, indicating that they occasionally paused or rested, possibly utilizing velocity refugia behind perturbation boulders. However, these pauses were notably shorter and less frequent than those observed for dace, indicating that the resting areas were either inadequate or unnecessary for suckers while ascending the ramp.

We optimized detection efficiency but a potential source of error may have occurred if a fish initially was detected on A2 upon entering the ramp, moved back into the tailwater pool but

out of the detection range of antenna A1, and later ascended without a second detection on A2. This scenario could artificially inflate travel times if the second, true entry went undetected. Nevertheless, the high detection efficiency of the PIT tag system suggests that missed detections were minimal. Furthermore, the extended travel times for dace are consistent with behavioral observations indicating extended refuge occupancy prior to resuming ascent. Another potential limitation of the PIT detection system was the absence of a middle antenna, which would have enabled the detection of fallback events and multiple passage attempts. While a redundant passage antenna (A4) was installed to ensure successful passage was detected, the system's extremely low missed detection rate suggests that this redundancy may have been unnecessary. In retrospect, placing an antenna at the midpoint of the ramp would have provided valuable data on fish behavior, including fallback and repeated ascent efforts. This information could have improved our understanding of passage dynamics and swimming strategies under varying hydraulic conditions.

Overall, these findings highlight distinct passage strategies: longnose dace rely on intermittent sprinting coupled with frequent refuge use, whereas white sucker are more capable of ascending the ramp using a continuous, sustained effort. Importantly, the rock ramp was conducive to successful passage for both strategies under many of the hydraulic conditions tested, demonstrating its potential to support species with varying swimming behaviors. By testing both longnose dace and white sucker, this study provides insight into how rock ramps can offer multiple swim paths that accommodate different movement strategies and body sizes, highlighting their effectiveness in supporting diverse fish species and maintaining lateral connectivity and aquatic biodiversity in river systems.

Longnose Dace Probability of Passage Model

Logistic regression results from this study demonstrate that fish length, flow rate, and slope each significantly influence longnose dace passage success. The logistic regression model we developed highlights the effect of increased fish length on increased passage probability, reinforcing the findings of Dockery et al. (2017), who observed that longnose dace swimming performance generally increases with body length. The curves also illustrate how passage probability decreases with increasing flow rate, with a much steeper decline observed on the 5% ramp. These findings underscore that, in addition to slope, flow rate plays a critical and independent role in determining fish passage success and warrants equal attention in design considerations. Similar patterns were observed by Jones (2022) at the Fossil Creek Reservoir Inlet Diversion (FCID) rock ramp, where passage success during extended high-flow monitoring was substantially lower than during the lower-flow enclosure study reported by Richer et al. (2020).

The passage probability curves are limited to the range of flows tested in this study. Additional trials at higher flow rates on the 3% ramp could help determine if there is a threshold above which passage is no longer possible. Similarly, testing lower flow rates for both slopes could help establish minimum flow thresholds needed to facilitate successful passage. These additions would further refine the predictive power of the model and inform more effective fishway design criteria.

Design elements of rock ramps, such as boulder size and spacing, can strongly influence the passage success of longnose dace across different body lengths. The positive relationship observed between fish length and passage success in this study contrasts with findings by Ficke (2015). Ficke (2015) observed no length effect on passage for a widely spaced rock ramp

(boulder spacing of approximately two diameters) and a negative length effect on passage for a closely spaced rock ramp (boulder spacing of approximately one diameter) at a 3% slope. A potential explanation for this difference is that smaller longnose dace might effectively exploit smaller velocity refugia created by smaller cobbles and tighter spacing (e.g. Ficke 2015 design), whereas the increased swimming abilities of larger dace were more advantageous in navigating ramps with larger boulders and wider open spaces, as used in the present study. The research from Ficke (2015) and subsequent studies (Brittain, 2022; Paik, 2024; Swarr, 2018) employing closely spaced, smaller boulder configurations demonstrated high passage success at steeper slopes (4–6%) for various small-bodied species. These studies collectively suggest that closer boulder spacing might better accommodate small-bodied fish by reducing the distance required for burst swimming between refugia. However, further investigation is necessary to determine the performance of closely spaced boulder ramps across a broader range of flow rates and their suitability for larger-bodied fish species.

Hydraulics

The wide range of velocities measured within the ramp under all hydraulic conditions highlights the capability of rock ramps to create diverse hydraulic environments, providing low-velocity refugia and suitable swim paths for small-bodied fish. However, while eddy regions behind perturbation boulders may serve as temporary refuges for small-bodied fish, these areas are likely insufficient as effective resting zones for larger species due to their limited size.

Dockery et al. (2017) estimated that longnose dace should achieve a 95% passage rate through a 5.4 m fishway at velocities up to 78 cm/s. Applying these passage probability curves to the average measured velocities or V_{bulk} values in this study predicts high passage rates for HC1

to HC7 based on V_{bulk} , and HC1 to HC6 based on average measured velocities. However, the observed passage results were substantially lower. For hydraulic conditions where mean velocity estimates exceeded 54.4 cm/s (HC3 average measured velocity), observed passage rates were notably reduced. The low observed passage rates at treatments where velocity estimations are within the swimming capabilities of the dace underscore the limitations of relying solely on V_{bulk} or mean measured velocities as predictors of passage performance for small-bodied fish in roughened channels.

Examining velocities specifically between perturbation boulders, where fish are forced into swim pathways where higher velocities typically occur, may be more important for predicting passage when paired with fish swimming capabilities than assessing V_{bulk} values. The velocity gradient maps (Figure 28 and Figure 29) indicate that fish could theoretically navigate the ramp without encountering velocities above 80 cm/s across HC1–HC7, provided they utilized the lower velocity zones near the bed. Although longnose dace can traverse velocities of this magnitude and greater for distances exceeding the boulder spacing (Dockery et al., 2017), observed passage rates of 64% or lower at HC3–HC4 and HC6–HC8 demonstrate that average velocity estimates alone are insufficient to predict successful passage. Ficke (2015) similarly reported low passage rates (31–38%) despite velocities maintained below dace sprint speeds. These results emphasize that measured velocities may be a poor predictor of passage for small-bodied fish, as success depends on how individuals navigate the spatially variable flow produced by a roughened channel rock ramp.

Several factors potentially contribute to reduced passage success under higher flow and steeper slope conditions. Firstly, eddies behind boulders at higher slopes, although visually

presenting low streamwise velocities, may provide inadequate or excessively turbulent resting zones for dace recovery between burst swimming efforts. Secondly, dace might not effectively utilize lower-velocity areas near the bed and instead experience higher velocities in the upper water column. Additionally, the ramp length itself may surpass the fish's endurance limits using a burst-and-rest swimming strategy, causing cumulative fatigue that prevents successful ascension under challenging conditions. Supporting this, Paik et al. (2024) showed small-bodied fish could successfully ascend shorter rock ramps at steeper slopes, but their passage success decreased notably at the full ramp length. Finally, higher-velocity regions possibly existed outside the coverage of the measurement grid, presenting unseen barriers.

Comparing hydraulic metrics and passage success between HC3 (3% slope, $0.0946 \text{ m}^3/\text{s}$) and HC6 (5% slope, $0.0631 \text{ m}^3/\text{s}$) provides insights into the role of ramp slope. V_{bulk} and average velocities for HC3 (62.8 cm/s and 66.1 cm/s) and HC6 (55.8 cm/s and 67.3 cm/s) were similar, as were Froude numbers (0.49 for HC3, 0.51 for HC6). Reynolds numbers, representing general turbulence levels, were higher for HC3 (58,154) than HC6 (41,506). Based on these metrics alone, HC6 would be expected to yield equal or better passage than HC3. However, actual passage at HC6 (47%) was notably lower than at HC3 (64%). In contrast, the EDF, possibly a better measure of turbulence intensity, was higher at HC6 ($27.9 \text{ kg}\cdot\text{m}/\text{m}^3\cdot\text{s}$) compared to HC3 ($18.8 \text{ kg}\cdot\text{m}/\text{m}^3\cdot\text{s}$), aligning with observed passage trends. The considerably higher EDF at the 5% slope treatments, even with comparable velocities, suggests notably greater turbulence, indicating that turbulence rather than velocity may be a factor limiting fish passage at the steeper slope. This supports EDF as a potentially more meaningful predictor of small-bodied fish passage in roughened channels, suggesting turbulence intensity rather than velocity alone may

critically limit passage under certain conditions. The higher EDF at HC6 might also indicate eddies at the steeper slope become ineffective resting zones due to increased turbulence.

These findings highlight EDF as a promising metric for designing and evaluating rock ramp fishways, particularly for turbulence-sensitive small-bodied species. Conversely, Reynolds numbers derived from the lateral depth cross section method provide limited utility, as they do not adequately capture the scale, structure, or spatial variability of turbulent flow features critical for fish navigation. Fine-scale turbulence metrics like turbulent kinetic energy (TKE), turbulent length scale, dissipation rate, Reynolds shear stress, or vorticity may offer improved descriptors for future studies.

In this study, passage success rates were high (83–100%) for conditions with EDF values at or below 16.7 (HC1, HC2, HC5), whereas higher EDF conditions (≥ 18.8) were associated with significantly reduced passage success. Current EDF design recommendations for roughened rock ramps are limited to maximum values established for salmonids ($< 20 \text{ kg}\cdot\text{m}/\text{m}^3\cdot\text{s}$) and American Shad (*Alosa sapidissima*, $< 15.7 \text{ kg}\cdot\text{m}/\text{m}^3\cdot\text{s}$) (Ficke, 2015; Haro et al., 2008). These findings align with Haro et al. (2008), suggesting EDF thresholds below 15 may offer conservative and effective design criteria for ensuring successful passage of small-bodied fish.

For larger-bodied fish, such as white suckers, mean velocity estimates may still be effective predictors. White suckers in this study averaged $381.5 \pm 46.6 \text{ mm}$ total length, and previous research by Haro et al. (2004) demonstrated that individuals exceeding 285 mm can successfully pass velocities up to 4.5 m/s—significantly higher than velocities measured in this ramp. Thus, the high passage success of white suckers across all hydraulic conditions observed in this study aligns with these known swimming capabilities. However, because velocities tested

in this study were substantially below these published limits, the results provide limited insights into the predictive power of velocity-based metrics for larger-bodied fish under more challenging conditions.

There was no control used in this experiment due to a constraint on the number of fish available. Previous research indicates that adding perturbation boulders to a ramp significantly alters hydraulic conditions; for instance, Ficke (2015) modeled smooth ramps versus ramps with perturbation boulders, reporting velocity reductions of 31–34%, Froude number reductions of 37–41%, and increases in energy dissipation factor of 31–36%. Similarly, Baki et al. (2014) found that ramps with perturbation boulders exhibited approximately threefold increases in depth and velocity reductions ranging from 54 to 71%. These findings reinforce the hydraulic influence of boulder configurations and suggest that their inclusion in this study likely played a key role in creating passable conditions at steeper slopes, particularly by enhancing depth, reducing velocity, and providing velocity refugia.

In comparing the hydraulic metrics from this study with those reported by Baki et al. (2014), several differences emerge. Under comparable flow and slope conditions, this study showed lower Reynolds and Froude numbers. However, because these metrics were calculated using V_{bulk} , which consistently underestimated velocities compared to average measured velocities, the reported values for Reynolds and Froude numbers may be underestimated. While methodological or discharge differences could explain some discrepancies, a notable distinction in this study was the inclusion of a gravel substrate. The gravel substrate likely increased boundary roughness, thereby reducing near-bed velocities and contributing to more favorable hydraulic conditions. This aligns with findings from Swarr (2018) and other studies indicating

that adding gravel substrate to rock ramps increases depth, decreases velocities, and enhances passage performance for small-bodied fish.

Conclusion

The experimental rock ramp fishway evaluated in this study effectively increased water depths and reduced velocities, creating passable conditions for both white sucker and longnose dace at slopes of 3% and 5%. White sucker exhibited consistently high passage rates (97%) under all tested hydraulic conditions, demonstrating that 5% slopes can effectively facilitate their passage over a range of flows. However, as the white suckers tested were mature individuals averaging 381.5 ± 46.6 mm in total length, results should not be extrapolated to smaller juveniles, whose swimming capabilities are likely lower.

In contrast, longnose dace successfully ascended the 3% ramp across multiple flow conditions, but exhibited declining passage rates at increased flow rates. At the steeper 5% slope, longnose dace showed moderate passage success at the lowest tested flow rate, but passage rapidly decreased with increased flow. These results provide strong evidence supporting the recommendation of using slopes of 3% or lower when designing fishways for small-bodied or weak-swimming species, as lower slopes offer suitable passage conditions across a broader range of flows.

Logistic regression analysis further supports these conclusions, identifying flow rate, slope, and fish length as significant predictors of longnose dace passage efficiency. The higher success rates observed among larger dace reinforce the importance of considering fish size and developmental stage when designing fishways. These results highlight the need to design rock ramps to accommodate the weakest swimmers in the target fish community to preserve

longitudinal connectivity. At the same time, physical design elements—such as boulder spacing—must also allow the largest species to navigate through the structure. Together, these considerations ensure the ramp supports the full-size range and swimming capabilities of the fish community. Overall, the findings of this study demonstrate the effectiveness of rock ramps as fish passage structures, as their complex hydraulic environments can facilitate movement for species with a wide variety of swimming strategies and behaviors.

Hydraulic measurements illustrated the broad diversity of velocities within the ramp, highlighting the complexity and variability in rock ramp hydraulics. The discrepancy between velocity estimates derived from bulk velocities (V_{bulk}) or average measured velocities and actual observed fish passage underscores the limitations of relying solely on simplified velocity metrics as passage predictors in roughened channel rock ramps. The results demonstrated that velocity distribution, spatial variability, turbulence, and energy dissipation patterns may provide more meaningful explanations for passage success than average or bulk velocities alone. Future research incorporating 3D CFD modeling to better characterize the complex hydraulics within rock ramps, particularly detailed turbulence patterns, and pairing this with fish passage data from studies like this one, could greatly enhance our understanding of the hydraulic conditions influencing fish passage.

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