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Complexities of Attraction Water Systems: A Review & an Experiment Showcasing their Effects

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COMPLEXITIES OF ATTRACTION WATER SYSTEMS:
A REVIEW & AN EXPERIMENT SHOWCASING THEIR EFFECTS

A Masters Project Presented

by

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ABSTRACT

STATE OF ATTRACTION WATER SYSTEMS
&
FISH BEHAVIOR AND HYDRAULIC ASSESSMENT OF WIDELY USED WALL DIFFUSER

Directed by: Prof. Richard Palmer, Dr. Kevin. Mulligan, and Dr. Brett Towler

The presence of dams has direct negative effects on populations of migrating fish and their riverine habitat as well as impacts on the ecosystem services they provide. Fishways, provide upstream and downstream passage that is safe and timely, comprising specifically of "physical structures, facilities, or devices necessary to maintain all life stages of such fish, and project operations and measures related to such structures, facilities, or devices which are necessary to ensure the effectiveness of such structures, facilities or devices for such fish" (National Energy Policy Act 1992). Fishways, sloped channels or elevators that connect the tailrace to the head of the dam, are one type of mitigation strategy; however there is a need for evaluating their effectiveness as populations of migrating fish continue to decline. This study is a two part investigation of the Auxiliary Water System (AWS), a pivotal technology in guiding fish into the fishway entrances. To effectively attract fish to the fishway, contributions from the AWS are essential; however, the hydraulic complexities associated with AWS inside the entrance channel may be causing negative behavioral responses to safe and timely fish passage.

The content of the research presented in this paper is twofold. First it provides a review of the state of AWS in the field through a review of criteria manuals and the building of the Fishway Systems at Hydropower (FiSH) database. The database hosts predominantly fishways from the Northeast. The results indicate most AWS designs are gravity fed floor diffusers followed by gravity fed wall diffusers.

Second, the study provides primary insight on the behavioral response of American shad to wall diffusers in the fishway entrance. During the spring of 2019, research was conducted on a full-scale wall diffuser using actively migrating American shad to evaluate the behavioral responses in a controlled flume environment. The experiment held constant flow conditions in the entrance channel immediately upstream of the diffuser. Flow through the AWS remained constant, while the diffuser velocity varied from 0.5 to 1.0 fps. Hydraulic data on the diffuser was gathered from a 1:8 scale physical model. The data analysis draws spatial and temporal correlations between the hydraulic parameters of the system, namely velocity, and the tracked fish movement through the study area. The data analysis from the behavioral and hydraulic experiments indicates better passage and preferable hydraulics for the 0.5 fps velocity treatment. The evaluation of this widely used technology further informs decisions regarding improvement and implementation of fishway technology.

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CHAPTER 1: THESIS INTRODUCTION

1.1 Importance of Research

Free flowing rivers are essential to the balance of physiological, biological, and chemical processes that characterize a healthy ecological system (Stockner 2000). Sediment transport processes, local river and estuarine habitats, and larger scale fish migrations are dependent on natural connectivity (Bunn & Arthington 2002). With the emergence of dams in medieval times for power production, these processes have been greatly affected (Hall et al. 2011, Katopodis & Williams 2011). One of the first notable impacts of dams to the general public is the decline in culturally and economically important fish (Mattocks et al. 2017, Green & Westbrook 2009, Atkins and Foster 1868, Judd 1997). Humans have explored a wide variety of adaptation strategies to limit the impacts of dams and provide means for fish to migrate around dams. The earliest account of the requirement of fish passage is from the 13th century Magna Carta, calling for the removal of inland weirs by the weir or dam owners, or mitigation by providing some other form of passage over the barrier (Towler 2012). These laws applied during America's colonization. An account of passage in the U.S., from 1714, involves a farmer named William Arnold who created a channel around Pawtucket Falls, Rhode Island to allow for fish passage (Goldfarb 2018). Despite more than 300 years of effort, the decline in migrating fish in the U.S. and around the world remains. Many previously important species are now endangered, extirpated, or at the worst extinct (Hall et al. 2011, Limburg & Waldman 2009, Silva et al. 2018). Although issues such as overfishing, discharge of wastewater, and chemical pollution have contributed to these declines, the construction of dams has continued to have a major impact on fish populations (Limburg & Waldman 2009).

In 1992, the National Research Council estimated between 2-2.5 million dams of all sizes are located in U.S. rivers (NRC 1992). The Army Corps of Engineers in its National Inventory of Dams (NID) estimates there are over 90,000 (NID 2018). This dataset only features dams that are taller than 25 feet, impound at least 50 acre-feet, or are deemed a public safety hazard by FEMA (Grabowski et al. 2018). Of these dams, only 3% are hydropower dams, yet these dams constitute 6.6% of the U.S. utility-scale electrical generation and 2.5% of the total energy produced in the U.S. These dams are the highest percentage of current clean energy alternatives in the U.S. (EIA 2019). As dam sciences continue to evolve and a better understanding of the economic, environmental, and socio-cultural impacts of dams is achieved, it is clear that improving fishways at hydropower facilities is necessary for continuing operation of hydropower facilities in the U.S.

Designing a fishway is a multi-objective problem that considers the physiological and biological needs of fish as well as the impacts of the fishway on the revenue generated by the hydropower facility. There are two major categories of fishways: nature-like and technical (U.S. Fish and Wildlife Service 2019). Nature-like fishways are bypasses containing natural materials such as rock, wood, and plants placed in the earthen channel for specific hydraulic goals. Technical fishways include sloped channels with hydraulic variation (e.g. the steps of a "ladder") and elevators made of engineered wood, concrete,

and metal materials. Most fishways at hydropower plants are technical fishways. Many hydropower projects are located relatively near urban areas and other constrained land areas. These technical fishways are engineered systems providing more control of flow. Managers can maintain flows necessary to attract fish at hydropower sites that have varying hydraulic characteristics, which can distract fish. Technical fishways are built to provide either upstream or downstream passage; helping fish go from the bottom tailwater area of the dam to the top forebay area or vice versa. There are three different types of upstream fishways: Chutes, Pool-type, and Mechanical. Chutes and Pool-type use fish positive rheotaxis, the instinct of the migrating fish to swim against the current. See common designs of these fishway types in Figure 1.1 below.

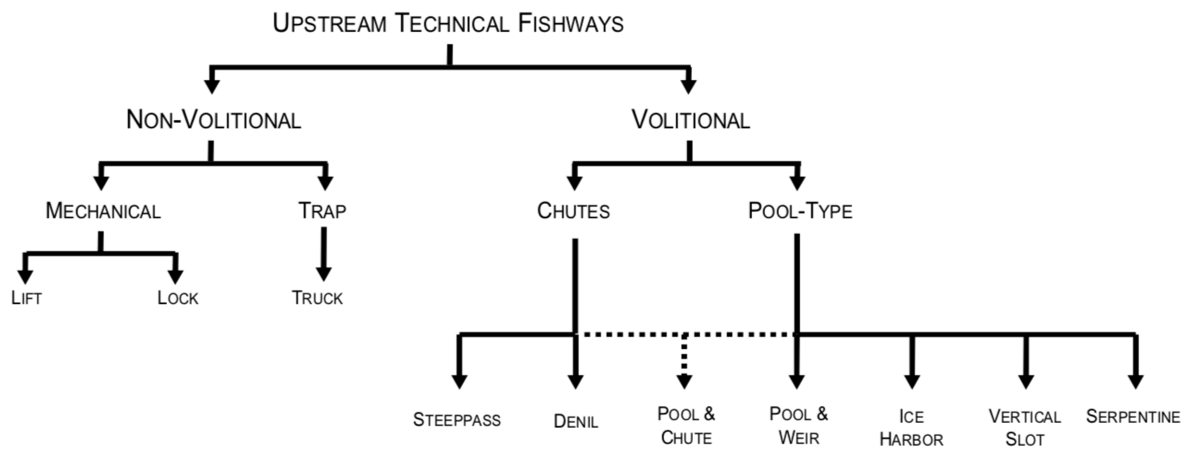

Figure 1.1 Types of upstream technical fishways. (USFWS 2019)

Though the volitional approach is more natural, there higher energetic costs for fish with these designs. The Mechanical category is primarily fish lifts (elevators). The energetic costs for lifts are low since the fish are mechanically moved upwards. However, moving parts and human handling are still possible stressors (USFWS 2019). In this thesis, “fishway” or “fish pass” consistently refer to technical fishways.

Fishways must provide attraction flow sufficient that migrating fish can locate the entrance without significant delay. Due to the complex and competing flows near dams (e.g. spillage, turbine outflow), a clear flow path is needed that aids the fish in identifying the fishway entrance. The attraction flow is produced by supplementing the fishway entrance channel with water that merges into the entrance channel through a vent-like diffuser, connected either vertically on the wall or horizontally on the floor of the channel. The two merged flows then exit the fishway entrance and move into the tailrace as a singular stream. This is called an Attraction Water System (AWS). The rate of flow is constrained by the velocity requirements within the fishway entrance channel. The added water increases the velocities in the downstream section of the fishway entrance channel and may require fish to swim at burst or near burst speeds. Site studies and professional experience suggest that the merging of the AWS flow disturbs the fish and creates delays in passage and fallback (J. Morales, B. Sojkowski, and B. Towler, *personal communication*, October 2018). AWS systems are widely used, yet their effect on the behavior and performance of fish inside the fishway has not been extensively evaluated.

1.2 Research Objectives & Study Approach

This thesis explores the state of the science of the AWS technology, documents current professional application of AWS in the New England region fishways, and evaluates criteria for wall diffuser-type AWS by performing a set of scale behavioral and hydraulic experiments with actively migrating American shad.

1.3 Thesis Structure

This thesis has three chapters. This chapter provides background on fishways and characteristics and concerns related to Attraction Water Systems. Chapter 2 explores the state of the science of AWS, with a focus on practices in the Northeast. In addition, a preliminary inventory of fishways with AWS and examples from the inventory illustrate the different types of AWS in use. This knowledge is essential to informing future efficiency studies and prioritization of fishway work. Information regarding AWS describing the types of systems, components, and flow and sizing recommendations exist within state and federal agency manuals such as the USFWS Regional Fish Passage Design Criteria and NOAA Fish Passage Criteria manuals.

Chapter 2 presents a comparative view of the criteria documentation and includes real-world examples of each type. The spatial nature of the currently operating diffusers in the Northeastern region of the U.S. is also presented as a map. In addition, existing issues with in-channel AWS and acceptable flow mixing challenges are presented from the new USFWS R5 2019 Fish Passage Engineering Design Criteria manual, academic literature, and a private engineering case study. To date, there are few studies that explore the internal effects on passage efficiency of AWS and none that validate the technology with consideration to system hydraulics or the fish response. Validating the technology is essential in understanding fish needs and improving options for these systems. The second chapter investigates the internal effects of one of the most common AWS systems.

Chapter 3 presents the biological and hydraulic evaluation of a wall diffuser AWS, assessing the fish behavior and local hydraulics throughout the entrance channel. The two experiments were performed in the hydraulics laboratory at the USGS Leetown Science Center S.O. Conte Anadromous Fish Research Laboratory in Turners Falls, MA. The laboratory consisted of a full-scale prototype 20-foot wide, 126-foot long flume and a small-scale 2.5-foot wide, 15-foot long flume. The behavioral study was conducted in the large-scale flume with passive integrated transponder (PIT) tagged stream-native actively migrating American shad. Measuring the hydraulic characteristics in the full scale flume was not possible, these were instead measured in the small-scale flume. The American shad is an east coast native species commonly included in conceptualizing fishway designs in the eastern U.S. Chapter 3 presents separate Methods and Results for the behavioral and hydraulics studies, then jointly exams the studies in the Discussion and Conclusion.

The technical study, along with the current criteria, and both spatial (location) and temporal (relicensing date, approximate age of the infrastructure, maintenance periodicity) information, provide a more complete understanding of needed design standards and criteria in terms of attraction technology and will support decision-making in the future.

CHAPTER 2: STATE OF ATTRACTION WATER SYSTEMS

This chapter characterizes in two approaches the role of attraction water systems (AWS) and the state of the technology. First, a review of existing baseline models and the design criteria are provided from literature. Second, a database provides an overview of existing AWS systems at hydropower facilities in the Northeast, along with a summary of that data and case studies for each type of AWS in the database. This initial regional database can be extended through collaboration between agencies and citizen scientists.

2.1 Attraction Water Systems Background

Hydropower projects often have complex hydraulics that vary spatial and temporally. Spills or turbine releases occur at different locations along the dam and operational plans can change on hourly, daily, and seasonal timescales. It is essential to have an appropriate flow stream that fish can distinguish from other flow patterns to guide fish to the fishway entrance location. The flow required for the fish to identify the fishway entrance is called "attraction flow," a vital element in fishway efficiency (Katapodis 1992, Environment Agency 2010). For upstream passage, attraction flow is typically the total discharge from the entrance of the fishway. This flow is the sum of the flow from the main pass (i.e. ladder) and the water entering the entrance channel of the fishway through a diffuser (Figure 2.1). The entrance channel is the lower zero-slope section of a fish pass. Fishways in the eastern U.S. are typically smaller than those in the west. The smaller size makes it a challenge to ensure attraction flows are sufficient for fish to perceive them over other competing flows (i.e. spilling over dams and turbine outflow). Larger fishways have sufficient area for the larger flows needed to attract fish. Equivalent flows in the smaller fishways result in high velocities, requiring fish to swim at higher velocities for prolonged periods that are detrimental to a successful migration. Providing appropriate attraction flow is one of the main factors in safe and timely passage because of its immediate role in fishway efficiency (Larinier 2002, Katapodis 2005, Limburg & Waldman 2009, Environment Agency 2010). Delays in finding the passage can expose fish to predation, disease, and competition, resulting in death, injury, illness, and unnecessary energy expenditure (Larinier, 1992, Nakamura 1993, OTA 1995).

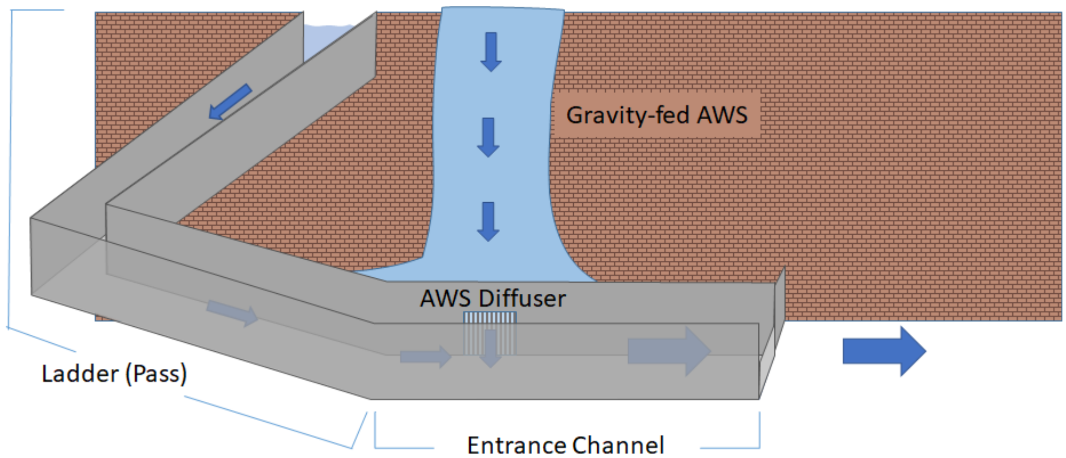

Figure 2.1 In this fishway, the attraction water comes from upstream of the barrier, spilling over, landing in a dissipation pool next to the fishway, and then entering into the horizontal entrance channel through a wall diffuser.

In addition to producing attraction flows at the tailrace of a dam, AWS impact hydraulics in other sections of the fishway. Castro-Santos (2012) presents a useful framework for conceptualizing fishway goals and the role of AWS. The author characterizes a fishway into three zones: approach, entry, and passage (Figure 2.2). Each zone has a specific goal in supporting the journey of fish over the barriers.

The first zone the fish encounters is the approach, located at the tailrace of the dam. This zone is the most often associated with AWS. The zone's design goal is for the attraction flow from the fishway to be recognizable by the fish and to divert fish from pursuing false flows (i.e. competing flows) (Larinier 2002, Downing et al. 1995, Castro-Santos 2012, Gisen et al. 2017). In this zone, the fish perceive the flow coming from the fishway, but also may recognize false flows such as the turbine outflow, spillways, floodgates, trash sluices, or cooling water returns (Towler 2016). Criteria and formal studies historically focus on attraction flow as it relates to leading fish into the fishway, since attraction flow in this zone is vital to successful passage (Katopodis 1992, Clay 1995, Lucas & Baras 2001, Marmulla 2001, Aarestrup et al. 2003, Bunt et al. 2016, Cooke & Hinch 2013).

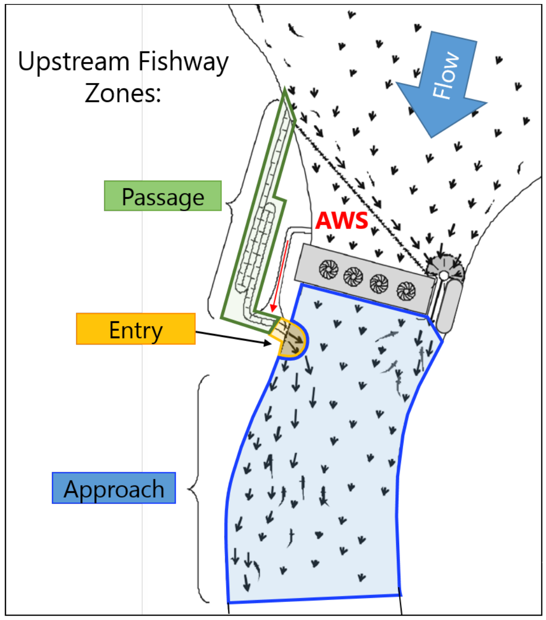

Figure 2.2 Zones Sketch. Approach - fish approach the tailrace area, where the water from the fishway must be identifiable over any spillage or turbine outflow. Entry - The fish enter the fishway and swim through the entrance channel. Passage - The fish now either begin their upstream ascent through the ladder, or are mechanically moved over the dam by lift, lock, or transport. Figure adapted from Castro-Santos 2012.

Once a fish reaches the entry zone, it must pass the entrance gate (if present) and move through the entrance channel, past the AWS diffuser. The channel at this point is level to the downstream water surface. The design goal for this zone is for the velocity, water levels and internal hydraulics to be acceptable for the physical abilities, size, and behavior of the fish (Pavlov 1982, Larinier 2002, Castro-Santos et al. 2009, Keefer et al. 2011, USFWS 2019). The merging flow from the AWS diffuser into the entrance channel is an important design consideration for this zone. The type of water conveyance and channel connector (if applicable) for the AWS system are key factors in creating appropriate hydraulics.

In the passage zone a fish begins its ascent over the dam, ideally, with no changes in the water quality and temperature. This section is what characterizes the type of fishway, be it a ladder type, a lift, a lock, or trap and transport. The passage and approach zones are not necessarily affected by the type of AWS, but rather by the simple absence or presence of the additional water. It is possible that the passage and approach zones are affected by the incoming AWS flow if the hydraulic features such as velocity, turbulence, or aeration of the incoming water extends into those areas.

An AWS has two main elements: the conveyance system and a connector type. The conveyance system provides water to the AWS structure. The connector is the type of diffuser connecting the water flow in the AWS channel to the fishway entrance channel. There are two types of AWS water conveyance designs: gravity (open channel and pressurized pipe) and pump. In the eastern U.S., the gravity-fed pressurized pipe AWS is the most common (USFWS 2019). All three designs have an intake screen component,

a hydraulic control gate, conveyance method, and dissipation pools. The USFWS recommends systems having baffles/turning vanes within the AWS channel (USFWS 2019, Heise 2011). The purpose of these is to create a more uniform velocity distribution before the flow enters the main channel through the diffuser. The baffles and turning vanes are located upstream of the diffuser in the AWS channel.

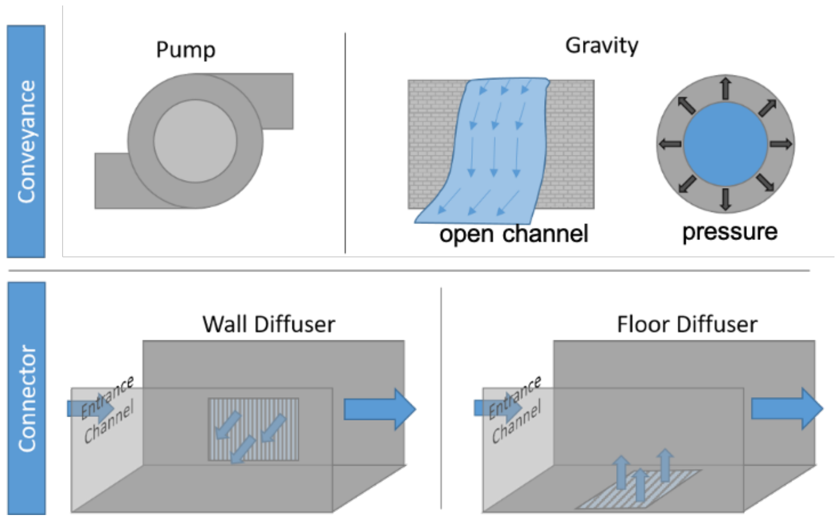

Figure 2.3 The two basic components of an Attraction Water System are the source of the water, and the connector into (or adjacent to) the fishway.

There are two common types of diffusers: a lateral diffuser on the channel wall and a horizontal diffuser on the floor. The conveyance and diffusers are chosen depending on the site. In rare cases, attraction water is introduced through near-entrance discharge systems. Examples of these are a strategically placed spillway with a guidance channel or some other variation of using available flows near the fishway entrance (Mulligan 2019, October 9, Fiedler et al. 2018). For the latter, an example is a "crossover" design: a mix between near-entrance discharge and a wall diffuser AWS (Fiedler et al. 2018). The AWS design includes the attraction discharge near-parallel to the main pass (Figure 2.4 right). The main pass and AWS flows are confined within a channel that then enters the entrance pool area. Redeker & Heimerl (2018) explored this design, using computer models with the intent for future implementation. Similarly, the "Entrance Palisade" is a near entrance discharge AWS design that outputs flow from a channel parallel to the fishway entrance (Mulligan & Palmer 2019, Figure 2.4 left). The downstream end of the channel features an angled, providing physical guidance into the entrance in the entry zone once fish have passed the approach area.

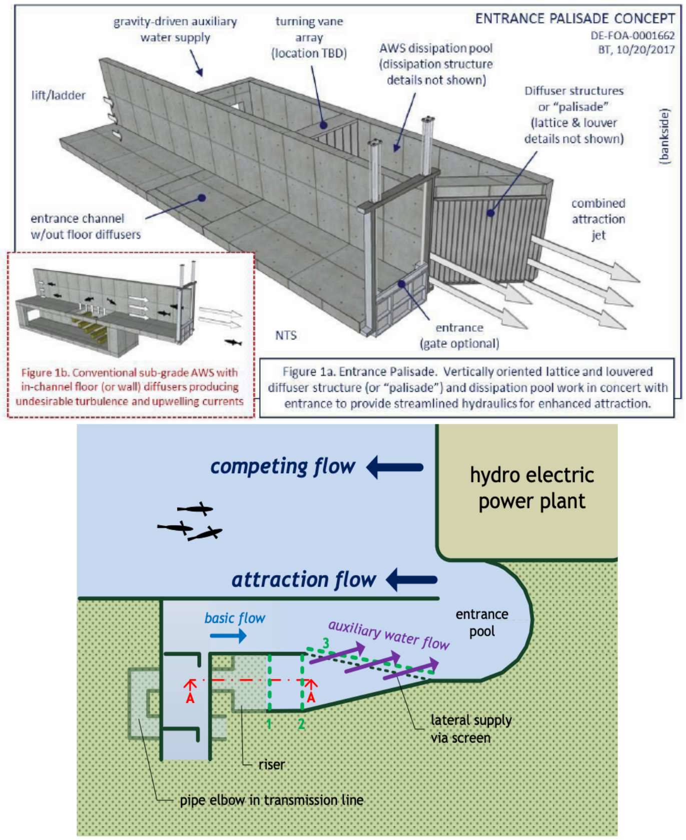

Figure 2.4 (LEFT) Entrance Palisade system from UMass, USGS, USFWS, and NOAA collaboration (Mulligan & Palmer 2019, October 9); (RIGHT) Entrance channel plan view diagram of a crossover design diffuser (Fiedler et al. 2018).

All AWS designs are adaptable to different settings and the choice is site dependent. Wall diffusers were the first and most dominant connector in the western and eastern U.S. Later on, there was a shift in the Northeast to using more floor diffusers. This change resulted from practitioners and operators noting that once inside the entrance channel, the species of interest was attracted to the wall diffuser structure when at higher velocities, delaying migration. In response, the wall diffuser velocity criterion was decreased and the floor diffuser velocity criteria was increased. The smaller diffuser cross-sectional area and associated lower cost made floor diffusers the preferred choice (B. Towler, *personal communication*, 2019).

2.2 General Criteria & Regulation

Design standards for fish passage facilities continue to evolve. Regulatory agencies in the U.S., including the National Oceanic and Atmospheric Agency (NOAA) and the U.S. Fish and Wildlife Service (USFWS), acknowledge in their design manuals the need for safe and timely passage as a design criteria (USFWS 2019, NOAA 2011). Discussions of attraction flow in these documents focuses on design of the approach zone. Attraction flow criteria are consistent among governmental agencies internationally (Gisen et al. 2017). There are

three typical approaches to establishing the attraction flow quantity: 1) a percentage of the false flows, 2) a percentage of the river flow, or 3) a function of the design flows at the peak flow and migration seasons (USFWS 2019, Bunt et al. 2016, NMFS 2011, Larinier 2002) (See Table 2.1 for details on AWS flow criteria). The NMFS suggests a percent of the high design flow for large streams and a larger percentage for smaller streams. The USFWS calls for the minimum of either a percent of the powerhouse hydraulic capacity or 50 cfs. Internationally, the German Association for Water, Wastewater and Waste (DWA) and Britain's Environment Agency (EA) both use Larinier's approximations in their fish passage manuals (Gisen et al. 2017, DWA 2014, Redeker 2014), which is a percent of the competing flow during the migration period (Larinier 2008). Generally, higher attraction flows result in a more effective facility (Bunt et al. 2016, NMFS 2011, Larinier 2002). Much of the regulation for fishways is established and enforced on a case-by-case basis.

Table 2.1 Adapted from IFC-USAID Fish Passage Workshop 2016, Nepal - Brett Towler

Agency/Experts	AWS Flow Criteria	Diffuser Criteria
USFWS R5 (2019)	5% of powerhouse hydraulic capacity *result of percentage may not be under 50cfs	0.5fps both for wall and floor diffusers + other guidelines for appropriate set-ups
NMFS Northwest Region - NOAA (2011)	non-hydro sites - Large streams: 5-10% of high design flow Smaller streams: larger percent	1.0 fps for wall diffusers 0.5fps for wall diffusers + other guidelines for appropriate set-ups
Larinier (2002)	2-5% of competing flows during migration period For rivers of Q > 3532 cfs (100 m^3s^{-1}), 1-1.5% highest design flow	
Environment Agency (2010)	Do not inject attraction jet where there might be cross-flows or high turbulence. Align with local velocities. Avoid recirculating eddies. 5% of annual daily flow (ADF) if possible, ≥10% (generally possible for ADF < 530cfs ($15m^3s^{-1}$) At sites with turbine outflow: pass discharge at Hands off Flow (HoF) is 5-10% of max turbine discharge Smaller/less effective fish pass	Insufficient attraction flow can be accommodated by preferably discharge into the final pool or fishway entrance. Discharge energy must be appropriately dissipated. Other method can be discharge adjacent the fishway can be used.

	locations: choose higher percent	

Most fishways cannot meet these attraction flow criteria alone, requiring additional water discharge systems that augment the original fishway flow. Common fishway flow designs range from 3 to 55 cfs (Table 2.2). For example, Woodland Dam, in Maine, has a hydraulic capacity of 11,600 cfs and has a 4-ft Denil. If the Denil has a normal flow capacity of 30 cfs, that is only 0.25% of the station capacity. To meet the USFWS minimum attraction flow criteria calling for 5% of the hydraulic capacity, an AWS would need to provide the extra 4.75%. Having no AWS would require a larger fishway to provide flows that satisfy the criteria. Such a structure would not be feasible for many sites with respect to dam operation requirements, land availability, and cost. Alternatively, raising the velocity in the Denil to satisfy the flow requirement would impede fish movement. The velocities might require fish to swim faster than recommended and could even be a barrier if fish cannot swim against them. Either way such cases would affect energy expenditure and result in migration delays. Depending on the design of a fish lift, passing all flow through the main channel is not as concerning. For example if the entrance channel leading to the hopper is relatively short in length, the fish would only be sprinting a small section and going into the lift, whereas in a Denil the fish would have to endure higher flows for a longer duration. However, if the lifts entrance channel is very long a fish ladder design is comparable effort for the fish.

These discharge design limits for the fishways are not just for structural reasons, the velocity is important to the fish's overall migration success. Though fish are motivated during migration by faster flows, continual sprint speeds are unnecessary for successful passage after their initial entrance to the fishway (USFWS 2019, Goodwin et al. 2006, Katopodis 1992b, Bell 1991, Clay 1995). A good design will maximize attraction flow downstream outside of the fishway entrance and minimize sprint speed areas The allowable velocity limit flowing out of the fishway and at the entrance is 4 to 6 fps for east coast fishways (USFWS 2019, Castro-Santos 2005). These criteria are based on physical limitations and behavioral responses of American shad and river herring (Castro-Santos 2005, Litaudon 1985, Weaver 1965), the fish species on the east coast with the most difficulty passing. Typical American shad prolonged (cruising) speeds are around 4.9 to 9.8 fps, while sprint speeds are around 9.8 to 19.7 fps. The upper fishway exit, fishway entrance gate, and flow quantity through the AWS control the velocity through the entrance.

Table 2.2 Fishway designs and typical main channel discharge range. From IFC-USAID Fish Passage Workshop 2016, Nepal - Brett Towler

Fishway Type	**Discharge (cfs)**
Steepass (22" wide)	3 – 10
4-ft Denil	16 – 35

16-ft Half Ice Harbor	30 – 50
8-ft W by 10-ft L V-slot	10 – 55

Another criterion associated with AWS is the velocity of the water flowing into the fishway through the diffuser. The maximum velocity recommended varies depending on regulatory agency. On the U.S. west coast, the guideline is 1.0 fps for wall diffusers and 0.5 fps for floor diffusers (NMFS 2011). On the east coast, the guideline was previously 1.0 fps for floor diffusers and 0.5 fps for wall diffusers (USFWS 2019). The most recent guideline is 0.5 fps for both wall and floor diffusers, and it is highly recommended to have a diffuser vane system that will produce a uniform velocity distribution (Table 2.1) (USFWS 2019).

In the 1950s, west coast states started to consistently implement fishways at hydropower sites. These fishways were for Pacific salmon (Nordlund 2011, Katopodis & Williams 2011). Maintenance for wall diffusers is easier and they require a smaller area (A) when considering the same flow (Q) requirement. This made wall diffusers prominent in western fishways. Salmon were less receptive to the floor diffusers due to upwelling. In the 70's and 80's, western fishways AWS criteria were implemented at hydropower sites on the east coast. Over time, engineers and biologists implementing the western criteria realized that American shad (one of the eastern design species) would cluster at the wall diffusers, causing delays in migration. The design response was to switch the criteria, lowering the wall diffuser velocity to 0.5 fps and raising the floor diffuser velocity to 1.0 fps. Floor diffusers built with these criteria were successful and attracted fewer fish to the grating (B. Towler, *personal communication*, March 2020).

2.3 AWS Considerations

The first impact on successful passage is in the approach zone. Fish can be delayed in this zone or in extreme cases, not find the fishway entrance. Once a fish moves through the entrance gate, there is no certainty it will successfully navigate the fish passage. Fish are exposed to a variety of complex variables including design flaws and other obstacles that limit passage success (Castro-Santos 2012, WDFW 2000). Fish passage is researched throughout the world (Towler 2012, Katopodis & Williams 2011), but the U.S. western states have contributed significant knowledge through systematic studies, testing physical models of fishways as well as fish biology and physiology as it relates to migration. As a result, many of the criteria for modern technical fishways come from local studies and experience from the western U.S., almost entirely specific to the strong swimming salmon populations (NMFS 2011). The criteria, however, are not always appropriate for other regions, where the native species interact differently with fishway designs.

Changes to design criteria based on regional and species-specific requirements are leading to the re-assessment of diffuser system designs and formal evaluation of the relationship of their hydraulics with fish behavior. Fish experience a wide range of water flow conditions throughout their lifetime. Though they are able to adjust their swimming under varying hydrodynamic conditions, studies show that fish expend more of their energy reserves under conditions of higher turbulence and unexpected flow (Pavlov et al. 2000,

Webb 1998, Odeh et al. 2002). Fish prefer predictable flow and varying levels of turbulence; conditions that reduce their physical efforts and give clearer directional guidance. The hydraulic complexities associated with AWS inside the entrance channel can cause behavioral responses that negatively affect successful fish passage (Gauley, 1964). Turbulence, possible air entrainment, and the unforeseen change in flow direction may elicit a confused behavioral response that leads to delay and possibly retreat from the fish pass (Larinier & Travade 2002, WDFW 2000). In a CFD model of conventional floor and wall diffusers, Heise (2017) shows that under normal conditions and standard practices the diffusers did not achieve flow uniformity. The study noted that in some sections of the velocity profiles the designs failed to meet regulatory velocity standards. Though fish do experience turbulent and nonuniform flows in nature, they have the ability to select more favorable conditions by relocating to a section of the river that better suits their needs. However, some turbulence has been shown to be a positive factor in fish conserving energy (Liao et al. 2007, Cotel et al. 2006).

Air entrainment is another hydraulic characteristic important to assess in AWS design (Stuart 1962). This phenomenon is especially relevant to sourcing the AWS water using the gravity method. A possible concern with gravity fed diffusers is the potential for interfacial air entrainment because of the air-water interaction from the spilling action (Chanson 2004). For all cases, dissipation pools can be used to both modulate the kinetic energy of the supplied water and remove entrained air.

AWS structures located within the entrance channel of a wall or floor diffuser should be carefully considered with respect to the effects of sudden directional changes of the flow. When fish swim into the fishway, they encounter the flow head-on through the first section of the entrance channel. Approaching the wall or floor diffusers, fish may experience either a gradual or an abrupt change in perpendicular flow (Heise 2017). From a floor diffuser the perpendicular cross-current is an upwelling, a hydraulic feature that is not recommended for American shad (Larinier & Travade 2002, WDFW 2000). Beyond the diffuser, the flow runs parallel again along the main pass. Flow separation experienced from near to just past the diffuser poses a risk to passage efficiency (WDFW 2000). Depending on the swim depth of the fish and the flow magnitudes, fish may or may not experience areas of flow separation.

Studies of AWS systems have been predominantly in controlled environments without fish present. Computational Fluid Dynamics (CFD) models solely evaluate the hydraulics and assess the results with preliminary knowledge of fish physiology and behavior (Schilt 2007, Gisen 2017, Heise 2017). Coupled hydraulic-fish behavioral models include fish physiology and behavior within the model along with the hydraulics (Goodwin et al. 2006). Field studies are vital sources of information but can be difficult and costly (Silva et al. 2018, Marriner et al. 2016). Another option is scaled representations of the hydraulic scenarios (physical hydraulic models) both with and without fish (Chanson 2004, Wang et al. 2010, Kynard et al. 2008). Some of the most valuable design studies for AWS reflect the knowledge and experience of engineers, biologists, and operators that observe and actively manage these systems. Such studies often appear in the grey literature and fishway reports.

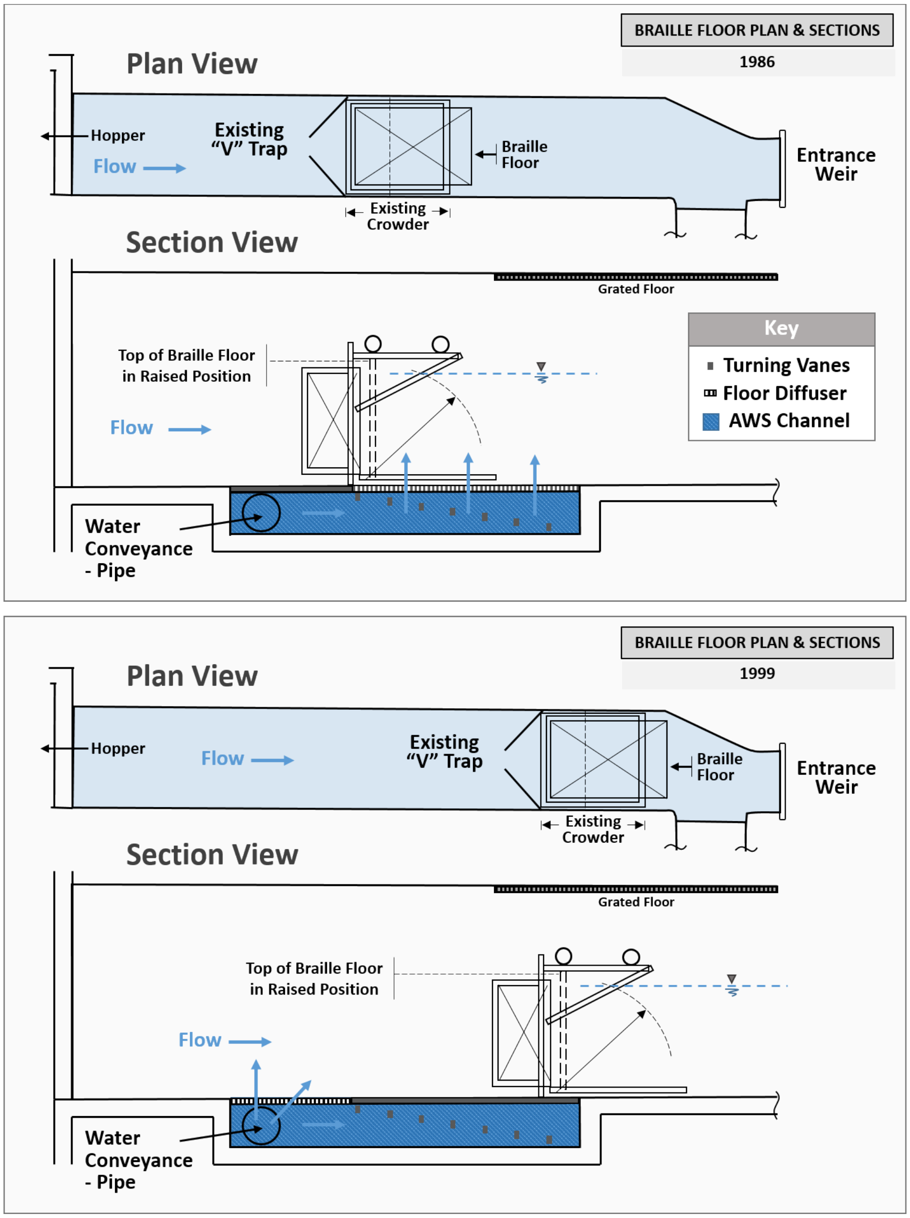

Figure 2.5 Adapted from Lowell Hydroelectric Dam fish lift entrance channel v-trap modification plans 1986 (TOP) and 1999 (BOTTOM) respectively. (Boott Hydropower Inc. 2000)

An example of this are assessments of the internal efficiency of the fish lift at the Lowell Hydroelectric project (Figure 2.5) (Boott Hydropower Inc. 2000, USFWS 2016).Both the 1986 and 1999 fishway plans have the same basic components. The hopper (or fish elevator) is on the up-stream side of the schematic. Behind the hopper, further upstream, but not shown in the plan, is the first and main flow source that runs through the hopper, past the v-trap and braille floor, and out the entrance weir into the dam tailrace. The v-trap dissuades fish from turning back once they reach the area near the hopper. A second flow is provided through a floor diffuser into the entrance channel. Between the 1986 and 1999

plans, the location where this secondary flow enters the main channel as well as the placement of the v-trap and braille floor differ.

In a study by Normandeau Associates and Boott Hydropower (Sojkowski 2016) on the original 1986 design, fish were seen entering the channel, but falling back likely because of the perpendicular flow out of the floor diffuser (Figure 2.5 top). Their proposed solution was to move the v-trap further downstream so that the fish did not perceive the flow from the floor diffuser until after passing the v-trap, dissuading them from falling back (Figure 2.5 bottom). Additionally, about two-thirds of the furthest downstream section of the floor diffuser was covered by solid panels and only the upstream third was open to let the secondary flow into the channel. The upstream third is also where the AWS pipe flow enters the AWS channel. In 1986, the upstream third was the section blocked off and the downstream two-thirds was the open diffuser. The diffuser therefore lost half of its original flow interface. The reduction in area of the floor diffuser increased the velocity to 1.5 fps, as opposed to the original design's 0.75 fps velocity.

The new 1999 v-trap arrangement improved efficiency by dissuading fish from turning back when experiencing the AWS floor diffuser flow. However, with the alterations, the fish were still subject to the flow that induced them stress in the 1986 design, and even at a stronger velocity. The stress that the upwelling may cause remained present in the update. Stress can decrease survivability in fish by raising their predation susceptibility, decreasing their energy (Mu et al. 2019, Quaranta et al. 2017, Midwood 2016,Wang et al. 2010, Cotel et al. 2006, Odeh et al. 2002).

2.4 Northeast Fishways & AWS Database

This section presents a survey of fishway and AWS technologies at 60 hydropower sites in the Northeast U.S. (Table 2.3, see Appendix A for further details). The database has three major objectives. Foremost, this is the first comprehensive database for fishway and AWS technology for the Northeast region. Second, the AWS and fishway type information from the database is summarized. The summary verifies current notions and gives insights into what the most commonly used technology in the region is. In collaboration with the USFWS Northeast Region Fish and Aquatic Conservation Program, data was collected on latitude, longitude, site name, waterway, state, fishway type (lift, denil, pool and weir (P&W), vertical slot fishway (VSF), trap and transport, and near entrance discharge), AWS conveyance (gravity/pump) and connector (wall/floor/near entrance), FERC ID, license type (licensed (L), license expiration date, hydraulic capacity, owner, NID number, dam height, dam length, and more. This is a subset of the data found in the Fishway Systems at Hydropower (FiSH) database (Table 2.3).

Table 2.3 Fishway Systems at Hydropower (FiSH) Database

LONGITUDE	LATITUDE	FERC ID	NID ID	NAME	WATERWAY	STATE	FISHWAY TYPE	AWS CONNECTOR	AWS	TURNING VANES	ATTRACTION FLOW(CFS)	BARRIER HEIGHT (FT)	CAPACITY (KW)	LICENSE	EXPIRATION	ISSUE	OWNER
												48	40800	L	4/30/19	8/3/79	TRANSCANADA HYDRO NORTHEAST INC.
												49	6650	L	11/30/29	6/29/89	BROOKFIELD WHITE PINE HYDRO, LLC.
-71.298056	42.629061	2998	MA00837	CENTENNIAL ISLAND	CONCORD RIVER	MA	DENIL, 4 FT	FLOOR	GRAVITY			20	640	E		9/29/81	CENTENNIAL ISLAND HYDROELEC CO (MA)
-70.8738	43.1964	4718	NH00547	COCHECO FALLS DAM	COCHECO RIVER	NH	DENIL, 3 FT	FLOOR	GRAVITY			9	714	L	12/31/22	12/8/82	COCHECO FALLS ASSOCIATES (NH)
-76.173814	39.660239	405	PA01940	CONOWINGO	SUSQUEHANNA RIVER	MD	LIFT	FLOOR	GRAVITY			104	574540	L	9/1/14	8/14/80	EXELON GENERATING COMPANY LLC.
-76.174711	39.657647	405	PA01940	CONOWINGO	SUSQUEHANNA RIVER	MD	LIFT	FLOOR	GRAVITY	N	450	104	574540	L	9/1/14	8/14/80	EXELON GENERATING COMPANY LLC.
-76.173814	39.660239	405	PA01940	CONOWINGO	SUSQUEHANNA RIVER	MD	TRAP & TRANS	FLOOR	GRAVITY			104	574540	L	9/1/14	8/14/80	EXELON GENERATING COMPANY LLC.
-67.478928	45.276068	NON FERC6	ME00219	GRAND FALLS	ST CROIX RIVER	ME	DENIL, 4 FT	FLOOR	GRAVITY			50	9500	N			WOODLAND PULP, LLC
-72.051405	41.538798	2441	CT00206	GREENVILLE/TENTH STREET	SHETUCKET RIVER	CT	LIFT	FLOOR	GRAVITY			15	2200	L	12/31/43	3/31/93	NORWICH CITY OF (CT)
-76.331601	39.827066	1881	PA00854	HOLTWOOD	SUSQUEHANNA RIVER	PA	LIFT	FLOOR	GRAVITY		1500	55	195500	L	8/31/30	8/14/80	BIF III HOLTWOOD, LLC.
-69.61901675	44.56297919	2611	ME00083	HYDRO-KENNEBEC	KENNEBEC RIVER	ME	LIFT	FLOOR	GRAVITY	Y	350	35	15433	L	9/30/36	10/15/86	HYDRO KENNEBEC LLC
-71.4645	42.7635	7590	NH00121	JACKSON MILLS	NASHUA	NH	DENIL, 4 FT	FLOOR	GRAVITY			33	1000	E		4/24/84	NASHUA HYDRO ASSOCIATES (MA)
-71.16516531	42.69955766	2800	MA00234	LAWRENCE	MERRIMACK RIVER	MA	LIFT	FLOOR	GRAVITY	Y	100	38	16800	L	11/30/28	12/4/78	ESSEX COMPANY, LLC
-71.32365302	42.65118758	2790	MA00837	LOWELL	MERRIMACK RIVER	MA	LIFT	FLOOR	GRAVITY	Y	120	38	24823	L	4/30/23	4/13/83	BOOTT HYDROPOWER LLC
-68.4646276	45.18666665	4202	ME83014	LOWELL TANNERY	PASSADUMKEAG R	ME	VSF, SINGLE	FLOOR	GRAVITY			27	1000	L	9/30/23	10/31/83	KEI (MAINE) POWER MGMT (II) LLC
-71.4725	43.0019444	1893	NH00102	MERRIMACK RIVER	MERRIMACK RIVER (AMOSKEAG)	NH	ICE HARBOR, HALF	FLOOR	GRAVITY	Y	100	29	29900	L	4/30/47	5/18/07	PUBLIC SERVICE CO OF NH (NH)
-68.64452265	44.94145543	2534	ME00141	MILFORD	PENOBSCOT RIVER	ME	LIFT	FLOOR	GRAVITY	Y	210	34	8000	L	3/31/38	4/20/98	BLACK BEAR HYDRO PARTNERS, LLC
-67.293281	45.175386	NON FERC1	ME00616	MILLTOWN DAM	ST CROIX RIVER	ME	VSF, SINGLE	FLOOR	GRAVITY			15.3	3900	N			NEW BRUNSWICK POWER
-76.390398	39.922809	1025	PA00855	SAFE HARBOR	SUSQUEHANNA RIVER	PA	LIFT	FLOOR	GRAVITY		300	75	380390	L	4/22/30	8/14/80	SAFE HARBOR WATER POWER CORP (PA)
-72.122132	41.665215	2662	CT00192	SCOTLAND	SHETUCKET RIVER	CT	LIFT	FLOOR	GRAVITY			37	3026	L	10/31/53	11/21/13	FIRSTLIGHT HYDRO GENERATING CO.
-72.57811159	42.58726285	1889	MA00849	TURNERS FALLS	CONNECTICUT RIVER	VT	ICE HARBOR, ALT.	FLOOR	GRAVITY			35	67709	L	4/30/18	5/5/80	FIRSTLIGHT HYDRO GENERATING CO.
-72.51410579	42.77140163	1904	NH00097	VERNON	CONNECTICUT RIVER	VT	ICE HARBOR, ALT.	FLOOR	GRAVITY			58	32400	L	4/30/19	6/25/79	TRANSCANADA HYDRO NORTHEAST INC.
-72.63820106	42.09921126	2608	MA00611	WEST SPRINGFIELD	WESTFIELD RIVER	MA	DENIL, 4 FT	FLOOR	GRAVITY			18	1400	L	9/30/34	10/24/94	A & D HYDRO INC (MA)
-72.3033971	43.66710486	1892	NH00259	WILDER	CONNECTICUT RIVER	VT	ICE HARBOR, ALT.	FLOOR	GRAVITY			59	35600	L	4/30/19	12/10/79	TRANSCANADA HYDRO NORTHEAST INC.
-67.401706	45.158088	UL892	ME00218	WOODLAND DAM	ST CROIX RIVER	ME	DENIL, 4 FT	FLOOR	GRAVITY			46	11600	N			WOODLAND PULP, LLC
-76.722663	40.143425	1888	PA00515	YORK HAVEN	SUSQUEHANNA RIVER	PA	VSF, DUAL	FLOOR	GRAVITY			8	19620	L	11/30/55	12/22/15	YORK HAVEN POWER COMPANY, LLC.
-69.96658446	43.91994965	2284	ME00001	BRUNSWICK	ANDROSCOGGIN RIVER	ME	VSF, SINGLE	FLOOR	PUMP		100	42	19000	L	2/28/29	2/9/79	BROOKFIELD WHITE PINE HYDRO, LLC.
-68.42916672	44.54487157	2727	ME00263	ELLSWORTH GRAHAM	UNION RIVER	ME	TRAP & TRANS	FLOOR	PUMP			62.3	8900	L	12/31/17	12/28/87	BLACK BEAR HYDRO PARTNERS, LLC
-70.02403283	43.9571606	4784	ME00003	PEJEPSCOT	ANDROSCOGGIN RIVER	ME	LIFT	FLOOR	PUMP			48	13880	L	8/31/22	9/16/82	TOPSHAM HYDRO PARTNERS LTD PT (MN)
-68.6477255	45.24976116	2600	ME00155	WEST ENFIELD	PENOBSCOT RIVER	ME	VSF, DUAL	FLOOR	PUMP		150	17	13000	L	5/31/24	6/26/84	BANGOR-PACIFIC HYDRO ASSOCIATE (ME)
-70.06133502	43.99404291	3428	ME00004	WORUMBO	ANDROSCOGGIN RIVER	ME	LIFT	FLOOR	PUMP		150	17	19100	L	11/30/25	12/24/85	BROWN BEAR II HDYRO, INC.
-70.4471905	43.4957013	2528	ME00030	CATARACT	SACO RIVER	ME	DENIL, 4 FT	NEAR ENTRANCE DISCHARGE	GRAVITY			49	6650	L	11/30/29	6/29/89	BROOKFIELD WHITE PINE HYDRO, LLC.
-73.0856	41.3672	6985	CT00089	KINNEYTOWN	NAUGATUCK RIVER	CT	DENIL, 4 FT	NEAR ENTRANCE DISCHARGE				20.5	2360	E		5/20/83	KINNEYTOWN HYDRO CO INC (CT)
-70.627	41.9172	6429	MA00392	RUSSELL MILL POND	EEL RIVER	MA	P & W	NEAR ENTRANCE DISCHARGE				25	15	E		5/9/83	MICHAEL GOODMAN
-72.122132	41.665215	2662	CT00192	SCOTLAND	SHETUCKET RIVER	CT	LIFT	NEAR ENTRANCE DISCHARGE	GRAVITY			37	3026	L	10/31/53	11/21/13	FIRSTLIGHT HYDRO GENERATING CO.
-67.7346	45.6646	2660	ME00221	FOREST CITY (STORAGE)	EAST BRANCH ST. CROIX RIVER	ME	VSF, SINGLE	NO AWS	NO AWS			12	0	L	10/31/45	11/23/15	WOODLAND PULP, LLC
-72.825999	41.520223	14550	CT00134	HANOVER POND DAM	QUINNIPIAC RIVER	CT	DENIL, 4 FT	NO AWS	NO AWS			25	220	E		5/19/16	HANOVER POND HYDRO.LLC
-68.657709	45.238722	2721	ME00155	HOWLAND	PISCATAQUIS RIVER	ME	DENIL, 4 FT	NO AWS	NO AWS			17	1875	S	9/30/00	9/12/80	PENOBSCOT RIVER RESTORATION TRUST
-68.40807673	45.56993363	2520	ME00143	MATTACEUNK	PENOBSCOT RIVER	ME	P & W	NEAR ENTRANCE DISCHARGE	GRAVITY			45	19200	L	8/31/18	9/30/88	GREAT LAKES HYDRO AMERICA, LLC.
-69.7153	45.5859	5912	ME00091	MOOSEHEAD	PISCATAQUIS RIVER	ME	DENIL, 3 FT	NO AWS	NO AWS			25.5	300	E		6/2/82	KENNEBEC WATER POWER CO (ME)
-72.0502	41.5971	11574	CT00576	OCCUM	SHETUCKET RIVER	CT	DENIL, 4 FT	NO AWS	NO AWS			14	800	L	8/31/39	9/29/99	NORWICH CITY OF (CT)
-70.1828	43.8015	8417	ME00187	OLD SPARHAWK MILL	ROYAL RIVER	ME	DENIL, 4 FT	NO AWS	NO AWS			8	270	E		5/24/85	YALE THOMAS L & LEMAISTRE
-70.8118	43.2266	11163	NH00395	SOUTH BERWICK	SALMON FALLS RIVER	NH	DENIL, 4 FT	NO AWS	NO AWS			18	1200	L	11/30/37	12/9/97	SALMON FALLS HYDRO, LLC
-67.427533	45.569462	2492	ME00220	VANCEBORO (STORAGE)	EAST BRANCH ST. CROIX RIVER	ME	VSF, DUAL	NO AWS	NO AWS			20	0	L	2/28/46	3/22/16	WOODLAND PULP, LLC
-69.55417087	44.58002758	5073	ME96126	BENTON FALLS	SEBASTICOOK RIVER	ME	LIFT	OTHER	OTHER			27	4330	L	2/28/34	3/8/84	BENTON FALLS ASSOCIATES (NY)
-69.41156644	44.7211165	11472	ME00109	BURNHAM	SEBASTICOOK RIVER	ME	LIFT	OTHER	OTHER			32	1050	L	10/31/36	4/7/04	KEI (MAINE) POWER MGMT (II) LLC
-69.62666217	44.54675626	2574	ME00082	LOCKWOOD	KENNEBEC RIVER	ME	TRAP & TRANS	THRU CHANNEL		N		17	6915	L	10/31/36	3/4/05	MERIMIL LTD PARTNERSHIP (ME)
-73.18725117	44.48890031	2756	VT00329	CHACE MILL	WINOOSKI RIVER	VT	LIFT	WALL	GRAVITY			29	7455	L	10/31/28	11/3/88	CITY OF BURLINGTON, VERMONT
-76.331601	39.827066	1881	PA00854	HOLTWOOD	SUSQUEHANNA RIVER	PA	LIFT	NEAR ENTRANCE DISCHARGE	GRAVITY			55	195500	L	8/31/30	8/14/80	BIF III HOLTWOOD, LLC.
-72.60210425	42.21185798	2004	MA00973	HOLYOKE	CONNECTICUT RIVER	MA	LIFT	WALL	GRAVITY			30	43840	L	8/31/39	8/20/99	CITY OF HOLYOKE GAS & ELECTRIC DEPT
-70.4471905	43.4957013	2528	ME00030	CATARACT	SACO RIVER	ME	LOCK	WALL	GRAVITY			49	6650	L	11/30/29	6/29/89	BROOKFIELD WHITE PINE HYDRO, LLC.
-71.504444	42.750606	3442	NH00116	MINE FALLS	NASHUA RIVER	NH	LIFT	WALL	GRAVITY			16	3000	L	7/31/23	8/4/83	MINE FALLS LTD PARTNERSHIP (ME)
-72.893665	41.9153	NON FERC5	CT00039	RAINBOW DAM	FARMINGTON	CT	VSF, SINGLE	WALL	GRAVITY			42.8	8000	N			FARMINGTON RIVER POWER COMPANY
-70.55779352	43.57067703	2527	ME00033	SKELTON	SACO RIVER	ME	LIFT	WALL	GRAVITY			75	21600	L	1/31/38	2/26/98	BROOKFIELD WHITE PINE HYDRO, LLC.
-72.04566	41.572544	NON FERC3	CT00204	TAFTVILLE	SHETUCKET RIVER	CT	DENIL, 4 FT	WALL	GRAVITY			30	2000	N			FIRST LIGHT
-72.040948	41.554964	NON FERC4	CT00637	TUNNEL	QUINEBAUG RIVER	CT	LIFT	WALL	GRAVITY			32	2500	N			FIRST LIGHT

The columns site name, waterway, state, fishway type, AWS type, FERC name, license type, expiration date, capacity, and owner are from the FERC Active Licenses spreadsheet (FERC 2019). The license type indicates if the sites are licensed (L), exempt from licensing E, licensed as small hydro (S), or conduit (NA). The capacity is the authorized power capacity for the turbines in kilowatts. The NID number and barrier height are from the National Inventory of Dams (NID) 2019 dam inventory spreadsheet. The NID lists dams and their identifying numbers individually. FERC considers "projects," so one project (ID #) might have multiple dams. The barrier height is the either the structural or hydraulic height of the dam, whichever is relevant. There are a variety of dam design/operation types, but ultimately the barrier's height is relevant as it relates to building the fishway. For example, a run of river dam or one located on a fall would not have accurate accounting of the structural height which is why the hydraulic height would be equivalent to the barrier height. The grey latitude-longitude data is a combination of a Google Earth geographic data file (Keyhole Markup Language, KML) from USFWS fish pass engineers, the coordinates in the NID data, and efforts of visually locating and obtaining or confirming the coordinates from google maps. The green columns are the fishway and AWS type data for the site. These were collected from engineers and biologists who created their own database of their work.

The majority of fishways and AWS technologies in the database are located in the Northeast, specifically most are in the New England region (Figure 2.6 and Table 2.4). There are more lifts and Denil fishways than all other types (Figure 2.7). The concentration of fishways in the database are mostly in Maine.

Table 2.4 Fishways with AWS per state in the FiSH database

No. of fishways with AWS per state in FiSH DB	
CT	8
MA	6
ME	24
NH	5
PA	4
VT	5
MD	3
SC	2
VA	3

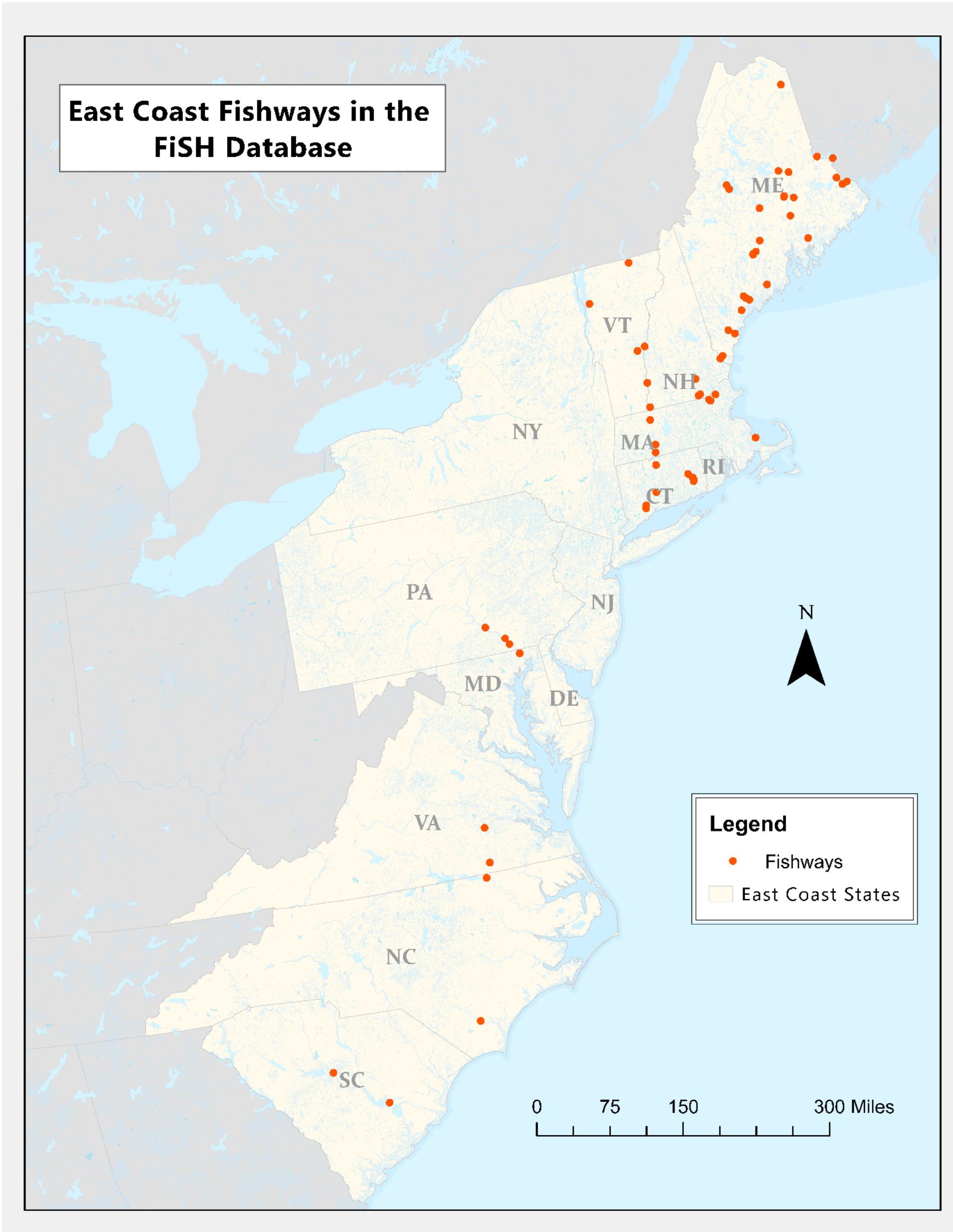

Figure 2.6 Map of Fishways in the Fishway Systems at Hydropower (FiSH) database.

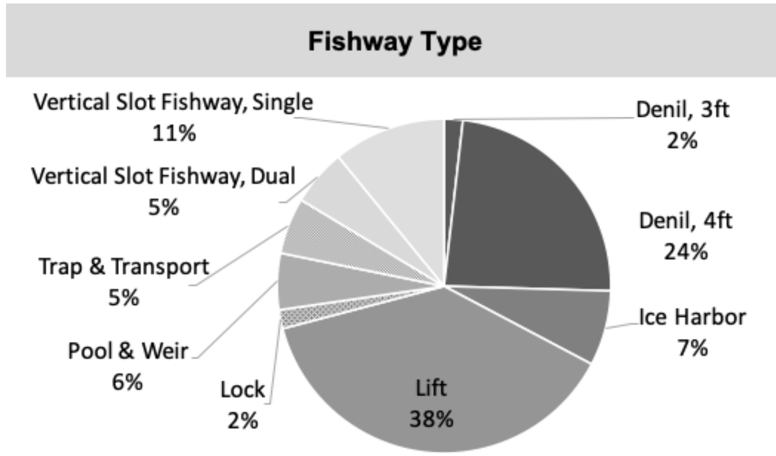

Figure 2.7 Fishway types in FiSH database pie chart

The database indicates that most fishways in the database are lifts (38%), 4ft Denil's (24%), and single vertical slot fishways (11%) (Figure 2.7). The most prevalent conveyance mechanism is gravity (68%), followed by no AWS (14%), pump (9%), unknown (5%) and other (4%) (Figure 2.8). The most common diffuser type was floor diffusers (55%), followed by wall diffusers (14%), no AWS (14%), near entrance (11%), other (4%), and thru channel (2%) (Figure 2.9).

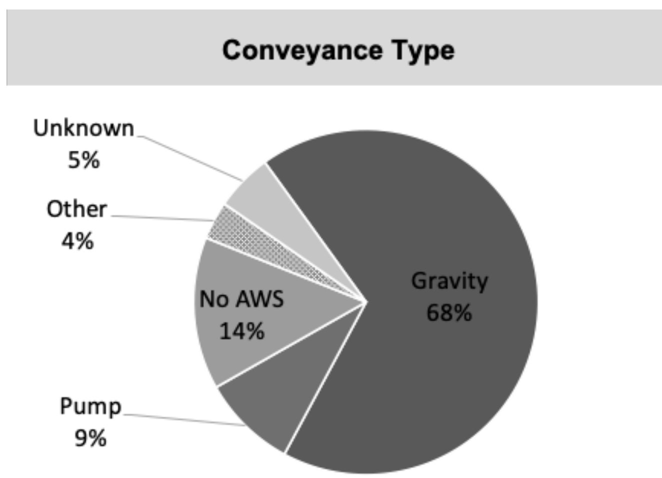

Figure 2.8 AWS conveyance types in FiSH database pie

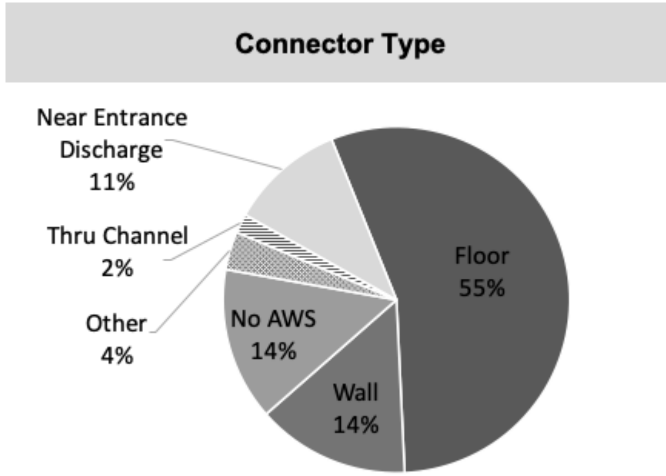

Figure 2.9 AWS connector types in FiSH database pie chart

Looking at the two main AWS features combined (Figure 2.10); the majority are gravity fed water systems with floor diffusers (46%). The absence of AWS is the second most common occurrence (14%) along with gravity fed water systems with wall diffusers (14%), followed by pumped water system with floor diffusers (9%). The last AWS types were gravity fed water systems with near entrance discharge (7%), unknown water conveyance system with near entrance discharge (4%), other (4%), and through-channel with unknown conveyance water system.

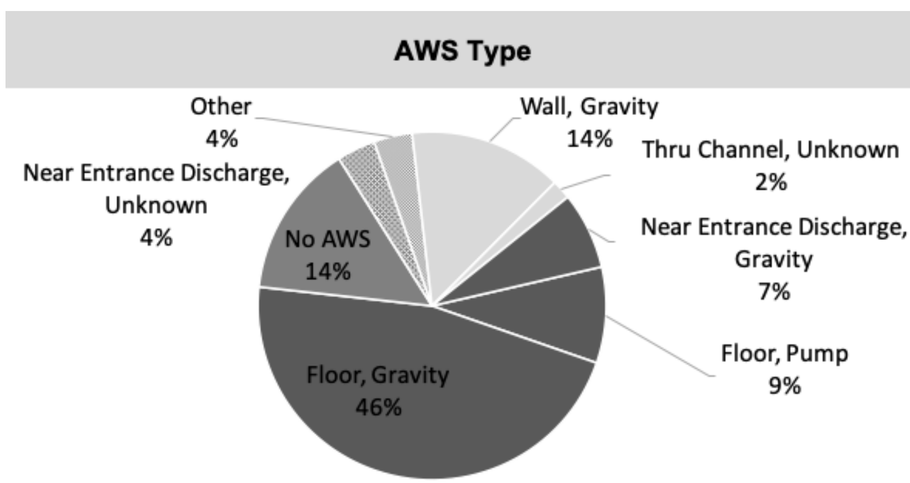

Figure 2.10 AWS types in FiSH database pie chart

2.4.1 Case Studies

This section presents examples of AWS technologies at hydropower sites. The examples are from the FiSH database. Further details of the sites were obtained from the database and engineers at USFWS Northeast Region Fish and Aquatic Conservation Program.

Gravity Floor Diffuser (47%)
The Pawtucket Dam is associated with the Merrimack Reservoir powerhouse and is located at approximately 40 river miles on the Merrimack River. The site features a fish lift on the powerhouse face (Figure 2.11). The fish lift has a floor diffuser that adds in water from a gravity-fed auxiliary channel. The total attraction flow from the AWS ranges from 80-120 cfs, which is 1-1.5% of the hydraulic capacity, 7500 cfs. These design flows were set in the 1980s. Current recommendations from USFWS are 5% of the hydraulic capacity. The diffuser chamber is 35' long x 10' wide and the diffuser grating is 20' long x 10' wide. The AWS flow is conveyed into the diffuser chamber through a 4-foot diameter pipe. At the entrance channel, the combined AWS and fishway flows produce a 1.5-2.0 fps velocity.

Figure 2.11 Pawtucket Dam fish lift in Lowell, MA. (Merrimack River Watershed - Massachusetts Division of Marine Fisheries Technical Report TR-18, Reback et al. 2004)

Gravity Wall Diffuser (11%)
The Turners Falls Dam in Turners Falls, MA, is located at approximately river mile 100 on the Connecticut River. This dam features two upstream Ice Harbor type pool fishways, one at the powerhouse and one at the dam (Figure 2.12). The Ice Harbor at the dam utilizes a gravity-fed open channel conveyance and wall diffuser connector to the fishway entrance. The attraction flow varies; however the maximum attraction flow is 300 cfs, 0.04% of the 67709 cfs hydraulic capacity in their FERC licensing (FERC 2019, FirstLight Power Resources 2018). The auxiliary water flow comes directly from the power canal, which is at a slightly lower elevation than the Turners Falls Dam impoundment . The water flows via gravity through a small spillway that drops and travels under the upper fishway structure, arriving at an energy dissipation pool. The pool connects to the fishway entrance via a wall diffuser.

Figure 2.12 Ice harbor fishway downstream in the tailrace of the Turners Falls dam.

Pumped Floor Diffuse*r *(9%)
The Worumbo Dam in Lisbon Falls, ME is located on the Androscoggin River and approximately 11 river miles downstream meets the Kennebec River at the Merrymeeting Bay. The Kennebec then flows out into the Atlantic Ocean, a distance of approximately 35 river miles. The Worumbo station has one fish lift with two entrances located within the tailrace on the powerhouse face (Figure 2.13). The lift has a floor diffuser and a pump conveys the water. Flow through the AWS is 160 cfs, where four pumps provide 40 cfs each. This totals to 1.7% of the hydraulic capacity, 9600 cfs. The entrance channel velocity is less than 1.5 fps.

Figure 2.13 Fish elevator at Worumbo Dam. Eagle Creek Renewable Energy.

Near Entrance Discharg*e *(6%)
The Merrimack Reservoir Dam is located in Lowell, MA on the Merrimack River, approximately 40 river miles from the Atlantic Ocean. At the reservoir, some flow spills over the dam continuing on the Merrimack, while the remaining flow continues down a power canal to the power station. The 38ft tall dam has an ice harbor fishway located 2700ft upstream of the powerhouse (Figure 2.14). This fishway has near entrance discharge for attraction flow. There are no turbines at the dam location, thus the attraction flow is not dependent on turbine capacity. Releases are made through the adjacent AWS system, near entrance discharge, at 300cfs and the fishway at 40cfs.

Figure 2.14 Pawtucket Dam Ice Harbor fishway in Lowell, MA– Massachusetts Division of Marine Fisheries Technical Report TR-18, Reback et al. 2004.

Through Hopper* *(Other 6%)

Lockwood power station in Waterville, ME is an example of a fish lift where all the attraction water is fed upstream of the hopper and no additional AWS is necessary (Figure 2.15). The water going through from behind the hopper is like a wall diffuser, except that the water is already flowing directly downstream since it is the main channel flow as well. The power station is located 33 miles from the Merrymeeting Bay, and another 35 miles from there to where the Kennebec meets the Atlantic.

Figure 2.15 Lockwood Dam fish lift. Cianbro

2.5 Discussion

A database of fishways at hydropower sites was developed for the Northeast region in collaboration with USFWS Northeast Region Fish and Aquatic Conservation Program. The database does not contain all Northeast fishways at hydropower sites. That task is beyond the scope of this study; however, the database does represent the range of fishways on the East Coast and most of the major hydropower dams in New England. The eventual completion and maintenance of the database could aid in future decision making and research.

Two existing databases with GIS and detailed dam information are the National Inventory of Dams (NID) and multiple databases related specifically to hydropower dams by the Federal Energy Regulation Commission (FERC). Any dam that produces power is required to go through a licensing process with the FERC licensing authority. Under Section 18 of the Federal Power Act, The Departments of Commerce and Interior, via National Marine Fisheries Service and Fish and Wildlife Service, have the authority to prescribe fishways to mitigate the environmental impact (FPA 2018). FERC is required to implement the prescriptions in the license conditions. Fishways are an important parameter when considering discharge optimization for financial and environmental hazard mitigation requirements. Despite their presence in the corporate, public, and environmental spheres, fishways are not listed on the Active Hydropower Licenses dataset or any other datasets in the FERC website, NID website, conservation organizations, non-profits, or in any other publicly available succinct format. Details related fishways from FERC licensed dams can be found in the FERC Docket, a licensing documentation repository (FERC n.d.). The Oak Ridge National Laboratory's HydroSource is a geospatial database with energy, water, and ecosystem research attributes. The HydroSource Environmental Mitigation Database includes information on presence or absence of fish passage, with detail only as to whether it is up- or downstream passage (Bevelhimer et al. 2015). Other existing fishway databases are likely used by local and state agencies for internal purposes, such as the one maintained by U.S. Fish & Wildlife Services. For example, the USFWS R5 office has a repository of projects that have been relicensed or are undergoing licensing. Employees also may keep separate databases acting more like lists of projects and overview details such as "fishway

type", "status", or "relicensing year" featured in columns. Depending on the office or employee, the list might just include their projects or might also include their predecessors or colleagues' projects as well. There is no all-inclusive fishway database because agencies are only called in to work on fishways during relicensing, when fish pass numbers are dramatically low, or an accident with an endangered species has occurred (B. Towler, *personal communication,* 2019). From speaking with USFWS R5, their situation of keeping a list of fishways as a secondary goal seems to be common among other government agencies like NOAA or NFMS. In response to the paucity of detailed publicly available consolidated fishway data, we created the Fishway Systems at Hydropower (FiSH) database.

The map for fishways with AWS systems indicates that most of the fishways in the database are located on mainstem rivers. It confirms that Northeast USFWS, where the data was sourced, mostly services the Northeast fishways, however there are also some in Pennsylvania, Maryland, Virginia, North and South Carolina. The highest concentration of fishways in the database is in Maine, leading with the most fishways at 24, three times more than the next state. This seems dramatic, but historically, federal and state resource agencies, in collaboration with industry, have been most diligent in implementing fishways in the state of Maine. Their efforts are primarily required by the presence of salmon, an economically valuable and endangered species. The U.S. laws passed earlier on before the Anadromous Fish Conservation Act of 1965 were focused on passing salmon (Katopodis & Williams 2011). Given that Maine has the highest salmon migration on the east coast, it is sensible to say that more fishway construction was encouraged by the value placed on that species. The importance of other species and their role on local habitats and economies has gradually become relevant to restoration efforts, encouraging the expansion of fishway implementation in other states. The Anadromous Fish Conservation Act (1965) and the U.S. Endangered Species Act (1973) raised concern for all anadromous species, supporting projects for anadromous fish like sturgeon (*Acipenser oxyrhynchus oxyrhynchus*, *Acipenser brevirostrum*), American shad (*Alosa sapidissima*), alewives (Alosa pseudoharengus), blueback herring (Alosa aestivalis), and striped bass (*Morone saxatilis*).

The USFWS notes in their criteria manual that most of the fishways in the Northeast use pressurized pipe water conveyance for the attraction water. In the database, the results show there are many more gravity type conveyance methods than pumped. With the observation from USWFS, this likely means that most of the gravity conveyance methods are pressurized pipes and a much smaller quantity are open channel water supplies.

The database does not include all hydropower fishways of the Northeast but is an initial effort to create an exhaustive inventory for the United States that can aid in research, conservation and regulatory efforts. Missing fishways in the database for other states might result in Maine being a dominant representation in the fishways data, however the general message remains the same. The database is an appropriate initial representation of the Northeast, according to engineers that service the East Coast region. The New England area specifically captured the major mainstem hydropower facilities well.

2.6 Conclusion

The FiSH database offers the ability to visualize the location of fishways, their characteristics, and their properties. A primary result of this database is an assessment on the current breakdown of the types of AWS systems in use and their prevalence in the Northeast. The data confirms previous knowledge, that most types of connectors are floor diffusers, followed by wall diffusers. The most common water conveyance system was the gravity method. Open channel gravity conveyance can result in excessive turbulence and air entrainment entering the fishway through floor or wall diffusers if not properly dissipated. These hydraulic conditions can be detrimental to passage. The majority of gravity methods are paired with floor diffusers and the remainder are paired with wall diffusers. Upwelling from floor diffusers is likely a larger problem for shad than side flow from a wall diffuser. These outcomes raise concern on the lack of research in the area of assessing internal hydraulics and conveyance flow energy dissipation.

Studies on internal hydraulics are vital to safe and timely passage. Proper attraction flow in the tailrace zone is essential, especially given the cumulative nature of the passage process. The internal conditions of the entrance channel are equally as necessary to focus on for providing fish with better passage conditions that are both safe (not stress inducing) and timely (not causing fallbacks or other delays).

The internal hydraulics of AWS, and their effect on fish movement, should be studied and the results included in criteria manuals. Criteria manuals are derived empirically from implemented fishway projects and available fishway research. Not all installed fishways have performance studies conducted once installed, but these are vital in informing a successful design. Additionally, it is important to incorporate the most recent and emerging fish passage science and fish biology findings. Collaborating with USFWS and NMFS agencies, dam operators, and citizen scientists ensures their professional and hands-on observations guide research studies and is generally a practical problem-solving strategy. Contributing to this effort, the next chapter is a study exploring wall diffusers both from a behavioral and hydraulic standpoint.

CHAPTER 3: WALL DIFFUSER STUDY

3.1 Introduction

This study explores the evolving criteria for wall-diffuser type attraction water system flows for fishway entrance channels and their potential impacts on fish passage. Attraction water systems (AWS) provide flows to guide fish efficiently into and through a fishway (O'Connor et al. 2015, Mallen-Cooper & Brand 2007, Thorncraft & Harris 2000). For many AWS, the flow initially runs parallel to the entrance channel (Figure 3.1). The water then typically enters into the fishway entrance through a wall or floor diffuser. The combined flows then exit the channel through the entrance gate, into the tailrace. Fish first experience the effects of AWS downstream of the fishway entrance. Second, for most systems, fish also sense the AWS flow within the entrance channel. Most AWS studies focus on their effectiveness outside the fishway in the lower tailrace area (Environment Agency 2010, Limburg & Waldman 2009, Katapodis 2005, Larinier 2002, White et al. 2001). Internal hydraulics of fishways are equally important.

This investigation assesses behavioral responses of fish to internal hydraulic effects of a wall-diffuser type AWS for two velocity treatments: 0.5 fps and 1.0 fps. The 1.0 fps velocity treatment was the previous east coast USFWS criteria recommendation. The current recommendation is half of that, 0.5 fps (USFWS 2019). Many fishways are decades old and designed with the older criteria. Some of those fishways have not yet gone through the relicensing process that might update this criterion and some are exempt from relicensing and will not be updated. Investigating the deprecated criteria of 1.0 fps is crucial to understanding the current existing impact this may be having on passage.

The change of criteria came about as engineers observed that fish were attracted to the wall diffuser, which in turn delayed passage. Even with the new criteria, it is possible that diffusers may still exceed 0.5 fps; maintenance issues can lead to partial blocking of the diffuser and produce higher velocities (O'Connor et al. 2015). This controlled experiment clarifies the empirical knowledge of the USFWS engineers. This information is also critical to understanding possible effects of malfunctioning AWS systems producing higher velocities than recommended. Equipped with these goals and context, the experimental design was created.

Two physical models provide the necessary data: 1) a full-scale 4-foot wide fishway entrance channel prototype with a wall diffuser, tested with actively migrating American Shad, and 2) a 1:8 scale model for collecting detailed information on the hydraulic characteristics of the design. To date, few studies have examined both the fish behavior and hydraulics of their study site or operational and hydrological conditions. The results from this study can inform future design choices for new projects or projects with ongoing relicensing.

Obstacles encountered by fish that have been observed by engineers and biologists motivate the experimental approach used to identify the effects of AWS. Internal AWS challenges are often due to two elements: geometric design constraints (i.e. space available for AWS and limitations on extent to which technology can manipulate hydraulic conditions) and the AWS water source (temperature and turbidity differences, turbulence, and aeration). This thesis explores specifically the challenge of geometric design constraints as it relates to AWS and manipulating hydraulic conditions that are most appropriate for fish. Elements of the AWS flow's incoming hydraulics such as aeration, turbulence, and velocity distribution affect fish passage efficiency.

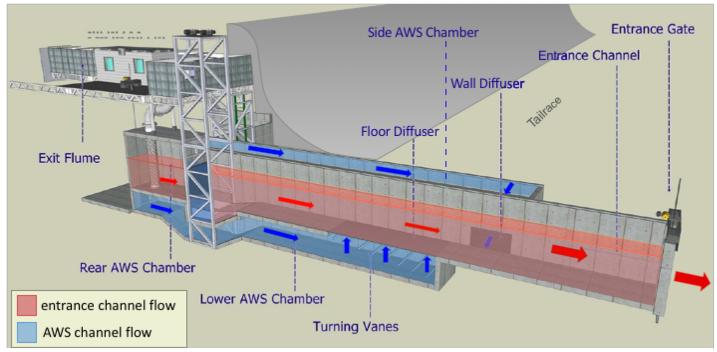

Figure 3.1 Fish lift with fish entrance cross-section, indicating entrance and AWS channels and the flow directions. Adapted from USFWS 2019 Manual.

Three design features aid in addressing the AWS effects on internal efficiency: 1) using receiving pools that reorder velocities and dissipate energy, 2) inserting turning vanes within the attraction channel to adjust the velocity distribution for uniformity, prior to flowing into the entrance channel, and 3) ensuring the diffuser bar-rack is angled such that the outflowing water from the AWS runs in a similar direction as the entrance channel flow (USFWS 2019, NFMS 2011, Larinier 2002, Clay 1995).

While the potential of turning vanes for producing streamlined flow has been evaluated, achieving this has proven difficult (Fiedler et al. 2018, Heise 2011, Nakato 1984). Studies have addressed obtaining streamlined flow in Computer Fluid Dynamics (CFD) models (Fiedler et al. 2018, Heise 2011), illustrating the hydraulic conditions in 2D and 3D representations of flow. These results are valuable, but do not aim to draw a link to the preferred flow conditions of a fish. Additionally, the results are providing information on the uniformity of the flow out of the diffuser, but do not investigate how that flow then interacts and changes in uniformity with the entrance channel flow. The acceptable degree of uniformity is often assumed from previous fish physiology and behavioral research but is not in itself tested in these studies. Research indicates that fish are disturbed by the flow conditions of unpredictable currents and turbulence (Quaranta et al. 2017, O'Conner et al. 2015, Lupandin 2005, Larinier & Travade 2002, Pavlov et al. 2000, WDFW 2000, Webb 1998, Clay 1995). The degree to which turbulence and velocity distribution have effects on fish in the entrance channel depends on the variation in the flow conditions themselves and the type of fish species in question. To understand the effects of AWS systems inside of a fishway, the typical physiological limitations and tendencies are not enough to understand the effects on passage. It is necessary to test the fish in this very specific fishway setting, where the physical features differ from a natural system or a testing site for developing physiological measurements.

The experiments presented in this thesis were performed at the United States Geological Survey (USGS) Leetown Science Center S.O. Conte Anadromous Fish Research Laboratory (CAFRL) in Turners Falls, MA. The CAFRL maintains a large flume for research (20-foot wide and 126-foot long) to conduct full-scale fishway experiments with migratory fish (e.g. American shad, blueback herring, white sucker). A second, small-scale flume is also maintained for more detailed hydraulic testing. A wall-type diffuser was selected for the experiments based on recommendations provided by experienced field engineers and biologists.

Choosing to study the wall diffuser was also supported by information found in the Northeast FiSH database; wall diffusers are one of the most common AWS in practice, with the other most common being floor diffusers. The study design featured antennas along key regions to detect individual fish locations during the course of the experiment.

Two types of data were obtained from these experiments. For the full-scale flume behavioral experiments, the data are time-series of passive integrated transponder tag (PIT) fish detections. These data are analyzed using plots of cumulative passage and fallback, two-proportion upper-tailed Z-tests of final passage percent results, summary statistic tables of attempt durations, and Cox multivariate regression models with mixed effects, typically used for time-to-event data. In addition, a cumulative plot and two-proportion upper-tailed Z-test of initial fishway entries were made to gain insight on any bias of the design's hydraulics outside the downstream end of the fishway. If biases were present, they might factor in the efficiency results later on within the entrance channel, in the assessment of the diffuser area.

The hydraulic experiment in the 1:8 scale model produced x-y-z velocity measurements and are reported in profile plots. These measurements provide context for the behavioral analysis by exploring not only the overall result of the diffuser on passage numbers, but the detailed spatial flow conditions. This provides insight into how the flows affect fish movements.

Due to the nature of the experiments, the behavioral full-scale flume and hydraulic characteristics model flume studies are presented separately in their Methods, Data Analysis, and Results sections. The behavioral and hydraulic studies are then presented together in the Discussion and Conclusion sections.

3.2 Behavioral Study

3.2.1 Methods

The interdisciplinary nature of the behavioral study required both biological and physical modeling. In the following portions of this thesis, the investigation's biological modeling methods are described in five sections. The Facility Overview provides a general description of the flow path of the large-scale flume. The Design Layout specifies the structural layout of the entrance channel and connecting wall diffuser. The Fish Collection section outlines how fish were obtained for the study. The Experiment section delineates how experiments were conducted. Finally, the Statistical Analysis section presents the methods of analysis used for the data collected.

3.2.2 Facility Overview

The USGS CAFRL is located on an island between the power canal leading to the Cabot Station hydroelectric dam and the mainstem of the Connecticut River. The facility utilizes water from the power canal for its hydraulic experiments and other fish research needs. The flume used is 126' x 20' x 20' in size. At the upstream end, automatic gates control the release of flows from the power canal into the facility. These flows enter a dissipation pool. The water then goes over stop logs used to regulate the flow rate into the design's two active channels, the entrance and AWS channels. The flow in the AWS later merges into the entrance channel, and combined, the flow exits the entrance channel over the entrance gate. The entrance gate height is a hydraulic control for the water surface elevation (WSE) in the entrance and AWS channels, as well as a control for the outflowing water velocities. On the downstream end past the entrance gate, automatic gates control WSE in what would be the dam tailwater area. The water is released into the mainstem Connecticut River. A set of rectangular circulating ponds near the flume are available for holding fish overnight before and after trials. These ponds are called Burrows ponds, structures typically used for rearing of fish hatcheries (Burrows & Chenoweth 1970). The Burrows ponds have a separate system that circulates water in from the power canal.

3.2.3 Design Layout

The goal of the behavioral study is to test the hypothesis that the 0.5 fps wall diffuser treatment shows better fish passage performance than the 1.0 fps treatment. This hypothesis was investigated by gathering data on passage success through the entrance channel area where the AWS flows are introduced.

The design consists of three channels (Figure 3.2). An effective means of achieving the two design velocities (V_w) is to maintain the same discharge through the entrance and AWS channels and vary the width (B) of the wall diffuser. The change in cross-sectional area (A_W) lowers or raises the velocity as desired. The height component of the area is

equivalent to the water surface elevation (WSE) of the channels. The desired water heights were obtained using weirs at the upstream end of each channel. The appropriate weir heights were derived from iterations in a small-scale model study, described in detail later on in the Hydraulics Study section.

The entrance channel is located at the center of the aerial view (Figure 3.2) and is 48 feet long, with 8 feet on the upstream end blocked off by a screen, a section inaccessible to fish. The walls of the channel are 10 feet tall and constructed of plywood panels. The entrance channel is 4 feet wide, a common size for fishways in the Northeast, which are generally smaller. The entrance gate is set at a height of 2.5 feet to produce the necessary 4 fps (V_E) velocity treatment required by the USFWS criteria manual. The AWS channel is located on the right is 28 feet long and 5 feet 7 inches wide. The right-side wall is the concrete wall of the flume, while the left is the same wall as that of the entrance channel, and vice versa for the third no flow channel on the left. The downstream end of the AWS channel reaches a perpendicular stop, blocked by a wood panel. On the left side of the AWS channel, the flow exits through the wall diffuser, combining with the entrance channel flow. To achieve the desired experiment velocities of 0.5 fps and 1.0 fps through the AWS diffuser (V_W), the diffuser widths (B) were set to 8 and 4 feet respectively. The material used for the wall diffuser is a metal mesh of grid sizes 1 by 3 inches, preventing fish from going into the AWS channel. The blocked off channel just after the AWS channel contains no flow, however, the grating at the end allows it to stay hydraulically connected to the tailwaters of the design and prevents fish from entering. On the left side of the entrance channel is a 10-foot wide channel with no flow, similar to the blocked and grated channel section mentioned earlier.

Stop logs are located at the upstream ends of the three channels. These weir structures allow for fine-tuning of the desired flows for each channel. From left to right channels, the stop log heights are 8, 4, and 4.3 feet. The left channel stop logs are higher than the upstream headwater WSE of 6.1 feet. The WSE throughout the experiment was measured using a radar water level logger (Flowline™ EchoPulse LR15). The entrance and AWS channels both had WSE of 5.26 feet (EL_{EC}, EL_{AWS}). The available water height above

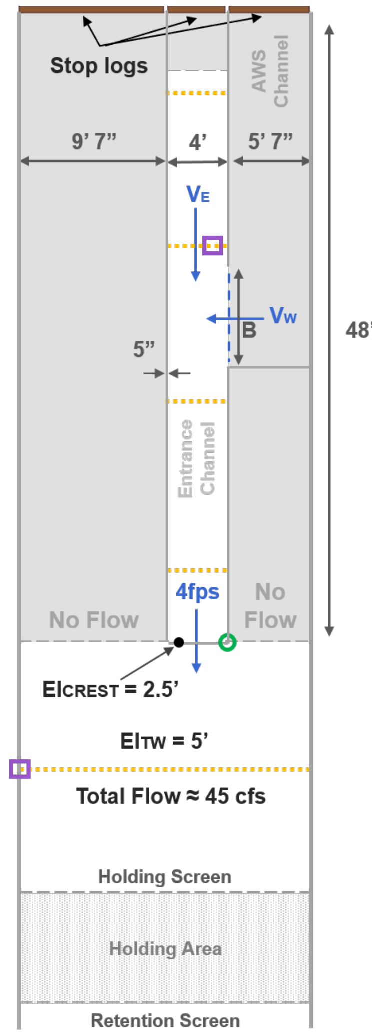

Figure 3.2 Plan view of the experiment design. Velocities are in blue. The entrance (VE) and AWS diffuser (Vw) velocities depend on the experiment condition tested. The outgoing velocity over the entrance gate is always 4 fps. Dimensions are in grey. Water surface elevations (ElCREST and ELTW) are black. PIT antenna locations (yellow), Flowline™ EchoPulse LR15WSE loggers (purple box), and camera (green circle)

Schematic is not to scale.

the entrance gate crest is 2.5 feet (EL_{CREST}). In the tailwater, the WSE is 5 feet (EL_{TW}). The average flow entering from the upstream to both channels and exiting combined through the entrance channel was 44 cubic feet per second (cfs). Entering the entrance and AWS channels from upstream, the flow was approximately 23 and 21 cfs respectively.

To monitor fish during the experiment, all fish were tagged with Passive Integrated Transponder (PIT) tags and five antennas were placed along the length of the design (Figure 3.2). The antennas were set to a detection range of about 2 feet. PIT receivers (Texas Instruments TIRIFD model S-2000) transmitted tracking information at a rate of approximately 15 detections per second. There is potential for recording errors with the antennae, as multiple fish passing at the same time can result in some fish being undetected. As a safeguard, two video cameras were used. One was placed near the entrance gate area to capture footage of the fish going into the entrance and the other was on the entrance channel wall, opposite the diffuser, to capture fish movement across the diffuser area.

3.2.4 Fish Collection

The fish species chosen for the trials was the American shad; a common target species for fishways on the east coast. Herring were considered for the study as well but due to scheduling limitations, this was not possible. The American shad were collected from the Holyoke Robert E. Barrett fish lift in Holyoke, MA. The facility has a sorting area that allows for easy and rapid counting and transfer of the fish. The ease and low handling required is important in decreasing performance biases from induced stress. The Holyoke fish lift is located 35 river miles downstream on the Connecticut River and is the first dam that fish must pass during their upstream migration. The experiments were run in the month of June within the final weeks of their migration season at this location in the river. Because of lower fish counts, collections were around 50 fish for each of the three collection days during the week of the experiments. The collected fish for the following day's trials were transported to the CAFRL in a truck with appropriately oxygenated water. Once at the facility, the fish were tagged, and their sex was determined. Typically, the fork length is also collected, but because of the time in the season, this was omitted to minimize handling time.

The fish acclimated in Burrows ponds for one day and were then used for a trial the following day. After their use in the experiments, they were retrieved from the Burrows ponds and transported back to Barton's Cove on the mainstem Connecticut River. The cove is located upstream of the two dams (Cabot Station and the Turners Falls Dam) that come after the Holyoke dam.

3.2.5 Experiments

We hypothesized that the lower V_W treatment would have higher passage efficiency past the diffuser structure. The null hypothesis of the study was that there would be no difference in passage between the V_W treatments. We also considered that for the higher

velocity condition the fish might linger below the diffuser area, within the entrance channel, longer before making a successful pass.

The two velocity treatments were run three times, for a total of six trials over the course of one week, June 16th to June 21st, 2019 (Table 3.1). All trials were conducted during the morning and afternoon hours, a natural time of migration for American shad. Weekly river temperatures ranged between 18.64 and 19.30 degrees Celsius. Turbidity levels (Hach, Model 2100Q) in the Connecticut River ranged between 2.86 to 4.03 NTUs. The PIT system data was processed with a multireader software that output the fish detections and the timing in TXT format.

Table 3.1 Experiment timeline and conditions

Tue 6/16	**Wed 6/17**	**Thu 6/18**	**Fri 6/19**	**Sat 6/20**	**Sun 6/21**
	Trial 1, 0.5fps *18.92 C* *3.41 NTU* *27 fish*	no fish	Trial 3, 1.0 fps *18.64 C* *3.29 NTU* *28 fish*	Trial 5, 0.5fps *19.11 C* *2.87 NTU* *27 fish*	Trial 6, 1.0 fps *19.3 C* *4.03 NTU* *22 fish*
	Trial 2, 1.0 fps *18.83 C* *2.86 NTU* *26 fish*		Trial 4, 0.5fps *18.73 C* *3.08 NTU* *26 fish*		
collection		collection	collection	collection	

In preparation for an experiment, fish were seined into the holding area, between the retention and holding screens from the Burrows ponds for the given trial. They were held there for 30 minutes to acclimate with the flow conditions of the experiment. After acclimation, the experiment was initiated by slowly opening the holding gate, to prevent startling the fish. The fish were then free to swim in the testing flume for four hours. Once the trial was over, the water levels were decreased to allow seining of the fish back into the Burrows ponds.

3.2.6 Statistical Analyses

A variety of statistical analyses were used to interpret the experimental results. The three primary analysis methods applied were: cumulative plots of the data, two-proportion upper-tailed Z-tests, and Cox regressions. The data were filtered appropriately for questions to be answered from each analysis. The raw time series was analyzed using R version 3.5.2 and RStudio version 1.1.463. For more detailed information on statistical analyses see Appendix B.

To understand the hypothesis tested and the statistical tests used, it was first necessary to create a conceptual framework describing the regions of the flume through which fish move. The study area was divided into four zones (Figure 3.3). The first is the Start/Restart Zone (Z1). Z1 is the area in which fish are detected by Antenna 2 (A2). For technical reasons cross-section of A2 actually had two antennas, A1 and A2. For the purpose of the analysis, grouping them as one (A2) sufficed. Fish are in Z1 either because they have just been released into the experiment area and are detected on their journey up the tailwater or because they have returned from the entrance channel and are potentially initiating a new attempt. Fish are in Z2 when detected by Antennas 3 and 4 (A3, A4). An individual fish attempt is initiated when the fish meets the condition of having traveled against the flow (positive rheotaxis) from Z1 and is detected either by A3 or A4. The first detection in Z2 is recorded as the start of an attempt. A fish may stay in the attempt zone, swimming between A3 and A4 until it makes its next zone decision. The fish can either swim past the wall diffuser or swim back towards the entrance channel and into the tailwater. The outcome of an attempt is successful (passage) once the fish is detected by either Antenna 5 or 6 (A5, A6), in the Success Zone (Z3). If the fish is detected in Z1, the fish is considered to have fallen back (fallback), and the attempt is failed.

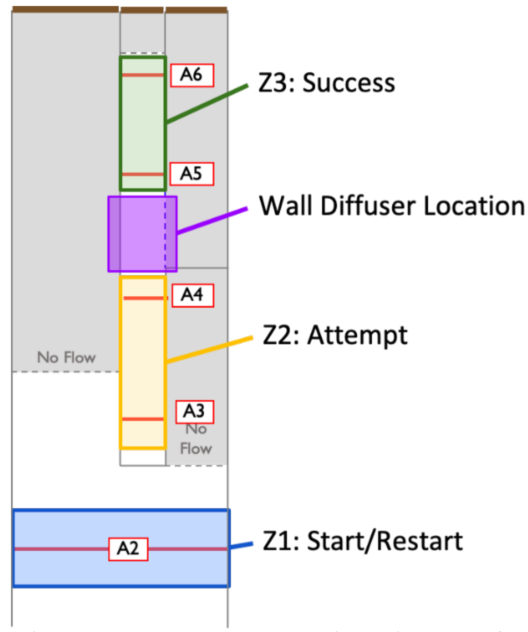

Figure 3.3 Zone locations for categorizing the occurrence of an attempt and its outcome indicated on design schematic.

3.2.7 Cumulative Plots & Two-Proportion Upper-tailed Z-Test

The fish attempt data was plotted into cumulative plots of passage percent over time. The cumulative plots allow comparison between the two velocity treatments of the success rates over the duration of an attempt. The final percent value on the plots indicates the overall percent of fish passed for the two velocity treatments. Cumulative passage and fallback plots were created for 6 different subsets of the data: first attempts per fish, first 2 attempts, first 3 attempts, first 9 attempts, first 17 attempts, and all attempts. A given fish in a trial could make several attempts during the experiment. For these plots, each attempt a fish made was recorded separately. The number of attempts for each fish varied. The two-proportion upper-tailed z-tests were then calculated using the overall percentages from the cumulative plots to determine whether the difference in passage between the two velocities were significant. The results from the analyses are the chi-square test of independence (χ^2) and p-values. Detailed explanation in Appendix B.

3.2.8 Mean & Median Time to Passage Table

A summary table of data categorized by dataset type, sex, and velocity were used to calculate the mean and median minutes for an attempt. There were three categories for dataset types: "all data," "pass data," and "fall data." Additionally, information on sex distribution and sample sizes were included. This table was produced to determine how different the mean and median times were between a pass and a fallback event, and if those differed from each other accounting for influence of fish sex. There could be differences in performance between the male and female fish; females have generally not performed as well as males in past CAFRL experiments, Mulligan et. al. (2019) being one example. For this reason, establishing the presence of males and females in the study was important.

3.2.9 Unique Fish Table & Scatterplots

A fish making multiple attempts can be problematic in the event that there might be outlier fish making more attempts than its cohorts. A table of fish participants in the trials, their number of attempts for both passage and fallback, and mean and median values for their overall attempt durations were calculated. In addition, the mean and medians for the fish attempt duration at the trial scale was also included. The scatterplots are derived from this information. The x-axis is an individual fish's number of passage events versus their number of attempts for the two diffuser treatments. These were also made for fallback.

3.2.10 Cox Proportional Hazards Model

The Cox proportional hazards model is a regression used to model the influence of covariates on the probability of an event occurring at a given time (Cox 1972). The question this analysis addresses is if covariates such as water temperature, fish sex, and diffuser velocity influence the probability of a fish passing over time.

3.2.11 Results

Cumulative Plots & Two-Proportion Upper-tailed Z-test

The goal of the study is to assess the effects of AWS wall diffuser velocities on internal fish passage efficiency. The scope of the data collected to address that question is focused on internal passage across the diffuser area. One unknown that would affect the scope is whether there are effects on fish from the AWS flows at the entrance gate or outside of the entrance channel in the tailwater area (Z1). Effects from AWS hydraulics in these areas would be cumulative and non-differentiable from those just at the internal AWS merging region.

To address this concern, a plot of cumulative entry (initial release to first detection at Z2) versus time was made to assess whether the wall Vw treatments affected entry (Figure 3.4a). By visual inspection of the plot, the rates of the two diffuser velocities were similar.

The final percentages were also similar at 78% and 71% for the 0.5 and 1.0 fps treatments respectively (Table 3.2).

The two-proportion upper-tailed z-test determines the significance of those percentages based on the sample size, answering the question of whether the results are meaningful, ensuring the fish had similar entry. A resulting p-value of 0.405, with confidence intervals (CI) -0.077 to 0.219, indicated that there was no difference between the two velocity treatments.

Figures 3.4c and d present the cumulative plots for percent passage and fallback for all fish attempts in the dataset. Unlike with the cumulative entry, where each fish had one exposure to the attempt zone, the data in this analysis included all the exposures of a given fish to the attempt zone; all attempts were considered as separate data points. The two plots complement each other; fish that do not pass are considered to have fallen back. Most attempt durations were under 25 minutes, fish moved quickly either into the next zone, Z3, or the previous, Z1. Only a few fish lingered in Z2 for a longer period of time. About 50% passed within the first two of minutes and 80% passed within the first seven minutes of an attempt (Figure 3.4b). Specifically, the slower treatments had more fish pass earlier; for the given percentages by half a minute and one minute respectively. For most of the percentiles the 0.5 fps treatment was leading, except after the remaining 20% of fish were left to pass.

The plot of individual trials also demonstrates how similar performance in the trials was. The 0.5 fps velocity in the cumulative passage plot (Figure 3.4c) had 72% final passage while the 1.0 fps velocity had 60% final passage. In fallback (Figure 3.4d), the 0.5 fps result was 28%, and the 1.0 fps result was higher at 40%.

The cumulative plots and test were made for five other subsets of the data: first attempt, first 2 attempts, first 3 attempts, first 9 attempts, and first 17 attempts (see Appendix C). These consistently showed a greater percent passage value for the 0.5 fps velocity than for the 1.0 fps velocity; however, the p-values started at 0.710 for the smallest dataset and decreased to the significant p-value of 0.014 for the whole dataset (Table 3.2). Sample size for all datasets was validated, see Appendix C for details.

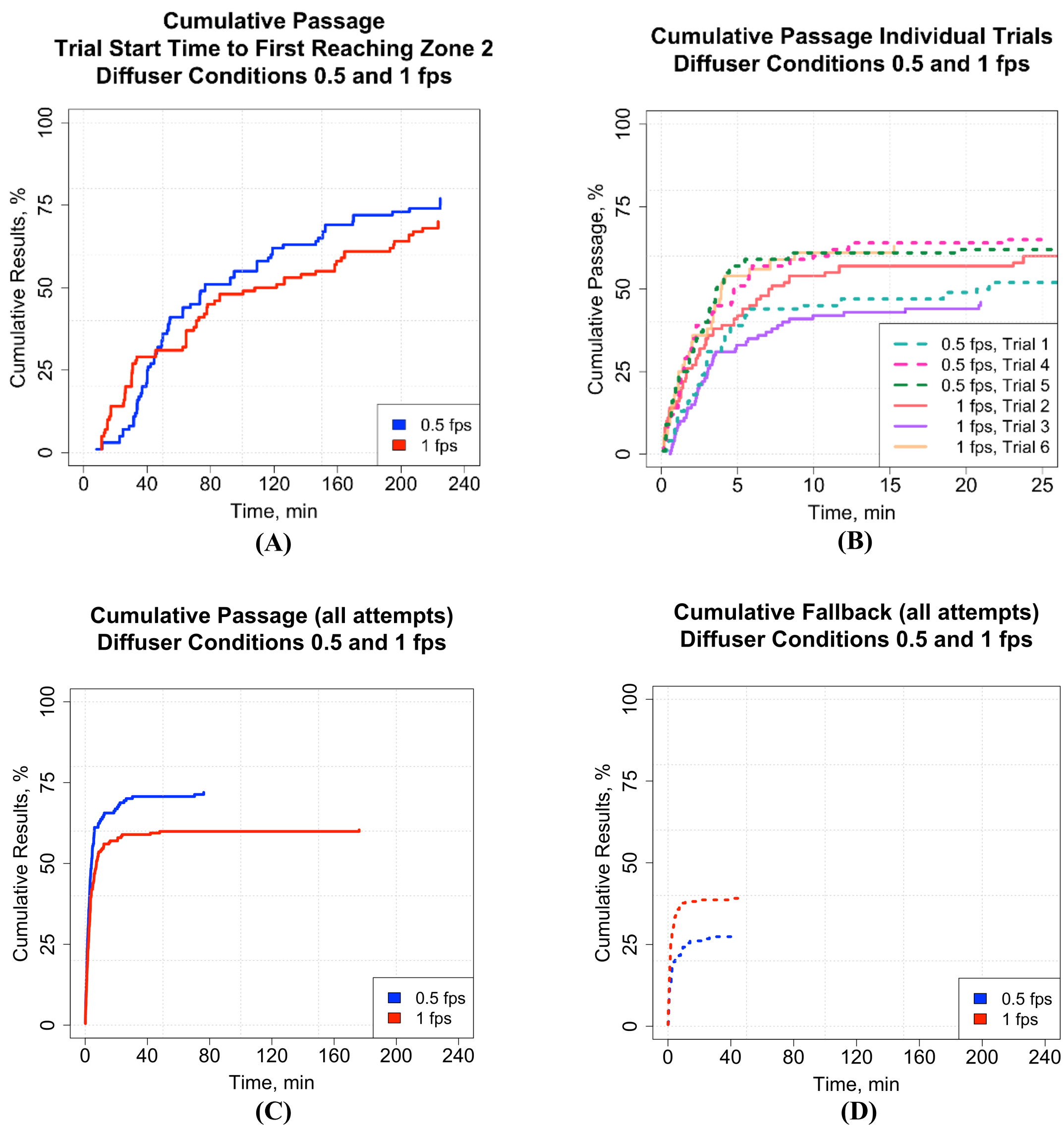

Figure 3.4 Cumulative passage plots for (A) initial entry, (B) view of first 25 minutes of all trials, (C) full trial time for all attempts data – passage, and (D) full trial time for all attempts data – fallback.

Table 3.2 Results from Z-test for passage, fallback, and initial entry datasets

Cumulative Plot	Percent Passage (PP)	Sample Size (passage and fallback events)	Test Type: Upper-tailed N*a*	chi-squared	p-value
Passage (first attempt)	0.5fps = 71.4% 1.0 fps = 78%	0.5fps = 56 1.0 fps = 53	0.5fps PP > 1.0 fps PP	0.305	0.710
Passage (first 2 attempts)	0.5fps = 73.7% 1.0 fps = 70.9%	0.5fps = 95 1.0 fps = 86	0.5fps PP > 1.0 fps PP	0.061	0.402
Passage (first 3 attempts)	0.5fps = 73.3% 1.0 fps = 69.2%	0.5fps = 120 1.0 fps = 117	0.5fps PP > 1.0 fps PP	0.307	0.289
Passage (first 9 attempts)	0.5fps = 72% 1.0 fps = 65%	0.5fps = 157 1.0 fps = 183	0.5fps PP > 1.0 fps PP	1.575	0.105
Passage (first 17 attempts)	0.5fps = 72% 1.0 fps = 62%	0.5fps = 157 1.0 fps = 200	0.5fps PP > 1.0 fps PP	3.852	0.025
Passage (all attempts)	0.5fps = 72% 1.0 fps = 61.5%	0.5fps = 157 1.0 fps = 207	0.5fps PP > 1.0 fps PP	4.798	0.014
Initial Entry	0.5 fps = 78% 1.0 fps = 71%	0.5fps = 79 1.0 fps = 77	*Two-tailed, Na* 0.5fps PP ≠ 1.0 fps PP	0.692	0.405

3.2.12 Mean & Median Time to Passage Table

Not accounting for fish sex, the mean and median values for attempt time (also equivalent to duration in the attempt zone) for a passage event in the 0.5 fps velocities were 5.5 and 2.4 minutes (Table 3.3). The subdivision of passage versus fallback was done to understand if there are differences in time duration (and in effect behavior) with passing or falling. The 1.0 fps velocity was 6.0 and 2.5 minutes, somewhat longer than the slower velocity treatment. On the other hand, fallback saw a decrease in mean and median attempt durations, going from 5.1 and 2.0 minutes to 3.3 and 1.3 minutes. When analyzing the "all" dataset, which is the combined pass and fall datasets, the mean time and median times fell from 5.4 and 2.2 minutes to 5.0 and 2.0 minutes.

The sex distribution for the 0.5 fps data included approximately 3 times more attempts by females than males. The 1.0 fps treatment had a near split, but still had slightly more attempts by females. Passage had a higher ratio of females than the fallback data, by 0.24. Though sex information was not known for some of the fish in the study, these fish made up less than 5% in the samples. See Appendix D for more details.

Table 3.3 Summary results for "all", "pass", and "fall" datasets by velocity treatment (Vw). The dataset is described through sample size, the ratio of female to male fish in the study, proportion of fish with unknown sex information, and mean and median times that fish spent in the attempt zone before passing or falling back.

Data	Vw	Sample Size	Sex Ratio F/M	Fish Sex Unknown NA/sample size	Mean Time (min)	Median Time (min)
all	0.5	157	3.09	0.01	5.4	2.2
pass	0.5	113	3.11	0.02	5.5	2.4
fall	0.5	44	3.00	0	5.1	2.0
all	1	207	1.11	0.04	5.0	2.0
pass	1	125	1.22	0.05	6.0	2.5
fall	1	82	0.98	0.02	3.3	1.3

Though the mean time for the overall sample is important in understanding the effects for American shad as a whole, the difference between number of females and males could bias results. Additionally, any given fish with extreme attempt time due to a variety of factors (health, motivation, environmental comfort) could affect the results. The boxplot of male and females for each trial, subdivided by passage or fallback event, demonstrates the distribution of females and males in the given event and trial, as well as the outliers within that group (Figure 3.5). On the left column are boxplots for the entire dataset, and on the right are a series of plots with outliers greater than or equal to 50 attempt minutes removed.

The boxplots of the outliers removed show minor differences in the medians between females and males. In the passage dataset, under both treatments, in all trials except for trial 3, the interquartile range for males is overall higher than females. The interquartile ranges overlap and are of similar spread between the female and male fish in the passage dataset. For the attempts resulting in fallback events, females have a greater variation for four out of the six trials. The level of spread for both sexes for fallback is more varied between trial and treatments. The data is often skewed, especially for: Passage – Trial 1 males, Trial 6 males and females, Fallback – Trial 1 females, Trial 4 males, Trial 5 females, Trial 3 females.

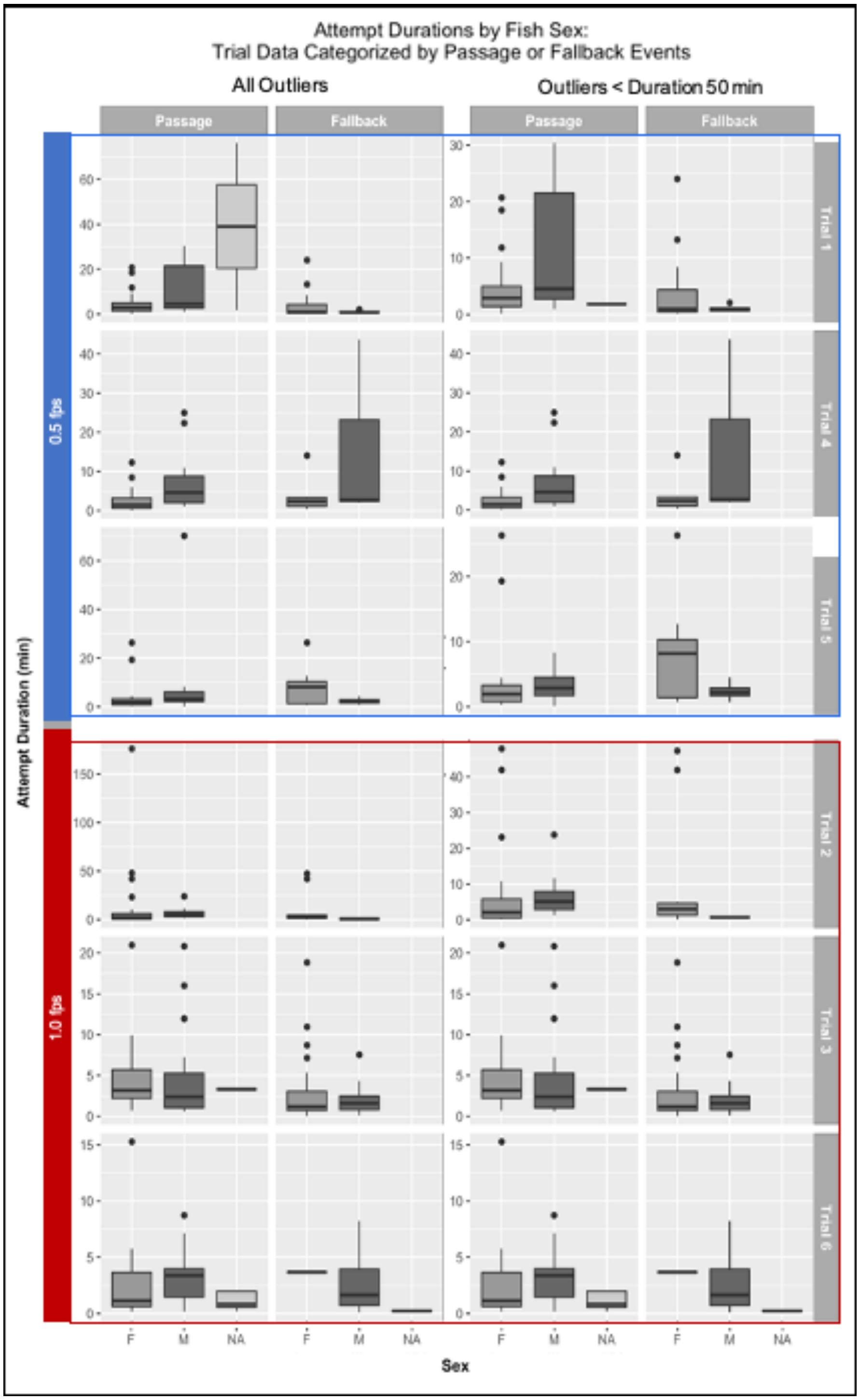

Figure 3.5 Attempt duration based on fish sex and trial boxplots

Table 3.4 details the mean and median raw data by fish sex for each diffuser velocity treatment. In the passage dataset, female fish doubled in mean time from the 0.5 to the 1.0 fps condition (2.2x), whereas male fish decreased by double (2.0x). For fallback comparing between the 0.5 and 1.0 fps velocity, female fish maintained a fairly similar mean time, while male fish mean times decreased by almost three times (2.8x).

Table 3.4 Descriptive statistics for "all", "pass", "fall" dataset arranged by sex and velocity treatment *with* outliers

Data	Vw (fps)	Sex Ratio (F/M)	Sex	Sample Size	Mean Time (min)	Median Time (min)	No. of Outliers
all	0.5	3.08	F	117	3.89	2.10	13
all	0.5		M	38	8.28	2.78	6
all	1.0	1.12	F	105	6.62	2.20	9
all	1.0		M	94	3.43	2.13	6
pass	0.5	3.11	F	84	3.46	2.10	7
pass	0.5		M	27	9.36	4.53	5
pass	1.0	1.25	F	66	7.63	2.44	6
pass	1.0		M	53	4.57	2.91	3
fall	0.5	3.00	F	33	4.97	2.14	2
fall	0.5		M	11	5.64	1.21	1
fall	1.0	0.95	F	39	4.92	2.04	4
fall	1.0		M	41	1.96	1.46	3

Table 3.4 was updated with the extreme outliers greater than or equal to 50 minutes removed (Table 3.5). This cut-off time was chosen visually (Figure 3.5). Though appearing to have more outliers in the left boxplots, more were not removed because natural variability in biological studies should be carefully retained. The table shows values are more consistent, such as all: 0.5fps – male, 1.0 fps – female and pass: 0.5 fps – male, 1.0 fps – female; being closer to the rest of the data. The median values remain fairly similar.

Table 3.5 Descriptive statistics for "all", "pass", "fall" dataset arranged by sex and velocity treatment *without* outliers

Data	Vw (fps)	Sex Ratio	Sex	Sample Size	Mean Time (min)	Median Time (min)	No. of Outliers
all	0.5	3.16	F	117	3.89	2.10	13
all	0.5		M	37	6.61	2.72	6
all	1.0	1.11	F	104	4.99	2.11	8
all	1.0		M	94	3.43	2.13	6
pass	0.5	3.32	F	84	3.46	2.10	7
pass	0.5		M	26	7.01	4.06	4
pass	1.0	1.23	F	65	5.04	2.38	5
pass	1.0		M	53	4.57	2.91	3
fall	0.5	3.00	F	33	4.97	2.14	2
fall	0.5		M	11	5.64	2.04	1
fall	1.0	0.95	F	39	4.92	1.21	4
fall	1.0		M	41	1.96	1.46	3

3.2.13 Individual Fish Table & Scatterplots

The scatter plot table from the individual fish table (Appendix D) shows that as there is an increase in exposures to the attempt zone, there is an increase in passage and fallback events. However, the linear fit to the data for 0.5 fps and 1.0 fps shows a greater rate of passage for the 0.5 fps than for the 1.0 fps velocity (Figure 3.6). For passage, the R-squared values are 0.53 and 0.31, and the p-value for this is 0.08 using a two-sample t-test assuming unequal variances. The fish that had an unusually large number of attempts (>10) did not have a proportional increase in passage events but did have many more fallback events. Removing the two outlier fish from the dataset, the results of the linear rates were the same for the 0.5 fps velocity data since the two fish were in the 1.0 fps velocity trials. The R-squared for the linear regression on the 1.0 fps passage data changed to 0.42 and had a p-value of 0.15.

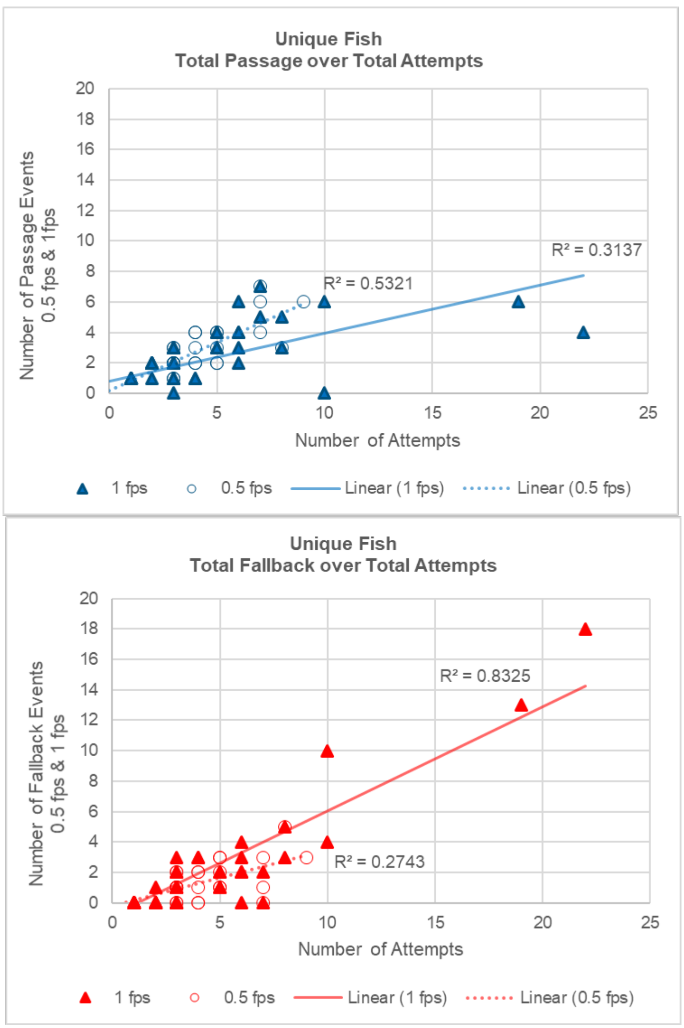

Figure 3.6 Scatterplot of individual fish and the ratio of their attempts and number of passage events off those attempts. Each point in the scatter plot is a fish. Their total attempts in the trial they participated in are on the x-axis and their total passes (or fallbacks) are on the y-axis. Hollow circles are for the 0.5 fps treatment and solid triangles are for the 1.0 fps treatment. Linear fits on the datasets demonstrate the relationship between the two treatments with respect to their rate of passing or falling for having the same number of attempts.

3.2.14 Cox Proportional Hazards Model

The Cox proportional hazards model was used to determine if the probability of passage for a given fish changed over time and how the probabilities between the two velocity treatments compare. The Cox multivariate regression method was used for two datasets, one being passage and the other fallback. Models were run with one (Vw) and three (Vw, fish sex, and river temperature) covariates. All models had p-values higher than the threshold significance of 0.05 (Table 3.6). Velocity, sex, and temperature did not affect the time-dependent probability of a passage event occurring. The frailty term was included in the model as a way to address the bias from repeated attempts by the same fish. The likelihood ratio had a p-value less than 0.05.The result is similar for the fallback data.

Table 3.6 Results from Cox multivariate regression for both passage and fallback data. Covariates for the model are the two Vw (categorical: 0.5 and 1.0 fps), the sex (categorical: F/M), and the temperature (continuous). Hazard Ratio (HR), significance value for covariates (p-value), and significance of Cox model construction indicated from likelihood ratio further describe the model.

Type	Covariates	HR	P-value	P-value for - likelihood ratio
passage	Vw (0.5 fps)	0.17	0.856	8E-06
	frailty	-	0.018	
fallback	Vw (0.5 fps)	0.25	0.295	1E-07
	frailty	-	0.0001	
passage	Vw (0.5)	0.17	0.956	2E-05
	sex (F)	0.18	0.170	
	temperature	0.42	0.727	
	frailty	-	0.034	
fallback	Vw (0.5)	0.27	0.656	8E-08
	sex (F)	0.28	0.657	
	temperature	0.65	0.333	
	frailty	-	0.0007	

3.2.15 Hydraulic Study

Physical modeling in a 1:8 scale flume facilitated the exploration of hydraulic conditions the fish encountered in the large-scale flume. The hydraulic characterization is pertinent to identifying the flow characteristics that may be prompting the behavioral responses of the fish between the two treatment conditions. This methods section details the facility and design of the experiment, data collection, and data analysis.

3.2.16 Methods

Facility Overview & Design Layout

The hydraulic study used a 1:8 scale model flume that measures 2.5' x 3' x 16.25' (Figure 3.7a-b). The flume was composed of plywood floors and acrylic sides. The walls of the model entrance channel are constructed of 5/8 inch thick mahogany. Dimensional analysis was applied to account for the Froude and Reynolds scaling factors. The Froude number was the same for both the prototype and model scales, while the Reynolds number in both setups had flows in the turbulent regime. Water was sourced from the Turners Falls Hydroelectric Project power canal (FERC#1889) via gravity. Flows in the flume were measured using a Venturi meter. WSE measurements were obtained from stilling wells connected to floor taps at various points in the model: AWS and entrance channels, and the tailwater. Once established, cross-sections of velocity data were collected using a Nortek Vectrino acoustic Doppler velocimeter (firmware Version 1.31+ and Software Version 1.22.00) with three-dimensional side-looking prongs, transmitting at a length of 1.8mm, with sampling volume of 5.5mm, and set at high power level. The sample recording rate was 200 Hz for 90 seconds at each measurement point.

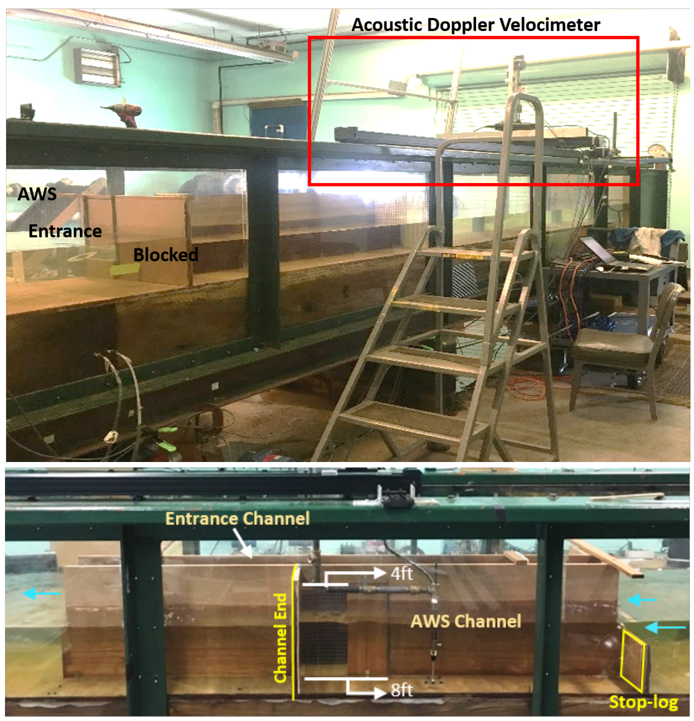

Figure 3.7 ***a)*** Model Flume for hydraulics data collection. Acoustic Doppler Coupled Profile velocimeter on top of flume moves in x-y-z directions. Laptop collects ADCP data. Tubes under the flume connect to the bottom the design to indicate WSE.
b) side view of AWS channel

Data Collection

The model flume was used for two data collection purposes. The initial collection was in preparation of construction of the large-scale flume. The goal was to determine the required stop-log heights at the upstream end of the AWS and entrance channel to achieve the desired hydraulic conditions. The second data collection was to map the hydraulics in the large scale flume in order to associate velocity patterns and hydraulic phenomena (such as upwelling, streaming flow, etc.) to the behavioral data.

Acquiring the heights for the stop logs was an iterative process that was significantly easier to perform in the small-scale flume. Each stop-log was installed and the flow was adjusted such that the headwater and tailwater stilling wells read 6.1 ft (EL_{HW}, full scale) and 5 ft (EL_{TW}, full scale). Then the stilling wells were measured for the AWS and entrance channels to determine water surface elevation. The overall discharge was determined via the difference between two large stilling wells connected to either side of a Venturi, demonstrating the pressure drop of the water source. Cross-sectional velocity data, collected using an ADV unit, was used to calculate flow rate in the AWS channel. V_w was then calculated based on flow in the AWS channel, water depth, and diffuser width. This process was conducted several times for each diffuser treatment using different stop log heights until the desired conditions for each treatment were reached. Using interpolation for the desired velocity, the stop log heights for both treatments were the same.

In the second data collection, hydraulic characterization for the two treatment conditions, eighteen cross section measurements were taken for each diffuser treatment. Each treatment had one cross section in the AWS channel, twelve in the entrance channel, one over the entrance gate, and four in the tailwater. The raw data were in the form of u-v-w velocity measurements collected at 200 Hz for each of the 840 points. The grid of points collected were 6 x 6 points for the entrance and AWS channel cross sections, and 6 x 14 points for the tailwater. Velocity components at each point were collected for 90 seconds. Only the velocity profiles for the entrance channel were analyzed; the data was insufficiently detailed to calculate turbulence. Much of the data for the entrance gate and tailwater cross section data was filtered out because of large amounts of spiking, poor signal to noise ratio, and correlation values.

Data Analysis

The ADV data were de-spiked using the Goring & Nikora (2002) method and filtered using a minimum correlation of 70% and 10dB signal-to noise. The mean was calculated for each velocity component ($\bar{u}, \bar{v}, \bar{w}$) and from this the velocity magnitude ($\sqrt{\bar{u}^2 + \bar{v}^2 + \bar{w}^2}$) was calculated.

For the hydraulic characterization of the two treatments, the ADV data were plotted using RStudio as horizontal cross sections of the entrance channel. Each diffuser treatment had the u-v-w components separately plotted as six evenly vertically (z) spaced contour plots.

All plots had arrays of u-v velocity arrows. Each diffuser treatment had 18 horizontal cross section plots.

3.2.17 Results

The hydraulics data in the small-scale flume exhibit detailed flow patterns and characteristics of the two diffuser treatment conditions. The data from this model scale flume can then be compared to the behavioral data to understand what regions might be impacting passage.

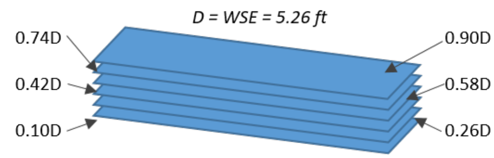

Figure 3.8 Horizontal cross-sections of entrance channel velocities at six depths with interpolation between x and y data points.

The velocity profiles were plotted as horizontal cross-sections of the entrance channel at varying depths (Figure 3.8). There are three sets of mixed contour-arrow plots for each velocity treatment. The arrows represent the u-v direction of flow, while the contours represent either u, v, or w in separate sets of plots (Figure 3.9, 3.11, & 3.13). The plots show the stop logs on the upstream end as brown rectangles. The blank space between the stop-logs and data is the area blocked off by a screen to prevent fish from going over and into the head-pond. The contour plot flow ranges (blue to red in increasing values) vary for the three velocity components. The x-axis is positive in the downstream flow direction, the y-axis is positive in the rightward flow direction, and the z-axis is positive in the upward direction. The depths of the cross sections are noted as a percent of the total WSE, progressing from lowest on the left to highest on the right.

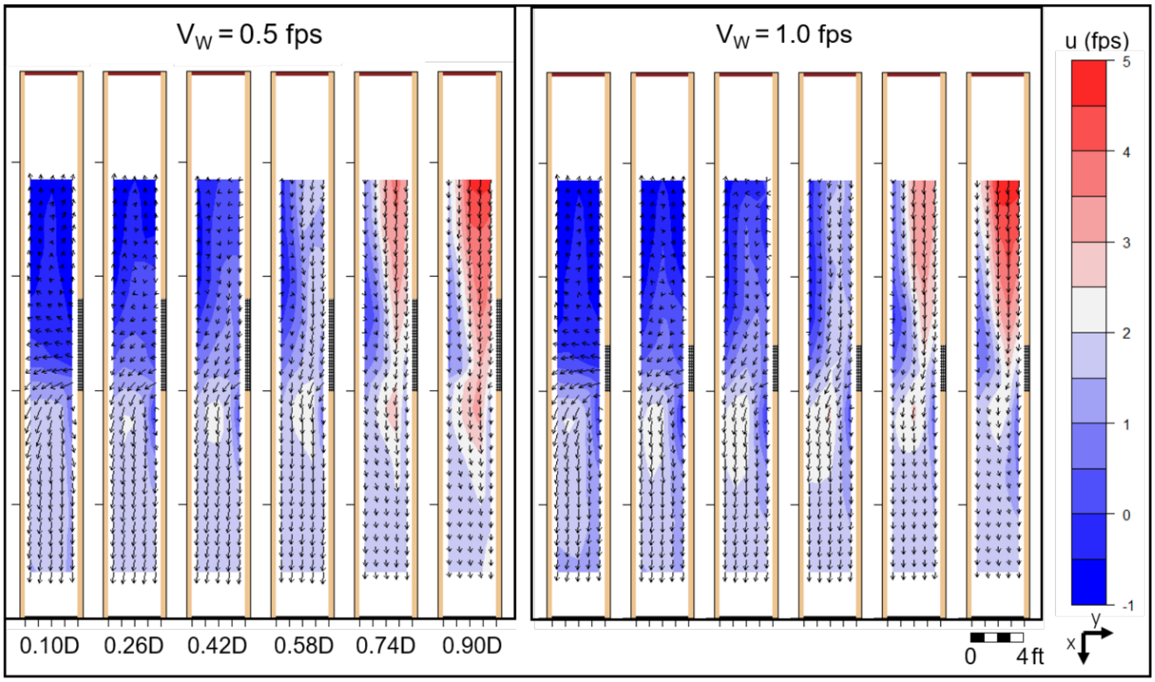

Figure 3.9 Contour cross-sections for u-component. Darkest blue to darkest red show a range from -1 to 5 fps. The six cross-sections are evenly vertically (z) spaced horizontal sections of the entrance channel. The range of the data in the plots are for just after the entrance gate and up to 8 feet before the stop logs, where a grid fencing prevents fish from going into the headwaters.

The contour plots for the u-component describe movement of flow up or downstream (Figure 3.9). In the upper two horizontal sections (0.74D and 0.90D) there is a strong flow coming into the entrance channel from the head-pond on the right hand side; a jet typical of streaming flow. Recirculation is common with streaming flow, where the majority of the flow is a downstream flowing jet of water at the surface and a portion of the flow recirculates below. The recirculation is depicted in the lower cross-sections, where the velocities are negative. These effects are also evident in the prototype design's surficial flow (Figure 3.10). The head-pond flow going into the channel has the strongest streamflow on the river-left side of the entrance channel for both treatments. The recirculation zone's surface jet behaves differently between the two treatment velocities. For both treatments the diffuser flow breaks up the surface jet and recirculation zone. The disruption from the wall diffuser flow can be seen as a magnitude and directional change pictured from the brighter red transitioning to light blue. The slowing effect and eddy formation are stronger in the 1.0 fps treatment.

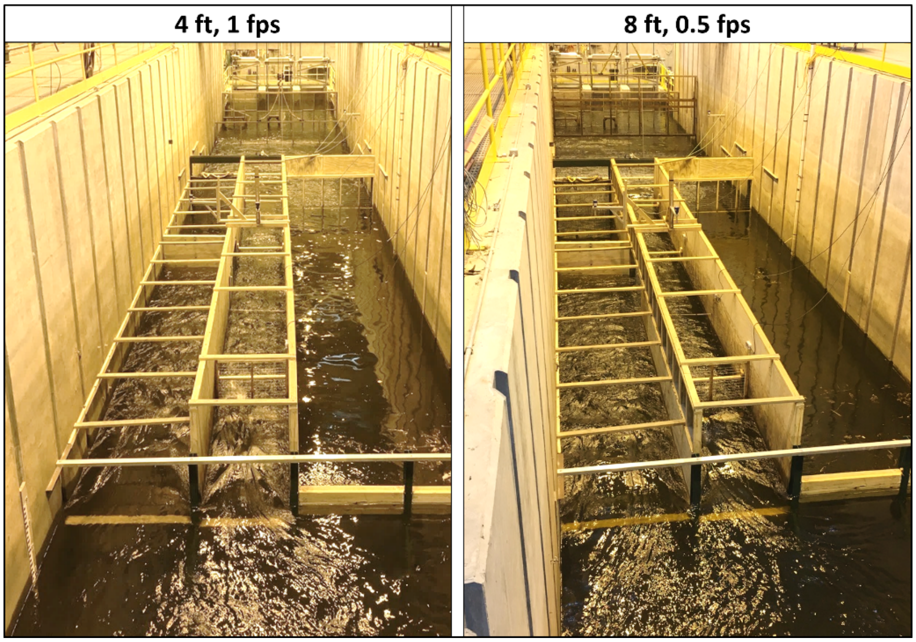

Figure 3.10 View from upstream tailwater of the two experiment treatments in the full-scale flume. The center channel's off-center river-left position results in the incoming flow being concentrated on the river-left side of the channel.

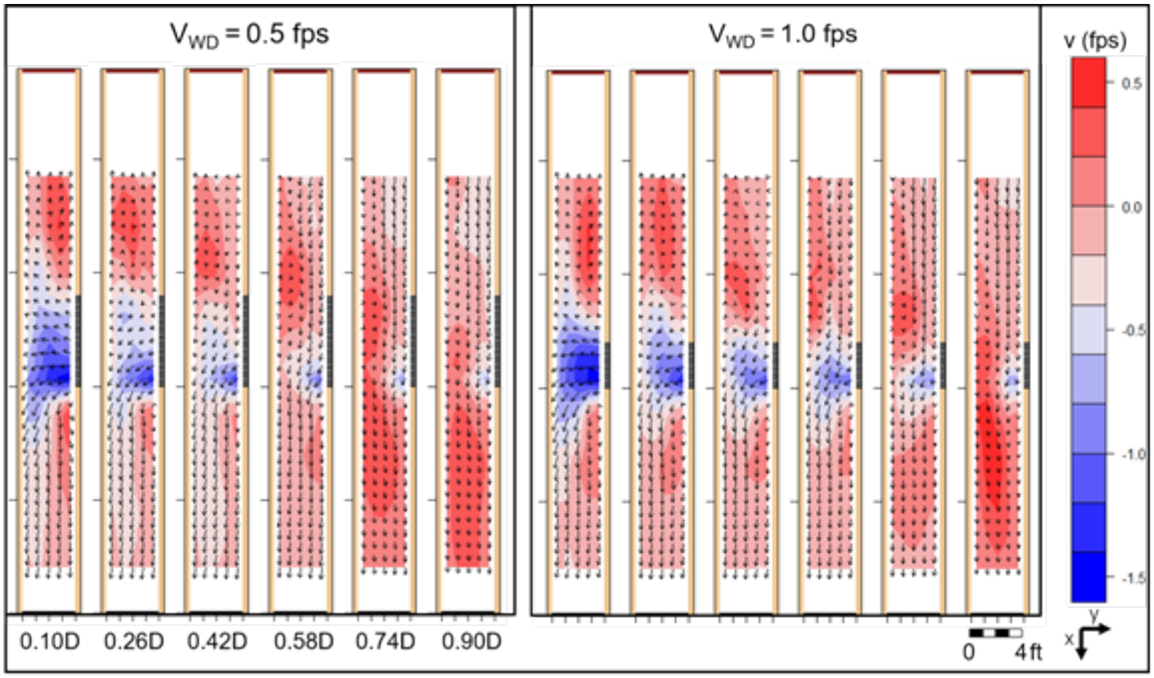

Figure 3.11 Contour cross-sections for v-component. Darkest blue to darkest red show a range from -1.5 to 0.5 fps. The six cross-sections are evenly vertically (z) spaced horizontal sections of the entrance channel. Data for the plot is for just after the entrance gate up to 8 feet before the stop logs, where a grid fencing prevents fish from going into the headwaters.

Figure 3.12 Contour cross-sections for v-component. Darkest blue to darkest red show a range from -1.5 to 0.5 fps. The six cross-sections are evenly vertically (z) spaced horizontal sections of the entrance channel. Data for the plot is for just after the entrance gate up to 8 feet before the stop logs, where a grid fencing prevents fish from going into the headwaters.

The v-direction specifies lateral flow movement (Figure 3.11). The strongest velocities from the diffuser are near the bottom (0.1D – 0.26D) and downstream end of the opening. The velocities in these areas are around 1.5 fps in both 0.5 fps and 1.0 fps treatments. This rightward flow just after the downstream of the diffuser was also visible during the experiment and was what looked like upwelling and overturning as well, visible in Figure 3.12 1b and 2b in the top image sections of the entrance channels.

An eddy is located at the bottom edge after the diffuser, where the velocity is around 0.5 fps towards the right. These eddies produced from the AWS and main channel flow mixing could be seen at the surface during the experiment (Figure 3.12). In general, the model flume shows the velocities are near zero downstream of the diffuser in the lower sections (0.10D – 0.58D). Towards the surface, velocities from the diffuser are smaller. The surface water from the streaming jet is able to move around the leftward diffuser flow, rather than mix with it and transition to a leftward direction. As the flow progresses downward, the v-components seem to move towards being no magnitude.

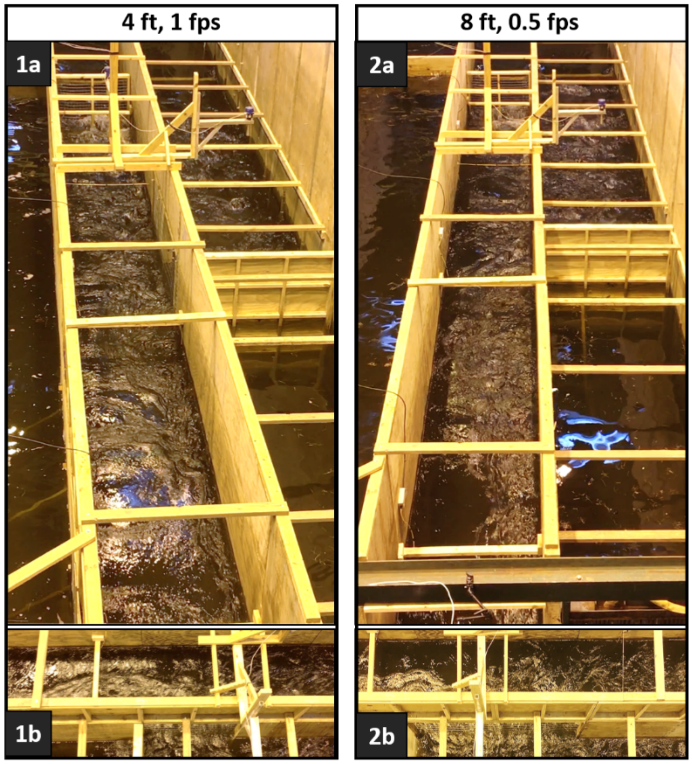

Figure 3.14 Two experiment treatments in the full-scale flume. 1a and 2a face upstream with entrance channel on left and AWS channel on right. 1b and 2b are a view over the wall diffuser with the AWS channel at the bottom and entrance channel top, water is flowing right to left.

Figure 3.15 Contour cross-sections for w-component. Darkest blue to darkest red show a range from -1 to 1.0 fps. The six cross-sections are evenly vertically (z) spaced horizontal sections of the entrance channel. Data for the plot is for just after the entrance gate up to 8 feet before the stop logs, where a grid fencing prevents fish from going into the headwaters.Figure 3.16 Two experiment treatments in the full-scale flume. 1a and 2a face upstream with entrance channel on left and AWS channel on right. 1b and 2b are a view over the wall diffuser with the AWS channel at the bottom and entrance channel top, water is flowing right to left.

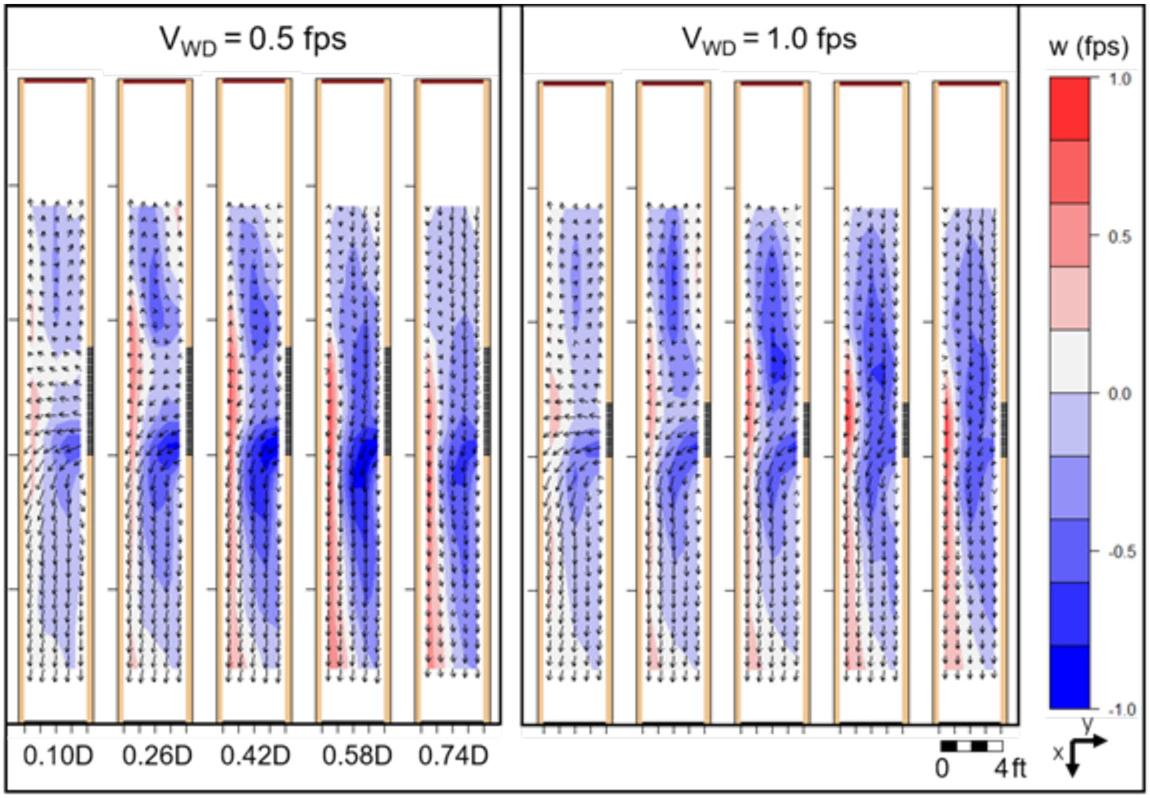

Figure 3.17 Contour cross-sections for w-component. Darkest blue to darkest red show a range from -1 to 1.0 fps. The six cross-sections are evenly vertically (z) spaced horizontal sections of the entrance channel. Data for the plot is for just after the entrance gate up to 8 feet before the stop logs, where a grid fencing prevents fish from going into the headwaters.

Figure 3.18 Contour cross-sections for w-component. Darkest blue to darkest red show a range from -1 to 1.0 fps. The six cross-sections are evenly vertically (z) spaced horizontal sections of the entrance channel. Data for the plot is for just after the entrance gate up to 8 feet before the stop logs, where a grid fencing prevents fish from going into the headwaters.

The w-component is the vertical upward (positive values) or downward flow (negative values) (Figure 3.13). Both treatments have the same flow coming into the entrance channel. These flows have the same downward trajectory, with the 1.0 fps treatment having a slightly higher velocity.

The treatments both have some upwelling on the left channel wall, opposite the diffuser (Figure 3.12 & 3.13). The 0.5 fps treatment has slightly higher velocities. The highest upwelling velocities of up to 1.0 fps occur in the upper section of the channel (0.42D – 0.74D). Though the two treatments are similar, the 1.0 fps treatment experiences downward flow slightly sooner. The upwelling extends downstream.

3.2.18 Discussion

The primary research question in this study is whether there is a difference in passage efficiency between a 0.5 fps or 1.0 fps wall diffuser velocity. To test the direct influence of the entering AWS wall diffuser flow on fish behavior, this study evaluated fish movement once a fish was in the entrance channel and was actively attempting to move upstream. The results from those tests were time series of their locations then analyzed for passage performance of the two velocity treatments. Hydraulics of the study design structure were also investigated to understand how more or less hydraulics favorability aligns with the results from fish testing. Experimental variables, such as design structure, environmental variables, and fish sex may have had effects on the research results to differing degrees.

Experimental Variables

The study sought to minimize the environmental and physical variables that might influence the passage decision, other than the presence of the wall diffuser. Environmental variables included river temperature (18.6-19.3 C), turbidity (2.86 - 4.03 NTU), time of day (morning-afternoon), and span of time during the season (6/16 - 6/21/20). The range of values of each of the environmental variables were relatively constant and it is unlikely that there was any significant influence from these individual variables based on their variation. Additionally, the environmental factors were tested in a Cox regression and were found to be insignificant and inappropriate for the model.

The physical variables considered were the hydraulic characteristics downstream and upstream of the diffuser. There was a possibility that downstream of the diffuser, the combined flow going over the entrance gate and into the tailwater had different mixing and velocity distribution characteristics for the two treatments. The concern was that a difference in the tailwater conditions could influence passage probability before the fish entered the attempt zone. Unfortunately, the hydraulic data collected over the entrance gate and tailwater area could not be used to inspect this question. After filtering, much of the data were not usable, having low Signal-to-Noise Ratios. However, the behavioral data served as a proxy for investigating this question.

Specifically, cumulative plots of the success rate for first release to initial entry provided information on whether one treatment lent itself to easier entrance. The proportions were similar at 77% and 70%. A two-proportion upper-tailed z-test was also completed to determine the significance of the entrance success percentages. The result was an inability to reject the null hypothesis (p-value 0.405) that the first percentage (77%) is equal to the second (70%), therefore the two entrance gate and tailwater conditions were not significantly different and can be considered to be similar. By visual inspection of the cumulative plot it is also noticeable that the rate of passage over time between the two conditions was similar as well.

A second physical flow variable to assess was the flow upstream of the wall diffuser. The flow going over the stop-logs and into the entrance channel is a streaming flow that has recirculation, (darkest blue in Figure 3.9). Without the wall diffuser, the recirculation would extend and gradually dissipate down the entrance channel. With the presence of the diffuser, the gradation of the recirculation dispersion is likely concentrated, especially in the higher velocity treatment. Normally, there are no stop logs on the upstream end of an entrance channel and therefore no recirculation, so without a control it is difficult to say whether the presence of any recirculation may be influencing the fish behavior. It appears from the hydraulic data that the 1.0 fps has a stronger impact on the transition of the recirculation, but it is likely not large enough to render a bias between the two treatments. Accumulated stress in relation to this difference is not believed to be a problem.

Possible effects on fish passage unaddressed in the study are the stress and physical exhaustion-related effects of going into and past the AWS area, reaching the success Zone 3 and either lingering there or going backwards to the beginning. Also, depending on the depth at which the fish swam, they could have encountered the recirculation eddy in Zone 3.

Hydraulics & Behavior

The wall diffuser has three main effects on the entrance channel: slowing the main channel's flow, mixing ability with the main flow, and changes it causes to flow paths. The hydraulic test results revealed that hydraulic characteristics vary with depth. The fish would encounter different flow velocities and flow patterns depending on the depth at which they swim.

The surface jet from the entrance channel in the full-scale experiments was interrupted by the incoming AWS waters, similarly to the results from the model study. The AWS in both treatments slowed the u- and v-components, however the effects were more pronounced for the 1.0 fps treatment. Such an abrupt change is not preferable during migration for fish.

Slower flowing water in the u-direction affects rheotaxis, a key motivator in migration for the fish to swim up against the flow. Dissuading rheotaxis could lead to delays in passage. With the u-component, in the lower depths <0.74D, the velocities are somewhat higher in the downstream direction for the 1.0 fps after the diffuser. Though this is good for rheotaxis, the transition (and presumably favorability) is smoother for the 0.5fps treatment.

Unpredictable flow can disorient fish and cause delays or retreat. The flow from the diffuser merging into the entrance channel is entering with a higher cross-channel (v-component) velocity than the main channel flow. When the fish try to pass the AWS, there is a stronger leftward velocity for the 1.0 fps treatment than the 0.5 fps treatment. For both, but more so for the higher treatment, the flow development into uniformity is slow. The changes between left and rightward velocities are more pronounced for the 1 fps treatment. The entrance gate in the experiment's facility likely aided in the downstream flow merging through streamline convergence. Depending on the facility, this feature might not be available to streamline flows, and the wall diffuser might actually affect the initial entry area.

The 0.5 fps treatment did not do as well with regard to the w-component, the upwelling and downwelling velocity magnitudes were higher. Upwelling is known to negatively affect passage for shad and other non-salmonids (Larinier & Travade 2002, WDFW 2000). Despite higher upwelling, the 0.5 fps still had better passage performance in the behavioral study. It may be possible that the fish avoided the upwelling areas, or that the other velocity components have a stronger influence on their behavior. A w-component velocity range of -1.0 fps to 1.0 fps might not have as much of an effect. For both treatments more than half of the channel had consistently downwelling or neutral values.

The behavioral and hydraulic studies are related by known preferred hydraulic from literature of their biological features and physical abilities. All velocities were under within or under the prolonged speeds for American shad (4.9 – 9.8 fps) (Castro-Santos 2005). The majority of the behavioral study data agrees with the overall better hydraulics in the 0.5 fps treatment. For the "all" attempts data, cumulative percent passage plots show higher percent passage for the slower velocity treatment. Data with lower allowable number of attempts are still showing this pattern, however they are not statistically significant. The concern associated with repeated attempts per fish was that there would be biases if a fish were to have more than normal attempts and have the majority be passes or the majority be failures.

Scatterplots for passage events over number of attempts of each fish showed that increasing attempts lead to a greater rate of increasing passage events for the 0.5 fps condition. For an additional attempt, the event of a pass would be higher for the 0.5 fps velocity, resulting in diminished delays in their migration. Without outliers (fish attempts > 10) the same relationship holds, though the p-value is not significant. In actual fishways, fish are likely to make multiple attempts before passing. The cumulative percentage is helpful in giving an instant result of which treatment had better passage overall. Though sample size might be influencing significance it is important to note that fish making multiple attempts had that increase in passage. It is possible that the increased passage meant there was learning involved in each attempt. Nonetheless, the rate of passage increasing per fish's attempt was still higher.

Striving for faster passage is key in minimizing passage delays, migration and, in turn, successful spawning. Two analysis methods indicate the, faster initial overall passage and better duration of attempts with relation to fish sex results for the 0.5 fps treatment. Cumulative plots show in general that most of the fish passed earlier on in the trial, within the first 5 minutes. Going from 0.5 fps to 1.0 fps treatment, the means for female fish were slower for passing and essentially the same for falling back. The medians were slower for passing and faster for falling back, but not by large differences. This might indicate that female linger more before passing in the 1.0 fps treatment. For the mean and median, male fish were faster in passing and falling back. Faster passing for the 1.0 fps would indicate less delays. However contrary to that, it is possible faster falling back might indicate it's an easy decision not to pass, which could negatively affect fishway performance. The variation in behavioral responses from the fish meant that the attempt means were not so similar to the median results.

The effects of sex on the mean and median time results are inconclusive. There are more females in the slower treatment, which would affect the overall mean seen by fish passing, skewing results to be more applicable to a higher female population. Looking at the data just by sex it seems there might be a delay in passage for females and no delay effects for males. Likewise, the decrease in duration for a failed attempt would be indicative of a greater ease to fail in the higher velocity condition.

The probability of passage over time did not show a significant effect for the sex covariate in the Cox proportional hazards regression therefore sex as a generalized effect or as a specific effect on passage probability at a given time was not influential in these aspects of passage. The velocity treatment (0.5 fps vs. 1.0 fps) as a covariate was also not significant in the regression, therefore probability of passage at a given time was not affected by the treatment either. Both trials had the same probability of passage consistent throughout the experiment duration, but the overall results were better for the 0.5 fps treatment.

3.2.19 Conclusions

Diffuser systems predominantly located within the entrance channel of fishways have been observed to encourage fish fallback. For this reason, the Region 5 USFWS changed the wall diffuser flow criteria from 1.0 to 0.5 fps. The results from testing a prototype wall diffuser with actively migrating American shad support this decision.

Firstly, there was a difference in passage performance between the two diffuser treatments for all different dataset portions tested; the slower 0.5 fps treatment did have higher passage. Second, the 0.5 fps treatment for the most part featured more favorable hydraulics. Merging of the entrance channel and diffuser flows among the u- and v-components was more uniform for the 0.5 fps treatment, and the transition of the flows throughout the entrance channel was smoother. Environmental and physical variables that might influence the results, other than the diffuser treatment velocities, were deemed insignificant with respect to their influence on the rate of a passage event occurring.

In the hydraulics, the w-component is the exception of the slower treatment having more favorable hydraulics since the treatment features more upwelling. Upwelling is not favorable for shad, however despite this, the slower velocity had better behavioral results. Most of the channel cross-section experiences downwelling rather than upwelling. Additionally, considering that the v-component flow on the right side was less and the u-component was stronger, and would thus have a greater positive effect on rheotaxis, it certainly is possible that the fish could find a way to avoid the upwelling area on the left side of the channel. Given that fish did perform better in the slower velocity treatment, the magnitude and placement of the upwelling might not be affecting passage between the two treatments. However, to prove this conclusively it would be necessary to track the fish in three-dimensions.

Based on the overall percent passage, mean and median attempt duration, and higher number of attempt to passage rate, fish had an overall better performance in the 0.5 fps wall diffuser velocity treatment. Although the final percent passage for the 0.5 fps treatment was higher than the 1fps treatment, at 72%, this passage percent should be improved. The study was done in a controlled environment and it is likely that in actual fish passage facilities maintenance, design, and environmental factors may arise that result in lower efficiencies for wall diffusers.

AWS is essential in attracting fish to fishways; however, its internal presence may be stressing fish and affecting passage. Changes in velocity criteria is one way to reduce internal effects. In this study, the more favorable hydraulic conditions, backed by behavioral data showing better passage, indicate the 0.5 fps wall diffuser velocity criteria is superior to the 1.0 fps velocity. This is in one way a recommendation to utilize the 0.5 fps treatment over the 1.0 fps velocity in the future designs, and in another, a note that older fishways built under the 1.0 fps and other higher criteria should be reassessed and altered if needed. Improvements to fishway technology and biological understanding of migration and passage occur faster than relicensing time periods.

Regarding up- and down-welling, near-entrance discharge could be a solution to remove any internal effects related to the w-component. The most substantial consideration for this kind of technology would likely be to ensure that the fish are not too attracted to the near entrance discharge structure itself.

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APPENDIX A

FISHWAY SYSTEMS AT HYDROPOWER (FISH) DATABASE

The following is documentation of the FiSH Database, describing methods of collecting and assembling fishways data into one cohesive database. Further fields containing information from FERC and NID can be accessed on the database spreadsheet upon email request.

METHODS

1) Building the Database

In collaboration with the USWFS database of fishways at hydropower facilities was created. The FiSH database contains fishway information such as coordinates, river and town location, barrier features, auxiliary water system type, and other attributes. This information was compiled using the FERC Active Licenses hydropower database, the National Inventory of Dams 2018 database, and three databases from different USFWS offices in the Northeast Region (Figure A.1). Both manual methods of data entry using excel as well as GIS for more complex joins and calculations were used. This database is generally representative of the New England region, and also includes fishways from other eastern seaboard states: Pennsylvania, Maryland, Virginia, North and South Carolina.

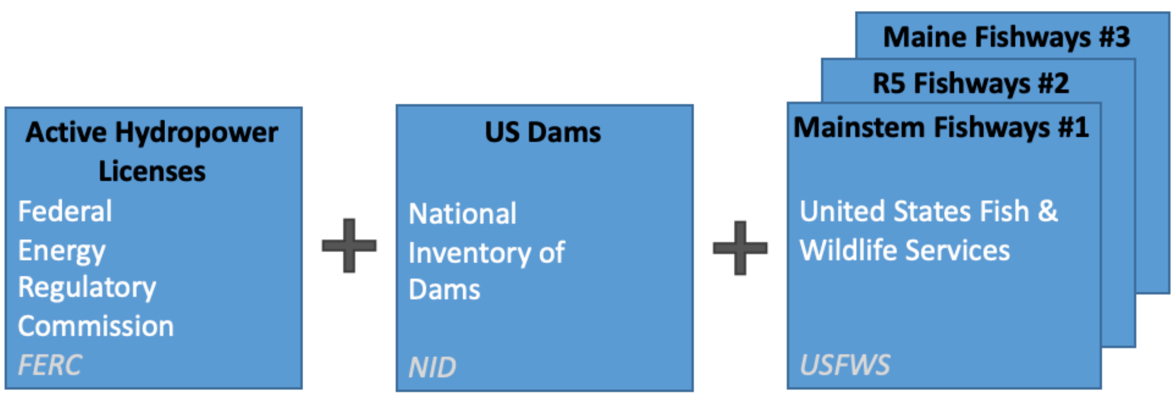

Figure A.1 Datasets making up the Fishway Systems at Hydropower (FiSH) database

Initially there was only one USFWS database, the *Mainstem Fishways*, which contained 40 entries. These were joined manually with the *Active Hydropower Licenses Database*. Unfortunately, a join by attribute would not work for this since often at least one of the following attributes differed: fishway names, hydro dam names, and their given waterways. Additionally, there were no coordinates for the either of the datasets and finding those would be just, if not more intensive than manually comparing a few of the names. Though an R-package called "energy" (Govan 2018) of the FERC data did exist (not agency sponsored), however the coordinate values had been calculated using address geocoding, which for our study held more error than desired (P. Govan, *personal communication*,

March 2019). Dr. Brett Towler from USFWS did have a personal KML file of hydropower sites his area works on and those coordinates were some of the ones used.

After this first example FiSH database was built a fishways engineer proofread its user-accessibility and emailed it to all USFWS offices in the New England region. From that email the following two USFWS databases were obtained: *R5 Query Fishways* and *Maine Fishways*. These were again manually added these to the draft FiSH database, especially now that some of the fishway entries overlapped.

At this point there were 70 fishways data entries. In order to get the remaining coordinate values, the fishways were individually queried using the *U.S. Dams* dataset. Some were searched on Google Maps. *U.S. Dams* and the Google Maps coordinates were in different geographic coordinate systems (NAD1983 and WGS1984 respectively) so the fishways were moved into a separate spreadsheets depending on the place the coordinates were sources. These were then uploaded into ArcGIS. After some data manipulation and choosing the data frame's coordinate system as USA Contiguous Equidistant Conic with an Equidistant Conic projection and having the NAD 1983 geographic coordinate system, these were merged into one dataset using the U.S. boundary.

Now having the FERC and fishways datasets in one database (FiSH) with coordinates, the US Dams information was added. Before spatially joining the two, the dams that were not a part of the fishways coordinates were buffered and flipped. For example, Holyoke has many dams that are secondary reservoirs, which do not have fishways. This thus concluded creating the database.

2) Creating the Maps

Three maps resulted: U.S. Dams, Hydropower Dams & FiSH Fishways, and FiSH Fishways. The U.S. Dams were plotted using only the NID data and other ground layers. For second map was the U.S. Dams data was reclassified for instances where the dam purpose included hydroelectric generation and then added that new layer and the FiSH layer, along with some ground layers. The third is only the FiSH data indicating the locations of the fishways in the database. An additional map was made using symbology to differentiate sites by AWS design, but this map was too busy. The data of AWS designs was better displayed as pie charts and tables.

Table A.1 Readme section of FiSH database

Fishways in Systems at Hydropower		contact information:	Marcia Rojas
			marciarojas@umass.edu

The FiSH database is a combination of personal databases from **U.S. Fish and Wildlife Region 5** (Brett Towler, Melissa Grader and Steven Shepard), **Federal Energy Regulatory Commission (FERC) Active Licenses data (2019)**, and the **National Inventory of Dams (2018). GIS was used to combine the three datasets, primarily using the FERC number and the geographical information of the dam/fishway.** The database for fishways is not complete of the United States, but is fairly representative of the Northeast Region. This is a work in progress and the ultimate goal is to have all the fishways at Hydropower sites documented. Unforunately, though required by FERC in physical form, fishways are not featured on their listing of licenses. Hopefully the care for this is taken in the future as it is an intrinsic balance to hydropower.

Categories	Description	Fishway Types		AWS Types
X	longitude	No US fishway		No AWS
Y	latitude	Lift		wall diff., gravity
Name	name of the project	Lock		floor diff., gravity
Waterway	river it is located on	Trap & Trans	(Trap and Transport)	wall diff., pump
State	state it is located in	P&W	(Pool and Weir)	floor diff., pump
BarrierHt	the height of the barrier/dam	Ice Harbor, Half		wall diff., combined
US_Fishway_Type	type of fishway (per U.S.A. fishway vocabulary conventions)	Ice Harbor, Alt.		floor diff., combined
AWS_Type	type of auxiliary (added) water system for providing attraction flow	Ice Harbor, Full		near entrance discharge
Turning_Vanes	Yes/No, does it have turning vanes that dissipate and direct energy from the AWS	Serpentine		Other
FERC_ID	Federal Energy Regulatory Commision ID given to the dam project	VSF, single	(Vertical Slot Fishway)	
License	license type of the project (E, L, N, S)	VSF, dual		
Expiration	License expiration date	Denil, 4 ft		
Issue	license issue date	Denil, 3 ft		
Capacity	capacity issued	Denil, 2 ft		
Owner	owner of the project	Steepass		

Table A.2 FiSH entries

X	Y	Name	Waterway	State	BarrierHt	AttractFlo	US_Fishway_Type	AWS_Type	Wall	Column1	Turning_Vanes	FERC_ID
-72.441882	43.133348	BELLOWS FALLS	CONNECTICUT RIVER	VT			VSF, single	floor diff., gravity	1	5		1855
-70.4471905	43.4957013	CATARACT	SACO RIVER	ME			Lift	floor diff., gravity	1			2528
-71.298056	42.629061	CENTENNIAL ISLAND	CONCORD RIVER	MA			Denil, 4 ft	floor diff., gravity	1			2998
-70.8738	43.1964	COCHECO FALLS DAM	COCHECO RIVER	NH			Denil, 3 ft	floor diff., gravity	1			4718
-76.173814	39.660239	CONOWINGO	SUSQUEHANNA RIVER	MD			Lift	floor diff., gravity	1			405
-76.174711	39.657647	CONOWINGO	SUSQUEHANNA RIVER	MD	90	450	Lift	floor diff., gravity	1	2	No	405
-76.173814	39.660239	CONOWINGO	SUSQUEHANNA RIVER	MD			Trap & Trans.	floor diff., gravity				405
-67.478928	45.276068	GRAND FALLS	ST CROIX RIVER	ME			Denil, 4 ft	floor diff., gravity				nonFERC6
-72.051405	41.538798	GREENVILLE/TENTH S	SHETUCKET RIVER	CT			Lift	floor diff., gravity	1			2441
-76.331601	39.827066	HOLTWOOD	SUSQUEHANNA RIVER	PA	60	1500	Lift	floor diff., gravity	1			1881
-69.61901675	44.56297919	HYDRO-KENNEBEC	KENNEBEC RIVER	ME		350	Lift	floor diff., gravity	1		Yes	2611
-71.4645	42.7635	JACKSON MILLS	NASHUA	NH			Denil, 4 ft	floor diff., gravity	1			7590
-71.16516531	42.69955766	LAWRENCE	MERRIMACK RIVER	MA		100	Lift	floor diff., gravity	1		Yes	2800
-71.32365302	42.65118758	LOWELL	MERRIMACK RIVER	MA		120	Lift	floor diff., gravity	1		Yes	2790
-68.4646276	45.18666665	LOWELL TANNERY	PASSADUMKEAG R	ME			VSF, single	floor diff., gravity	1			4202
-71.4725	43.0019444	MERRIMACK RIVER	MERRIMACK RIVER (A	NH	50	100	Ice Harbor, Half	floor diff., gravity	1		Yes	1893
-68.64452265	44.94145543	MILFORD	PENOBSCOT RIVER	ME		210	Lift	floor diff., gravity	1		Yes	2534
-67.293281	45.175386	MILLTOWN DAM	ST CROIX RIVER	ME			VSF, single	floor diff., gravity				nonFERC1
-76.390398	39.922809	SAFE HARBOR	SUSQUEHANNA RIVER	PA		300	Lift	floor diff., gravity	1			1025
-72.122132	41.665215	SCOTLAND	SHETUCKET RIVER	CT			Lift	floor diff., gravity	1	4		2662
-72.57811159	42.58726285	TURNERS FALLS	CONNECTICUT RIVER	VT			Ice Harbor, Alt.	floor diff., gravity	1			1889
-72.51410579	42.77140163	VERNON	CONNECTICUT RIVER	VT			Ice Harbor, Alt.	floor diff., gravity	1			1904
-72.63820106	42.09921126	WEST SPRINGFIELD	WESTFIELD RIVER	MA			Denil, 4 ft	floor diff., gravity	1			2608
-72.3033971	43.66710486	WILDER	CONNECTICUT RIVER	VT			Ice Harbor, Half	floor diff., gravity	1			1892
-67.401706	45.158088	WOODLAND DAM	ST CROIX RIVER	ME			Denil, 4 ft	floor diff., gravity	1			UL892
-76.722663	40.143425	YORK HAVEN	SUSQUEHANNA RIVER	PA	15		VSF, dual	floor diff., gravity	1	4		1888
-69.96658446	43.91994965	BRUNSWICK	ANDROSCOGGIN RIVE	ME		100	VSF, single	floor diff., pump	1			2284
-68.42916672	44.54487157	ELLSWORTH GRAHAM	UNION RIVER	ME	90		Trap & Trans.	floor diff., pump	1			2727
-70.02403283	43.9571606	PEJEPSCOT	ANDROSCOGGIN RIVE	ME			Lift	floor diff., pump	1			4784
-68.6477255	45.24976116	WEST ENFIELD	PENOBSCOT RIVER	ME		150	VSF, dual	floor diff., pump	1			2600
-70.06133502	43.99404291	WORUMBO	ANDROSCOGGIN RIVE	ME		150	Lift	floor diff., pump	1			3428
-70.4471905	43.4957013	CATARACT	SACO RIVER	ME			Denil, 4 ft	near entrance discharge, gravity	1			2528
-73.0856	41.3672	KINNEYTOWN	NAUGATUCK RIVER	CT			Denil, 4 ft	near entrance discharge	1			6985
-70.627	41.9172	RUSSELL MILL POND	EEL RIVER	MA			P&W	near entrance discharge	1	6		6429
-72.122132	41.665215	SCOTLAND	SHETUCKET RIVER	CT			Lift	near entrance discharge, gravity				2662
-67.7346	45.6646	FOREST CITY (STORAG	EAST BRANCH ST. CRC	ME			VSF, single	No AWS	1	18		2660
-72.825999	41.520223	HANOVER POND DAM	QUINNIPIAC RIVER	CT			Denil, 4 ft	No AWS	1			14550
-68.657709	45.238722	HOWLAND	PISCATAQUIS RIVER	ME			Denil, 4 ft	No AWS	1			2721
-68.40807673	45.56993363	MATTACEUNK	PENOBSCOT RIVER	ME			P&W	near entrance discharge, gravity	1			2520
-69.7153	45.5859	MOOSEHEAD	PISCATAQUIS RIVER	ME			Denil	No AWS				5912
-72.0502	41.5971	OCCUM	SHETUCKET RIVER	CT			Denil, 4 ft	No AWS	1			11574
-70.1828	43.8015	OLD SPARHAWK MILL	ROYAL RIVER	ME			Denil, 4 ft	No AWS	1			8417
-70.8118	43.2266	SOUTH BERWICK	SALMON FALLS RIVER	NH			Denil, 4 ft	No AWS	1			11163
-67.427533	45.569462	VANCEBORO (STORAG	EAST BRANCH ST. CRC	ME			VSF, dual	No AWS	1			2492
-69.55417087	44.58002758	BENTON FALLS	SEBASTICOOK RIVER	ME			Lift	Other	1			5073
-69.41156644	44.7211165	BURNHAM	SEBASTICOOK RIVER	ME			Lift	Other	1			11472
-69.62666217	44.54675626	LOCKWOOD	KENNEBEC RIVER	ME			Trap & Trans.	All flow through fishway channel	1		No	2574
-73.18725117	44.48890331	CHACE MILL	WINOOSKI RIVER	VT			Lift	wall diff., combined	1			2756
-76.331601	39.827066	HOLTWOOD	SUSQUEHANNA RIVER	PA			Lift	near entrance discharge, gravity	1			1881
-72.60210425	42.21185798	HOLYOKE	CONNECTICUT RIVER	MA			Lift	wall diff., gravity	1			2004
-70.4471905	43.4957013	CATARACT	SACO RIVER	ME			Lock	wall diff., gravity	1			2528
-71.504444	42.750606	MINE FALLS	NASHUA RIVER	NH			Lift	wall diff., gravity	1	5		3442
-72.693665	41.9153	RAINBOW DAM	FARMINGTON	CT			VSF, single	wall diff., gravity				nonFERC5
-70.55779352	43.57067703	SKELTON	SACO RIVER	ME			Lift	wall diff., gravity	1			2527
-72.04566	41.572544	TAFTVILLE	SHETUCKET RIVER	CT			Denil, 4 ft	wall diff., gravity	1			nonFERC3
-72.040948	41.554964	TUNNEL	QUINEBAUG RIVER	CT			Lift	wall diff., gravity				nonFERC4

APPENDIX B

STATISTICAL ANALYSES DETAILED DESCRIPTIONS

This appendix describes in detail the statistical analyses used for the cumulative plots, two-proportion upper-tailed z-test, and the cox proportional hazards model.

Cumulative Plots

Initial descriptive statistics were performed by creating cumulative plots and a summary table for those. These are useful to concurrently demonstrate the effects of an independent variable on the dependent variable over time. Cumulative passage and fallback plots were created for 6 different dataset portions: first attempts per fish, first 2 attempts, first 3 attempts, first 9 attempts, first 17 attempts, and all attempts. A given fish in the trial made several attempts during the experiment. For these plots, each attempt a fish made was kept as separate new attempts. The number of attempts for each fish varied. Increasing the sample size and expanding the data in this way is useful because performing enough trials to have the equivalent number of samples with new fish every time would be quite intensive due to time constraints and facility limitations. During analysis of these results, we made sure to be aware of possible biases that repeated measurements of a given fish might bring.

The y-axis shows the cumulative proportion of the dependent variable. In this study, the dependent variable is the fish and the proportion is the number of fish passed or fallen back, over the total number of fish attempts in the experiment for the respective datasets. A percent passage or fallback enables a comparison between the two wall V_W conditions simultaneously in one plot, despite the number of fish in the two cases being somewhat different. The x-axis is the time over which the dependent variable is changing. The times are related to the total time spent in Z2 of a given fish's attempt.

Visualizing the rate of passage and fallback of the two conditions can show if the relationships are different or the same. The final cumulative value is then the overall percent passage or fallback. An experiment could have different rate trajectories, but similar final percentages, or vice versa. Similar rates and different final percentages, for example, would indicate that one condition was better than the other.

An additional cumulative plot was created for each Vw of the start of trial to the first detection at the entrance channel for each fish. This plot was to ensure that fish experienced similar outcomes in the approach and initial entry areas.

Two-Proportion Upper-tailed Z-Test

A two-proportion upper-tailed Z-test indicates whether one of the two proportions being greater is significant. This will inform whether the results from the experiment are significant, or if there is no real difference between the two velocity condition results based on the data. One results from the analysis are the chi-squared test of independence value, which is equal to the square of the z-statistic. The analysis also returns a p-value, which is the same for the z-test and the chi-square test. The chi-square value is also used to test whether there is a significant relationship between the two velocity treatments.

This inferential statistic was used to confirm whether the two final passage and fallback percentages from the cumulative plot analyses for the two velocity conditions were significantly different. The results from this test point to whether overall one Vw is superior to the other based on overall success and failure.

The two-proportion upper-tailed Z-test was also used as a proxy to determine whether the Z1 and initial entry of the design (first detection at Z2) areas were hydraulically similar. Each decision from Z1 to Z3 is dependent on the previous, therefore it was important to evaluate whether hydraulic differences in Z1 between the two velocities might bias later fish attempts to pass the diffuser. For this inquiry, only the first instance of a fish swimming into Z2 was used for the final percent calculations for the two conditions.

In this test, there are two groups of data analyzed, in this study those were the 0.5 fps (p_A) and 1.0 fps (p_B) percentages written as proportions. Overall proportions of successful fish p and unsuccessful fish q for both trials.

$$z = \frac{p_A - p_B}{\sqrt{\frac{pq}{n_A} + \frac{pq}{n_B}}}$$

$$p_A = \frac{A}{n_A}, p_B = \frac{B}{n_B} \qquad (2, 3)$$

$$p = \frac{p_A + p_B}{2} \qquad (4)$$

$$q = 1 - p \qquad (5)$$

The three hypotheses addressed by this test are: are the values equal to each other, is one less than the other, or greater than the other?

$$\begin{aligned} H_0&: p_A = p_B \\ H_0&: p_A \leq p_B \\ H_0&: p_A \geq p_B \end{aligned} \qquad (6)$$

The alternative hypotheses are that they are different from each other, greater, or less than the other:

$$\begin{aligned} H_a&: p_A! = p_B \\ H_a&: p_A > p_B \end{aligned} \qquad (7)$$

$$H_a: p_A < p_B$$

In R a function already exists as a part of its base functions called Test of Equal or Given Proportions and “prop.test()”. This function tests the null and hypotheses that the proportions in the two groups are the same, or that they are equal to given values. The three alternative hypotheses can be explored.

```
prop.test(x = c(cnt05, cnt1), n = c(ttl05, ttl1),
          alternative = c("two.sided", "less", "greater"))
```

$x = thetwocountsofsuccesses, oneforeachdiffusercondition$
$n = thetotalsforeachdiffusercondition$
$alternative = alternativehypothesistoasses;$
$"greater", "less", "two.sided" isdefaultandtestsequality$

The results from this function are the chi-squared value, p-value, 95 percent confidence interval, and sample estimates for both proportions.

The combination of the cumulative plots, one having a greater percent passage than the other, and z-tests, confirming whether one being greater than the other is actually significant, indicate whether overall one diffuser condition is superior to the other based on overall success and failure. In addition to overall success, timing of success is important. Timely passage is vital in fish migration success.

Cox Proportional Hazards Model

In addition to overall success, it is also important to account for timing of success. Timely passage is vital in fish migration success. The Cox proportional hazards model was used to understand whether the probability of passage for a given fish changed over time and how the probabilities between the two velocity treatments compare. The Cox proportional hazards model is an inferential statistical tool that addresses the time element of success as a probability over time (Cox 1972). This regression model is used predominantly in medical research, for which it was developed and commonly referred to as Survival Analysis. It is also useful for any research where variables affect the rate of an event occurring, or the instantaneous time to the event occurring (Mulligan et al. 2018, Goerig & Castro-Santos 2017, Haro et al. 2015, Pollock 1991, Chambers and Leggett 1989, Lowther and Skalski 1997). This model is also referred to as a Time-to-Event Analysis.

Results from this model are the hazard ratio (HR) and p-value. The HR is the exponential of the regression coefficient (β). These results are for each of the variables (covariates) stated into the model’s function. First it is important to note whether the covariate has a significant p-value and assess the covariate’s HR afterwards. An HR of one means that the covariate has no effect on the probability of the event occurring, less than one means that the covariate’s increase decreases the likelihood of the event, and vice versa for an HR greater than one.

The covariates included in the regression were the Vw, sex, and river temperature. Vw and sex were categorical covariates. The Vw was either 0.5 or 1.0 fps, sex was F for female or M for male. Temperature was a continuous covariate since each trial took place under a slightly different temperature.

In addition, the R function for the Cox regression presents the likelihood ratio test. The test evaluates the null hypothesis. If the p-value for these tests is less than 0.05 it indicates that the model is significant and that the null hypothesis is rejected.

APPENDIX C

CUMULATIVE PLOTS & TWO-PROPORTION UPPER-TAILED Z-TEST

This appendix presents all cumulative passage and fallback plots made for both treatment conditions, for all data subsets tested. In addition, a table shows the sample size validation for the data in the two-proportion upper-tailed z-test.

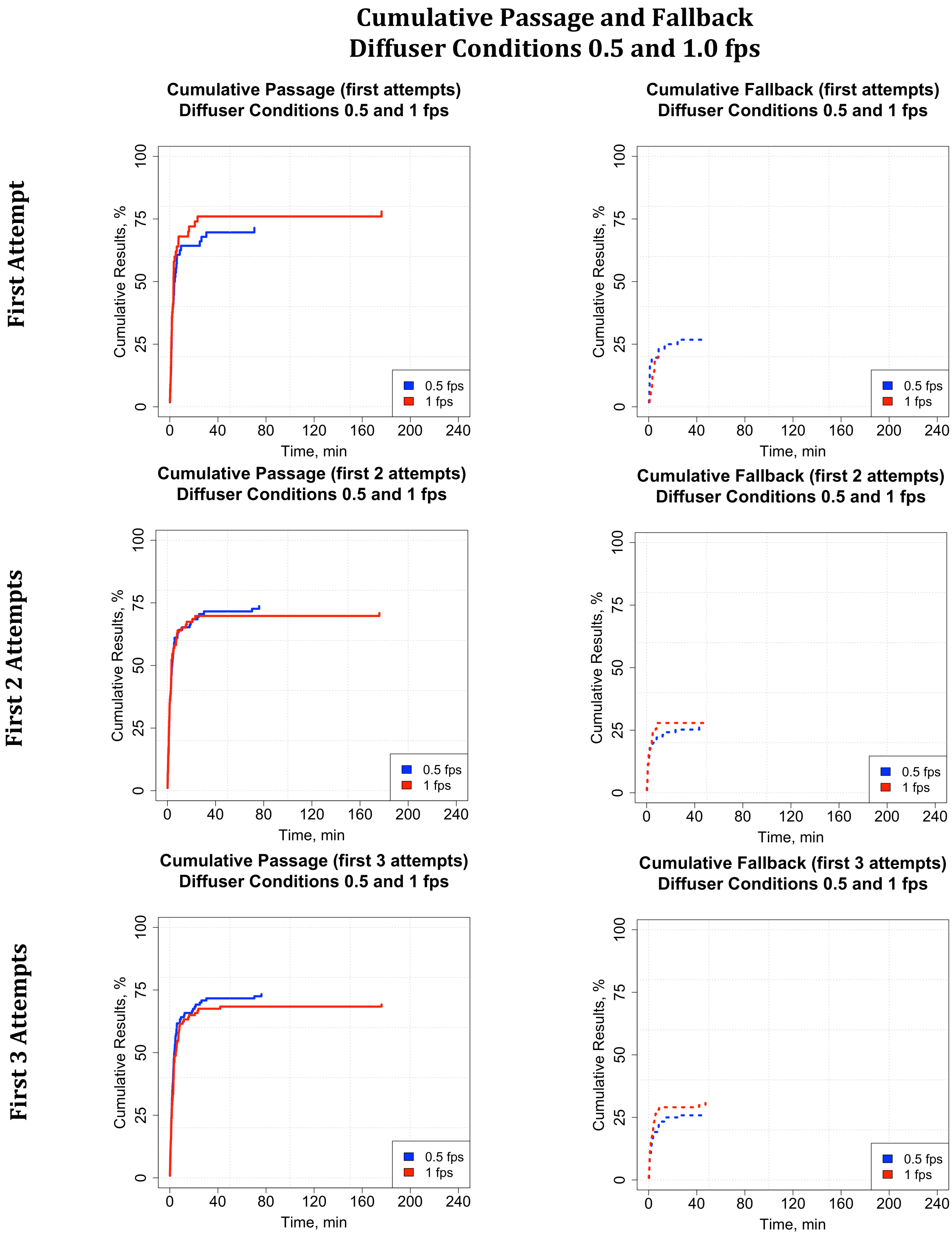

Figure C.1 Cumulative plots for varied sample sizes of attempts

Figure C.1 Cumulative plots for varied sample sizes of attempts

Cumulative Passage and Fallback
Diffuser Conditions 0.5 and 1.0 fps

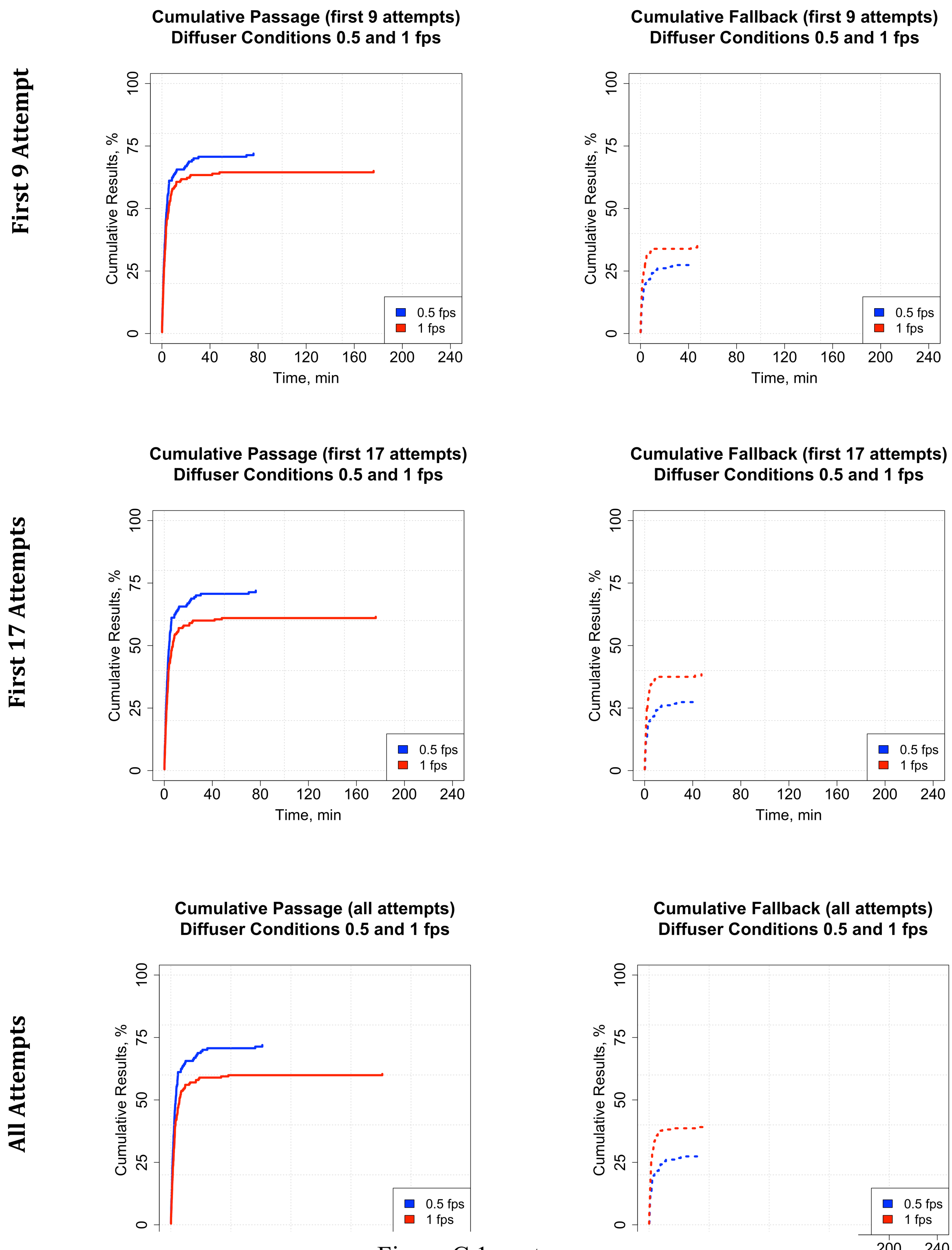

Figure C.1 cont.

Figure C.1 cont.

Table C.1 Sample Size Validation

Sample Size Vailidity (≥ 5)				
dataset, attempts	p_A_0.5	p_B_1	n_0.5	n_smpl 1
1	0.793	0.679	58	53
2	0.737	0.709	95	86
3	0.733	0.692	120	117
9	0.72	0.65	157	183
17	0.72	0.62	157	200
all	0.72	0.6	157	207
	n_A	n_B	p	q
	45.994	35.987	0.738568	0.261432
	70.015	60.974	0.723696	0.276304
	87.96	80.964	0.712759	0.287241
	113.04	118.95	0.682324	0.317676
	113.04	124	0.663978	0.336022
	113.04	124.2	0.651758	0.348242
	n_A *p	n_A *q	n_B *p	n_B *q
	33.96968	12.02432	26.57883	9.408169
	50.66958	19.34542	44.12665	16.84735
	62.69433	25.26567	57.70786	23.25614
	77.12985	35.91015	81.16238	37.78762
	75.05603	37.98397	82.33322	41.66678
	73.67475	39.36525	80.94837	43.25163

APPENDIX D

INDIVIDUAL FISH TABLE & SCATTERPLOTS & STATISTICAL SUPPORT

The following document includes the table for individual fish participants in each trial, the velocity condition, their sex, total attempts, total passes, total fallbacks, mean time of the fish's attempt, median time of the fish's attempt, mean time for the trial, median time for the trial.

The document also includes the scatterplots created with outliers removed, t-test assuming unequal variances for assessing the scatterplot results, and boxplots to validate why unequal variances t-test method was used.

Table D.1 Descriptive statistics for each individual fish in both velocity treatments, *with* outliers

fishID	trial	Vw	sex	number of attempts	number of passes	number of fallbacks	mean time for fish's attempts	median time for fish's attempts	mean time of the trial	median time of the trial
1_1013	1	0.5	F	5	2	3	0.9	0.9	5.9	2.4
1_1026	1	0.5	F	5	2	3	2.6	0.5	5.9	2.4
1_1137	1	0.5	F	5	3	2	1.9	1.5	5.9	2.4
1_1022	1	0.5	F	5	4	1	3.8	3.0	5.9	2.4
1_1139	1	0.5	F	4	2	2	6.0	2.5	5.9	2.4
1_1049	1	0.5	F	4	2	2	4.7	4.0	5.9	2.4
1_1198	1	0.5	F	3	1	2	0.6	0.3	5.9	2.4
1_1178	1	0.5	F	3	1	2	5.4	3.8	5.9	2.4
1_1152	1	0.5	F	3	3	0	1.9	1.7	5.9	2.4
1_1363	1	0.5	M	3	3	0	18.8	21.5	5.9	2.4
1_1273	1	0.5	M	2	0	2	1.3	1.3	5.9	2.4
1_1354	1	0.5	M	2	1	1	1.8	1.8	5.9	2.4
1_1124	1	0.5	F	2	1	1	14.0	14.0	5.9	2.4
1_1014	1	0.5	F	2	2	0	2.1	2.1	5.9	2.4
1_1125	1	0.5	NA	2	2	0	39.0	39.0	5.9	2.4
1_1129	1	0.5	F	2	2	0	15.0	15.0	5.9	2.4
1_1148	1	0.5	M	1	0	1	0.7	0.7	5.9	2.4
1_1206	1	0.5	F	1	0	1	13.2	13.2	5.9	2.4
1_1130	1	0.5	F	1	1	0	0.8	0.8	5.9	2.4
1_1168	1	0.5	M	1	1	0	1.0	1.0	5.9	2.4
1_1066	1	0.5	F	1	1	0	5.5	5.5	5.9	2.4
2_1131	2	1	F	7	7	0	0.9	0.4	9.5	2.5
2_1293	2	1	F	6	4	2	11.7	5.0	9.5	2.5
2_1128	2	1	M	5	3	2	6.5	2.9	9.5	2.5
2_1177	2	1	M	4	1	3	2.6	0.8	9.5	2.5

2_1138	2	1	F	4	1	3	2.6	2.6	9.5	2.5
2_1147	2	1	F	3	0	3	30.0	41.9	9.5	2.5
2_1247	2	1	F	3	1	2	3.1	3.1	9.5	2.5
2_1180	2	1	F	3	1	2	2.8	2.8	9.5	2.5
2_1224	2	1	F	3	2	1	2.0	2.0	9.5	2.5
2_1232	2	1	F	3	2	1	16.0	3.4	9.5	2.5
2_1078	2	1	F	3	3	0	2.8	1.2	9.5	2.5
2_1142	2	1	F	3	3	0	2.1	0.2	9.5	2.5
2_1121	2	1	M	3	3	0	6.1	5.3	9.5	2.5
2_1038	2	1	F	3	3	0	4.8	4.0	9.5	2.5
2_1141	2	1	M	2	1	1	8.4	8.4	9.5	2.5
2_1011	2	1	F	2	2	0	3.9	3.9	9.5	2.5
2_1034	2	1	F	1	1	0	0.2	0.2	9.5	2.5
2_1100	2	1	F	1	1	0	0.5	0.5	9.5	2.5
2_1043	2	1	M	1	1	0	1.3	1.3	9.5	2.5
2_1146	2	1	F	1	1	0	2.0	2.0	9.5	2.5
2_1192	2	1	M	1	1	0	2.8	2.8	9.5	2.5
2_1149	2	1	F	1	1	0	23.1	23.1	9.5	2.5
2_1118	2	1	F	1	1	0	176.1	176.1	9.5	2.5
3_1070	3	1	M	22	4	18	2.7	1.7	3.4	1.8
3_1297	3	1	F	19	6	13	5.0	2.3	3.4	1.8
3_1336	3	1	F	10	0	10	1.0	0.6	3.4	1.8
3_1270	3	1	F	10	6	4	3.0	2.4	3.4	1.8
3_1248	3	1	M	8	5	3	3.7	2.2	3.4	1.8
3_1143	3	1	M	6	3	3	3.0	2.5	3.4	1.8
3_1126	3	1	M	6	4	2	4.9	4.1	3.4	1.8
3_1325	3	1	M	6	6	0	2.6	2.8	3.4	1.8
3_1133	3	1	M	5	3	2	0.8	0.9	3.4	1.8
3_1010	3	1	M	5	4	1	1.6	1.5	3.4	1.8
3_1046	3	1	F	5	4	1	5.5	5.5	3.4	1.8
3_1087	3	1	M	3	1	2	3.0	1.7	3.4	1.8
3_1221	3	1	F	2	2	0	4.8	4.8	3.4	1.8
3_1115	3	1	F	2	2	0	3.3	3.3	3.4	1.8
3_1226	3	1	F	1	1	0	1.6	1.6	3.4	1.8
3_1140	3	1	NA	1	1	0	3.3	3.3	3.4	1.8
3_1004	3	1	M	1	1	0	20.8	20.8	3.4	1.8
4_1135	4	0.5	F	9	6	3	3.0	2.4	4.7	2.1
4_1184	4	0.5	M	7	7	0	4.9	3.5	4.7	2.1
4_1102	4	0.5	M	5	4	1	11.1	4.8	4.7	2.1
4_1292	4	0.5	F	4	3	1	3.0	0.3	4.7	2.1
4_1350	4	0.5	F	4	4	0	0.9	0.8	4.7	2.1
4_1061	4	0.5	F	3	2	1	2.8	2.6	4.7	2.1
4_1346	4	0.5	F	3	2	1	1.1	0.6	4.7	2.1

4_1214	4	0.5	F	3	2	1	1.6	1.6	4.7	2.1
4_1175	4	0.5	M	3	2	1	2.7	2.0	4.7	2.1
4_1186	4	0.5	F	3	3	0	1.6	1.2	4.7	2.1
4_1291	4	0.5	F	2	1	1	1.0	1.0	4.7	2.1
4_1303	4	0.5	F	2	1	1	7.9	7.9	4.7	2.1
4_1157	4	0.5	F	2	2	0	7.7	7.7	4.7	2.1
4_1379	4	0.5	M	1	0	1	43.7	43.7	4.7	2.1
4_1335	4	0.5	F	1	1	0	1.3	1.3	4.7	2.1
4_1282	4	0.5	F	1	1	0	1.6	1.6	4.7	2.1
4_1123	4	0.5	M	1	1	0	5.1	5.1	4.7	2.1
4_1331	4	0.5	F	1	1	0	5.9	5.9	4.7	2.1
5_1253	5	0.5	F	8	3	5	5.7	1.3	5.6	2.3
5_1305	5	0.5	M	7	4	3	2.7	2.7	5.6	2.3
5_1320	5	0.5	F	7	6	1	2.6	1.4	5.6	2.3
5_1005	5	0.5	F	4	4	0	7.0	3.4	5.6	2.3
5_1235	5	0.5	F	3	2	1	4.0	3.2	5.6	2.3
5_1019	5	0.5	F	2	1	1	4.3	4.3	5.6	2.3
5_1268	5	0.5	F	2	1	1	0.6	0.6	5.6	2.3
5_1246	5	0.5	M	2	1	1	2.8	2.8	5.6	2.3
5_1245	5	0.5	F	2	2	0	0.7	0.7	5.6	2.3
5_1254	5	0.5	F	2	2	0	13.7	13.7	5.6	2.3
5_1048	5	0.5	F	2	2	0	3.4	3.4	5.6	2.3
5_1294	5	0.5	M	1	1	0	0.7	0.7	5.6	2.3
5_1368	5	0.5	F	1	1	0	1.7	1.7	5.6	2.3
5_1260	5	0.5	F	1	1	0	2.6	2.6	5.6	2.3
5_1046	5	0.5	F	1	1	0	3.0	3.0	5.6	2.3
5_1264	5	0.5	F	1	1	0	3.5	3.5	5.6	2.3
5_1378	5	0.5	F	1	1	0	4.2	4.2	5.6	2.3
5_1240	5	0.5	M	1	1	0	8.3	8.3	5.6	2.3
5_1328	5	0.5	M	1	1	0	70.3	70.3	5.6	2.3
6_1061	6	1	M	8	3	5	4.5	4.2	2.7	1.7
6_1378	6	1	NA	7	5	2	0.9	0.6	2.7	1.7
6_1295	6	1	M	6	2	4	1.8	1.4	2.7	1.7
6_1265	6	1	F	3	2	1	2.0	1.8	2.7	1.7
6_1294	6	1	M	3	2	1	1.8	1.1	2.7	1.7
6_1316	6	1	M	3	3	0	2.4	3.3	2.7	1.7
6_1301	6	1	F	2	2	0	2.1	2.1	2.7	1.7
6_1255	6	1	F	2	2	0	0.6	0.6	2.7	1.7
6_1227	6	1	F	2	2	0	3.4	3.4	2.7	1.7
6_1268	6	1	F	2	2	0	2.3	2.3	2.7	1.7
6_1305	6	1	M	1	1	0	3.0	3.0	2.7	1.7
6_1214	6	1	M	1	1	0	7.1	7.1	2.7	1.7
6_1320	6	1	F	1	1	0	15.3	15.3	2.7	1.7

Scatterplots of outliers removed data:

Outlier fish removed: attempts >10

As attempts increase, passage events increase more for the 0.5 fps diffuser.

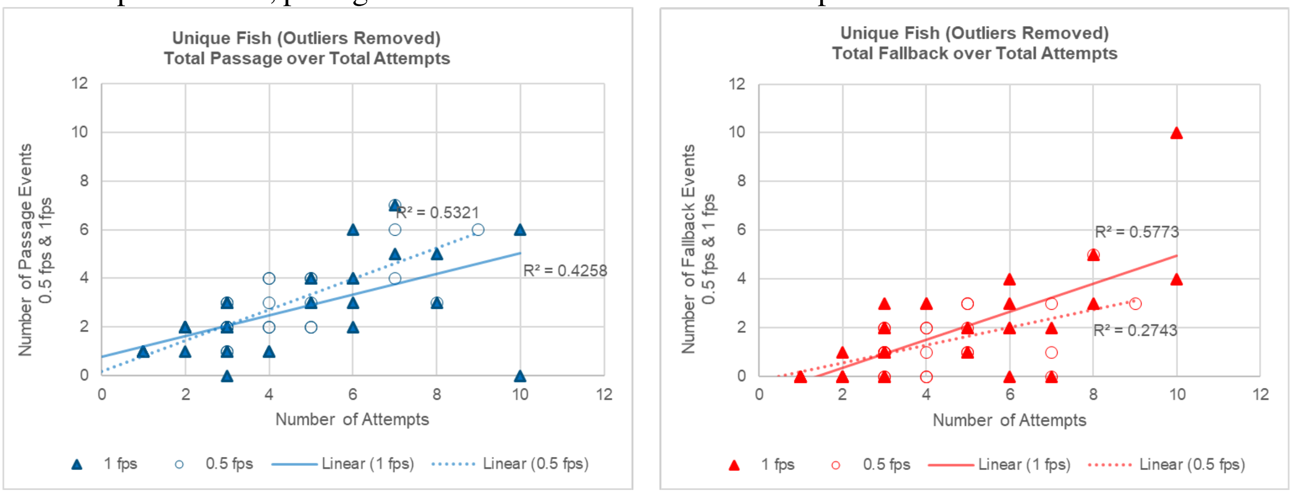

Figure D.1 Scatterplot of individual fish and the ratio of their attempts and number of passage events off those attempts, *without* outliers

Null Hypothesis for Passage:
There is no difference between the 0.5 pass vs. attempt data and the 1.0 fps pass vs. attempt data.
Null Hypothesis for Fallback:
There is no difference between the 0.5 fallback vs. attempt data and the 1.0 fps fallback vs. attempt data.

Table D.2 t-test summary table for pass and fall data using unequal variances, *with* outliers

t-Test: Two-Sample Assuming Unequal Variances			**t-Test: Two-Sample Assuming Unequal Variances**		
	Variable 1	*Variable 2*		*Variable 1*	*Variable 2*
Mean	1.948276	2.358491	Mean	0.827586	1.735849
Variance	2.155172	2.695936	Variance	1.127647	11.04427
Observations	58	53	Observations	58	53
Hypothesized Mean Difference	0		Hypothesized Mean Difference	0	
df	105		df	62	
t Stat	-1.38264		t Stat	-1.90288	
P(T<=t) one-tail	**0.084855**		**P(T<=t) one-tail**	**0.030851**	
t Critical one-tail	1.659495		t Critical one-tail	1.669804	
P(T<=t) two-tail	**0.169709**		**P(T<=t) two-tail**	**0.061702**	
t Critical two-tail	1.982815		t Critical two-tail	1.998972	

Table D.3 t-test summary table for pass and fall data using unequal variances, *without* outliers

t-Test: Two-Sample Assuming Unequal Variances (outliers removed)			**t-Test: Two-Sample Assuming Unequal Variances (outliers removed)**		
	Variable 1	*Variable 2*		*Variable 1*	*Variable 2*
Mean	1.948276	2.254902	Mean	0.827586	1.196078
Variance	2.155172	2.473725	Variance	1.127647	3.360784
Observations	58	51	Observations	58	51
Hypothesized Mean Difference	0		Hypothesized Mean Difference	0	
df	103		df	78	
t Stat	-1.04764		t Stat	-1.2614	
P(T<=t) one-tail	**0.148628**		**P(T<=t) one-tail**	**0.105462**	
t Critical one-tail	1.659782		t Critical one-tail	1.664625	
P(T<=t) two-tail	**0.297255**		**P(T<=t) two-tail**	**0.210925**	
t Critical two-tail	1.983264		t Critical two-tail	1.990847	

Validation that "Unequal Variances" type t-test should be used:
The histograms show that the variance (boxes) between 0.5 and 1.0 fps passage datasets are not the same. The 0.5 fps has less variance. The same goes for the fallback datasets and when looking at these without the two outlier fish.

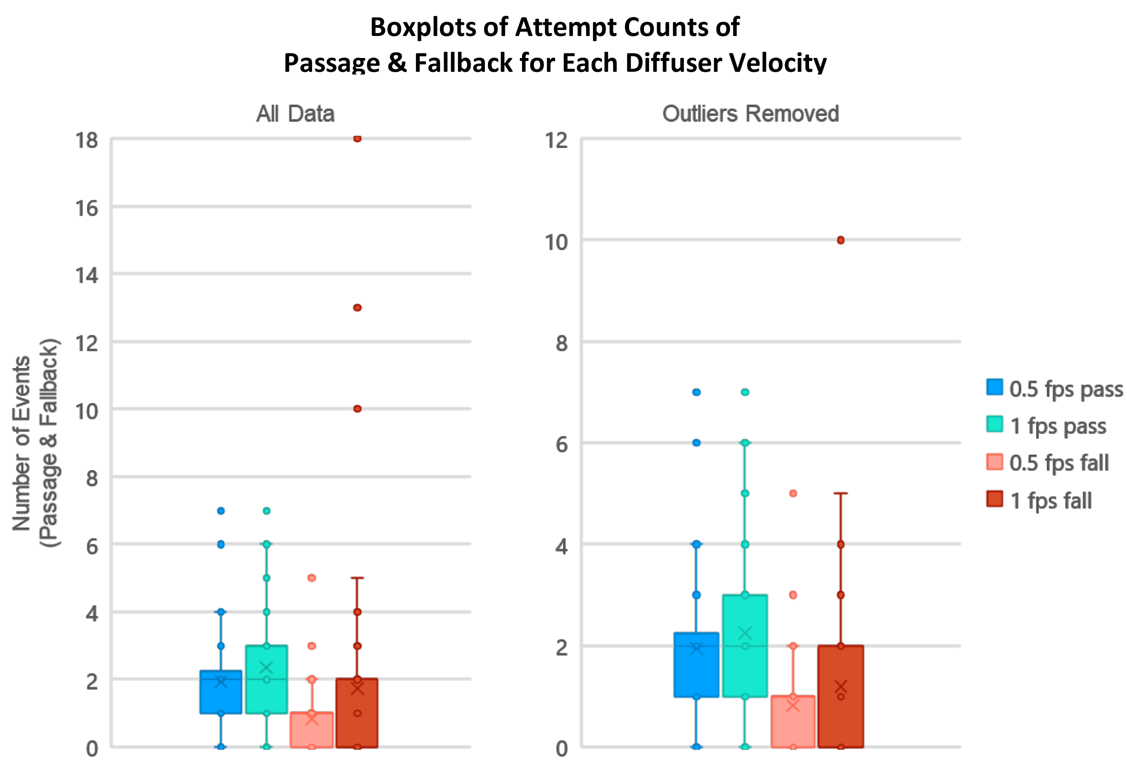

Figure D.2 Boxplots for testing events data unequal variance