Fishway Entrance Palisade

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Executive Summary

This technical report summarizes work that was conducted by the University of Massachusetts Amherst and the U.S. Geological Survey (USGS), along with other project partners, on the Fishway Entrance Palisade, a project funded through the Department of Energy's (DOE) funding opportunity titled 'Innovative Solutions for Fish Passage at Hydropower Dams' (DE-FOA-0001662). The period of performance spanned from September 1, 2018 through September 30, 2021.

The Entrance Palisade (EP) is a novel fish passage engineering technology designed to provide more favorable entry conditions for fish into fishways and to reduce costs relative to conventional fishway auxiliary water systems (AWS). The EP project has four primary components.

First, the Northeast United States Auxiliary Water Systems Database was created (Rojas 2020). The database, developed with material provided by the U.S. Fish and Wildlife Service, contains information on fishway type (e.g., lift, Denil, pool and weir) and AWS details (e.g., water conveyance method, diffuser type) for 60 hydroelectric sites in states on the East Coast from Maine to South Carolina, through primarily concentrated in New England (Rojas 2020). Findings indicate that nearly 4 out of every 10 fishways in the region is a fish lift and approximately 1 out of every 4 is a Denil ladder. The remainder are a mix of vertical slot fishways, pool and weirs, and Ice Harbor fishways. Furthermore, over half of all AWS systems use floor diffusers to discharge the auxiliary (or attraction) water into the entrance of a fishway, whereas only 14% use wall diffusers.

Second, limited experiments on a conventional AWS with live, actively migrating fish were conducted at the USGS Eastern Ecological Science Center (EESC) S.O. Conte Research Laboratory at Turners Falls, Massachusetts (MA) (Rojas 2020). This study determined how water velocity through a wall diffuser, without turning vanes or timber baffles to distribute the flow, affected the behavior and passage of adult American shad (*Alosa sapidissima*), a conservative surrogate species for migratory fish

on the east coast of the United States. Two gross diffuser velocity treatments were examined, 0.5 ft/s and 1.0 ft/s. These wall diffuser velocities represented current (0.5 ft/s) and past (1.0 ft/s) design criteria guidelines set forth by the USFWS North Atlantic-Appalachian Region (Rojas 2020; USFWS 2019). Six trials with a total of 151 American shad (hereafter shad) were conducted in June 2019 for the two treatments. No differences in shad passage efficiency were discovered between the two treatments, while approximately 3 in every 4 attempts were successful at passing the diffuser. While these results may appear to indicate that the generally accepted gross wall diffuser velocity criteria for shad of 0.5 ft/s could be safely increased to 1.0 ft/s, further analysis is warranted. Furthermore, it is unknown how other migratory and resident fish species that traverse these structures would be impacted by such a change. Studying the wall diffuser hydraulics led to a key AWS observation. Without turning vanes or timber baffles in this study, doubling the diffuser area was insufficient at producing the type of flow field change one may expect by halving the gross diffuser velocity. Instead, the flow fields throughout each treatments study area were similar, which led to similar results in shad passage efficiency. This flow field similarity not only highlights the importance of installing flow guidance devices like turning vanes, but also illustrates the importance of properly maintaining them, which can be costly.

Third, more expansive experiments on the novel EP were conducted in the spring of 2019 and 2021 (Fishway Entrance Palisade Experiments). The goal of this study was to determine how adult shad responded to a variety of conditions at a full-scale EP. A total of six treatments were examined by changing the average auxiliary channel velocity between 1.0 and 5.0 ft/s in intervals of 1.0 ft/s and by inserting/removing an entrance gate at the opening of the fishway. Thirty trials with a total of 1,273 shad were conducted over the two years. In all treatments, at least 7 out of every 10 fish successfully passed the EP diffuser and swam into the entrance channel within the 3.5-hour long trial, highlighting the general effectiveness of the novel AWS technology. In both study years, lower velocities through the EP diffuser led to increased shad passage efficiency, though efficiency peaked for the 2 ft/s velocity treatment. This treatment condition represents an approximate six-fold increase in gross diffuser velocity relative to conventional auxiliary water systems, which in turn presents opportunities for cost savings (e.g., reduction in diffuser size).

Shad passage efficiency was generally poorer in 2019 relative to 2021. The fish collected in 2019 experienced a 20% reduction in entrance efficiency, including a 16.7% drop for the 3 ft/s velocity treatment in 2019 relative to 2021 (the only carryover treatment between years). This reduction in passage efficiency is possibly due to the timing of fish collection, where fish in 2019 were collected at the conclusion of the run.

Lastly, adding an entrance gate caused a significant delay to entry. The time duration it took for 25% of the fish to enter increased by ~20 minutes from the near instantaneous 25% entry that was reported for the other treatments conducted in the same year (2021). However, by the end of the 3.5-hour trial, the entrance efficiency nearly matched those of the other 2021 treatments.

The fourth and final component of the EP project was an economic analysis that focused on the cost of attraction and environmental flows (Lotter 2021). The study assessed the economic impact of meeting environmental flow requirements at Scotland Dam, a representative hydroelectric facility and fish lift in the Northeast United States. The dam is located on the Shetucket River near Willimantic, Connecticut (CT) with a 429-square-mile drainage basin and a median flow rate of 552 ft^3/s. Owned by FirstLight Power Resources, its powerhouse is a single-unit, 2.0-megawatt (MW) capacity hydroelectric generating facility. An initial finding of the study was that a paucity of published data exist on the costs of meeting attraction and environmental flows. This paucity of information is due, in part, to the proprietary nature of these data. To explore the costs associated with these flows, three types of environmental flows were assessed: upstream fishway attraction flows, downstream fishway attraction flows, and habitat maintenance minimum flows. A physics-based model was developed and calibrated with three years of hourly generation and flow data as inputs. Gage flow inputs were adjusted and used to calculate power generated. To address hydrologic variability, the model was executed to simulate 30 years of historical flows.

Results of the model indicated that both interannual and seasonal climatic factors would impact the costs of meeting environmental flow requirements. Generation potential is most strongly curtailed during dry years in terms of maximizing the capacity factor (the percent of time a plant generates at capacity). Dry years, and especially dry summers, have the most significant costs associated with mitigation flows. Of the three types of flows, habitat flows are most costly in terms of power production, followed by upstream attraction flows, and downstream attraction flows are least costly. This finding is the likely the result of differences in both flow rates and duration of the seasonal requirement for each flow. Overall, environmental flows represented a 2-12% loss in annual generation, but losses during a dry summer can exceed 20%.

In summary, this research project produced several key findings: 1) the development of an auxiliary water system database for the Northeast region of the United States highlighted the prevalence of floor diffusers as the primary means of discharging attraction flow, 2) experiments testing a conventional wall diffuser with shad underscored the importance of flow guidance devices inside auxiliary channels to properly distribute flow across the diffuser, 3) experiments testing the novel EP diffuser with shad demonstrated the effectiveness of the technology, and 4) an economic case study showed how hydrological conditions and station capacity have strong impacts on generation at a site in Connecticut, both individually and in conjunction with each other.

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Acronyms and Abbreviations

Acronym / Abbreviation	Definition
AWS	Auxiliary Water System
DOE	Department of Energy
EESC	Eastern Ecological Science Center
EP	Entrance Palisade
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometric Turbidity Unit
PIT	Passive Integrated Transponder
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

Introduction

The Fishway Entrance Palisade project represents a fundamental shift in how to deliver auxiliary water to a fishway entrance. The Entrance Palisade (EP) provides favorable hydraulics for fish passage while also reducing construction and maintenance costs relative to conventional auxiliary water systems (AWS).

Current State-of-the-Art

Most existing upstream fishways lure fish by discharging water in a "coherent volume of downstream-directed velocities" that are sufficient to attract fish and low enough to pass target species (Gisen et. al. 2017). Since migrating fish tend to be drawn to areas of higher flow, fishways must also discharge large volumes of water to adequately compete with flow from turbines, spill, and other hydropower project conveyances. Resource agencies and researchers suggest that fishway attraction flows may require 5% or more of all competing flows (USFWS 2017; NMFS 2011; Larinier 2000). Conventional fishways introduce this supplemental water into the fishway entrance channel at 90 degrees (relative) to the direction of downstream flow through in-channel floor and wall diffusers. These present numerous challenges for fish and the hydropower industry (Figure 1a). The size of in-channel diffusers is dictated by velocity criteria (e.g., 0.5 to 1.0 feet per second) and by the quantity of attraction flow (USFWS 2017; NMFS 2011). Consequently, in-channel diffusers are large and necessitate significant excavation below grade. Floor diffusers cannot be accessed without de-watering (or employing divers) creating debris removal and maintenance problems. The angle at which supplemental water is introduced generates a complex, 3-dimensional flow field with variable velocities and turbulence, that violate "best-practices" in fish passage design. Moreover, debris maintenance and design challenges inherent in the construction of sub-grade, pressurized auxiliary water system conduits often exacerbates the poor hydraulics by introducing localized upwelling and air-entrainment through the floor diffusers.

Proposed Solution

The EP is an innovative upstream fish passage structure that integrates a vertically oriented louvered exclusion diffuser, an at-grade free-surface dissipation pool, and a conventional fishway entrance (Figure 1b). These components work in concert to enhance fish attraction while reducing diffuser size and sub-grade excavation (compared to conventional fishway designs). The EP discharges attraction water through an angled palisade (i.e., louvered exclusion diffuser) adjacent to the actual entrance. This angled palisade eliminates the adverse, confusing hydraulics created by in-channel diffusers. The angled palisade delivers flow adjacent to the fishway entrance at the same biologically suitable velocity as at the entrance (typically 4-6 ft/s). This higher diffuser velocity reduces the necessary size of diffusers by a factor of 4 to 12 with associated reductions in construction cost. Furthermore, the angled EP creates a physical guide into the entrance that, conceptually, borrows from picketed lead designs employed in West Coast fishways (Clay 1995). Finally, the EP's AWS flows through a free-surface pool before passing through diffusers. This design significantly reduces the potential for air-entrainment in the attraction jet, eliminates the need to excavate for a sub-grade AWS conduit, and reduces the maintenance concerns associated with floor diffusers. Relative to other technical fishway components, the EP has broad applicability to many target species including Atlantic salmon (*Salmo salar*), American shad (*Alosa sapidissima*), alewife (*Alosa pseudoharengus*), and blueback herring (*Alosa aestivalis*).

Cost savings to the hydropower industry may be realized in both construction and maintenance of the EP in contrast to costs in construction and maintenance of standard floor diffusers. Standard floor diffusers are fed by below-grade channels (USFWS 2019) and thus may require additional excavation in the river environment. The EP reduces this excavation by incorporating the diffuser at the same elevation as the fishway entrance. Construction cost savings may be realized in the following ways:

a) Reductions in quantity (i.e., volume) of additional sub-grade excavation and associated incremental costs in the extent of coffer damming, duration of dewatering, depth of excavation, and volume of deposition area.
b) Elimination or mitigation of contingencies attributable to the additional duration of sub-grade, in-river work, and associated flood risks.
c) Avoidance of possible dam safety issues that may necessitate measures to ensure dam stability when sub-grade excavation is required near the toe of the dam (e.g., rock anchors, buttresses).

Standard floor diffusers are also difficult to access because they require de-watering (USFWS 2019). This need for de-watering complicates maintenance and repairs over the design life of the fishway. The EP diffuser is at-grade (i.e., same level at the fishway entrance) and not pressurized. Therefore, inspections, cleaning and repairs may be simpler and less costly to the owner.

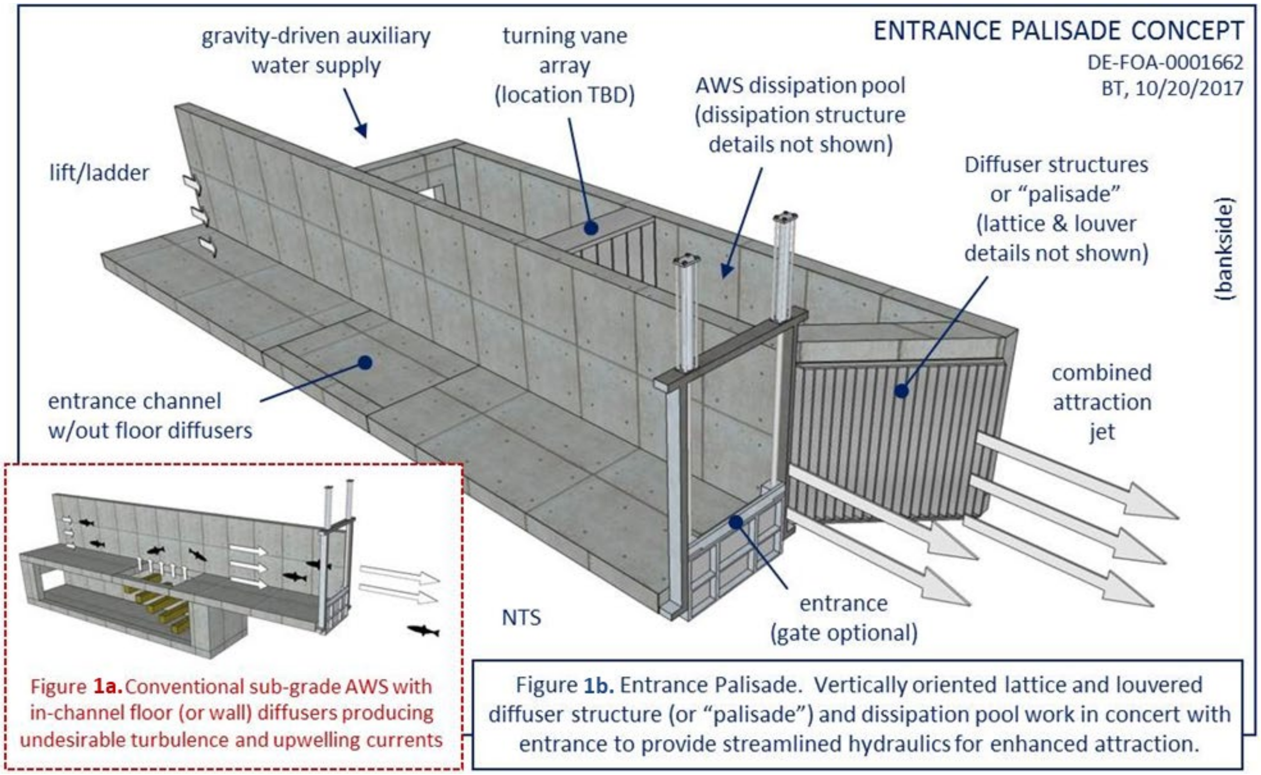

Figure 1: (a) Conventional sub-grade auxiliary water system (AWS) with in-channel floor (or wall) diffusers producing undesirable turbulence and upwelling currents; (b) The Entrance Palisade (EP), a vertically oriented lattice and louvered diffuser structure and dissipation pool work in concert with entrance to provide streamlined hydraulics for enhanced attraction.

Project Overview

The EP diffuser project began in September of 2018. Initial work focused on the development of an AWS database for the Northeast United States (Rojas 2020) in part to evaluate the marketplace for the EP. In late 2018 and early 2019, the project team developed the EP design and constructed a prototype and scale model of the structure in the U.S. Geological Survey (USGS) Eastern Ecological Science Center (EESC) S.O. Conte Research Laboratory at Turners Falls, Massachusetts (MA). Trials were conducted with live, actively migrating fish in the spring of 2019. These trials were exclusively with American shad (hereafter shad). These experiments included both a conventional AWS technology (Rojas 2020) and the novel EP (Fishway Entrance Palisade Experiments). Additional trials for the EP were scheduled in 2020 but were postponed to 2021 due to the COVID-19 pandemic. The additional trials, again with shad, were completed in May and June of 2021. Hydraulic evaluations were conducted throughout the project using physical scale models and hydraulic data collection within the prototype. Additionally, an economic analysis that focused on the cost of attraction and environmental flows was completed in 2021 (Lotter 2021).

Fishway Entrance Palisade Experiments

Introduction

Experiments to evaluate the efficacy of the EP diffuser (Figure 1b) were conducted at the S.O. Conte Research Laboratory in the spring of 2019 and 2021. As with the conventional AWS experiments described in the previous section, all trials were conducted with shad, a conservative surrogate species for migratory fish of the east coast on the United States. A total of six treatments were examined by changing the average auxiliary channel velocity between 1 and 5 ft/s (2 to 10 times the currently accepted wall or floor diffuser velocity criteria (USFWS 2019)) and by inserting/removing an entrance gate at the opening of the fishway. Due to the limited testing window during the migration season, emphasis was placed on varying the conditions surrounding the original concept design of the EP, rather than testing multiple EP designs.

Methods

Flume Facility Description

A prototype EP was constructed in the flume facility at full-scale (Figure 2). The EP diffuser was made of a series of 59 steel, rectangular slats, installed vertically at a spacing of ¾", and aligned 45 degrees from the flume wall (Figure 2a). The channel on the left (Figure 2b,2c) was also open to flow, allowing for some competing flow beside the mock fishway entrance opening. While this competing flow channel allowed water to pass through, it was blocked off via a screen at the downstream end as shown in Figure 2b. Water surface elevations were measured using a radar water level logger (Flowline™ EchoPulse LR15) in the headpond, entrance channel, auxiliary channel, and tailwater. The headpond and tailwater were maintained at 6.1 and 5.0 ft respectively within all treatments.

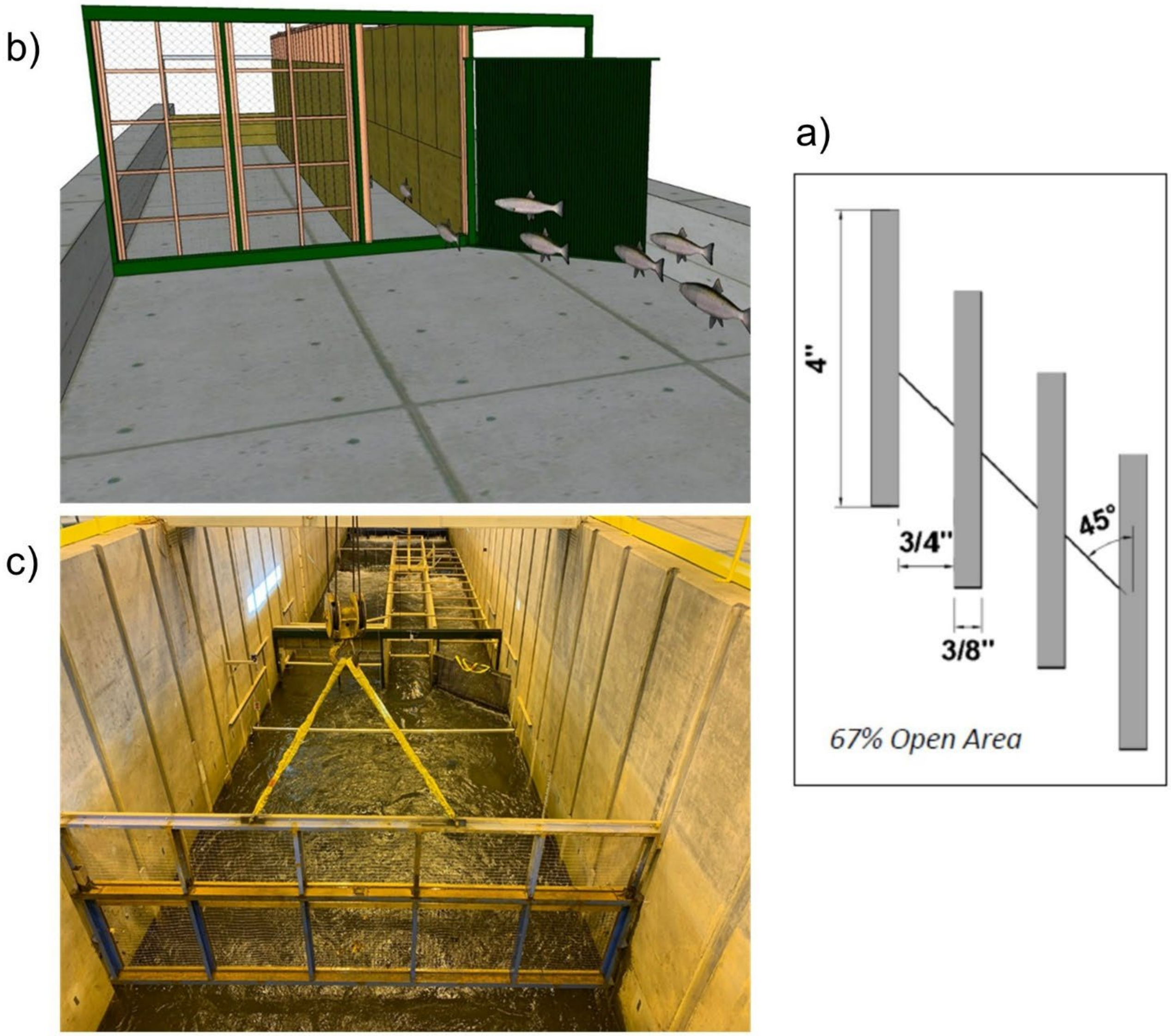

Figure 2: (a) Geometry schematic, in plan view, of the Entrance Palisade diffuser. (b) Drawing of the Entrance Palisade experiment in the full-scale flume at the U.S. Geological Survey Eastern Ecological Science Center S.O. Conte Research Laboratory; (c) Photo of the flume, looking upstream, with the Entrance Palisade diffuser on the right.

Hydraulic Measurements

Prior to trials with shad, a 1:8 physical scale model of the flume, designed to achieve Froude similarity and turbulent flow, was constructed in the S.O. Conte Research Laboratory. The scale model was a replica of the flume shown in Figure 2b. The heights of the stoplogs in this scale model were adjusted to achieve the desired velocities in each of the three channels, given the fixed headwater and tailwater elevations. Velocity cross-sections were subsequently taken for select treatments.

Additional hydraulic measurements were conducted at full-scale. In 2021, the total flow rate into the full-scale flume was measured via a SonTek-IQ Pipe meter. In 2019, water velocity in a cross-section of each of the three channels was measured using a SonTek SL3000 velocity meter. Both the flow rate in 2021 and the cross-sectional water velocities in 2019 were collected to verify the physical scale model measurements.

Experimental Design

Average cross-sectional water velocity within the competing (V_C), entrance (V_E), and auxiliary (V_A) channels varied depending upon the treatment condition. A total of six EP treatments were evaluated in this study (T_1, T_2, T_3g, T_3, T_4, and T_5). V_C was fixed throughout at 1 ft/s, within the range of what might be expected for the velocity of a river beside a fishway entrance. V_A was varied from 1 to 5 ft/s by intervals of 1 ft/s with two treatments using a V_A equal to 3 ft/s. In one of the two treatments where V_A equalled 3 ft/s, a 2.5 ft high, vertical sharp-crested entrance gate was installed at the downstream end of the entrance channel (T_3g). This was the only treatment with an entrance gate. The gate was set to a height that produced an entrance jet velocity of 4 ft/s, within the range recommended by the USFWS (2019) for shad and was equivalent to V_E for the other five treatments.

A total of 30 trials were conducted over the two test years (14 in 2019 and 16 in 2021). All trials were run for a minimum of 3.5 hours during daylight hours. There were ~40 shad in each trial. Trial treatments were semi-randomized to ensure they were conducted over a wide range of river conditions in each year. Prior to both experiments, preliminary trials were conducted to evaluate the methodology and telemetry systems to ensure accurate data collection.

In 2019, trials were conducted between June 4th and June 12th. The focus of this experiment was to see how shad responded to changes in the auxiliary channel velocity, V_A. Treatments consisted of 3 ft/s (T_3), 4 ft/s (T_4) and 5 ft/s (T_5). Four to five trials per treatment were completed. These trials occurred late in the migration season due to several factors, including abnormally low river temperatures throughout May, high turbidity, problems at the collection site, and contractor delays that resulted from the 35-day federal government shutdown earlier in the year.

The project was extended through 2020 following the completion of the 2019 trials, then postponed to 2021 due to the COVID-19 pandemic. In the second year of trials, the following new treatments were added: 1 ft/s (T_1), 2 ft/s (T_2) and 3 ft/s with an entrance gate (T_3g). The goal in the second year was to examine how shad responded to 1) lower auxiliary channel velocities, V_A, and 2) and the installation of an entrance gate. Five trials each were conducted for T_1 and T_2, four trials were conducted for T_3g, and two trials were conducted for 3 ft/s without the gate (T_3; the only carryover treatment from 2019). Trials were conducted between May 18th and May 28th. We intentionally conducted trials within a similar temperature range from 2019 to minimize temperature effects on our results between years, though this led to trials being conducted at an earlier stage of the migration season relative to 2019.

River temperature (HOBO, Model U20-001-04) ranged between 15.59 and 19.21 degrees Celsius in 2019 and between 14.44 and 20.35 degrees Celsius in 2021. Turbidity (Hach, Model 2100Q) ranged between 3.99 and 17.4 NTU in 2019 and 1.65 and 2.77 NTU in 2021.

Fish Collection, Transport, and Disposal

Over a three-year period, 1,272 actively migrating adult shad were collected from the Holyoke Robert E. Barrett fish lift in Holyoke, MA and transported via truck in a 1,100-gallon tank to the S.O. Conte Research Laboratory. Collection methods followed those described in Mulligan et al. (2019). In 2019, 611 shad were collected over 8 trips. In 2021, 661 shad were collected over 8 trips. No fish were collected in 2020.

Telemetry Data Collection & Post-Processing

Shad were tracked via passive integrated transponder (PIT) antennas installed within the tailwater zone and entrance channel (PIT multi-reader system described in Castro-Santos et al. 1996). The data were analysed in RStudio 3.5.1. A univariate, non-parametric Kaplan-Meier curve was fit to the data set to estimate entrance efficiency over time (Kaplan and Meier 1958) for each of the six treatments. Based on these curves, the time to which 50% of the fish swam into the entrance channel was calculated. Also, the total entrance efficiency (i.e., the percentage of fish that swam into the entrance channel one or more times by the end of the 3.5-hour trial) was calculated for each treatment.

Results & Conclusion

Shad had the greatest entrance efficiency at the lower auxiliary water velocity (V_A) treatments, T_1 and T_2, both of which were conducted in 2021 (Table 1). Nearly all the fish swam into the entrance channel and did so at a faster rate relative to the other treatments. The treatment with V_A = 3 ft/s without a gate (T_3) in 2021 performed nearly as well as the two lower velocity treatments, though the bulk of the fish tended to enter more slowly. Adding an entrance gate at the same V_A (T_3g) caused an even greater delay to entry. The time to 25% entry raised ~20 minutes from the near instantaneous 25% entry that was reported for 1, 2, and 3 ft/s without a gate in 2021.

Shad passage efficiency was worse in 2019 than in 2021, potentially due to the difference in run timing when our trials were conducted. 2019 trials occurred near the end of the migration season, unlike in 2021 that occurred closer to the peak of the run. While we matched river temperatures between years, a factor known to cause significant changes in shad passage performance (Mulligan et al. 2019, Bayse et al. 2019), we were unable to account for the impact of run timing with this approach.

Treatments in 2019 had an approximately 20% reduction in entrance efficiency by the trial end, including a 16.7% drop for T_3 in 2019 relative to 2021 (the only carryover treatment between years). In 2019, shad entrance efficiency and entry rates tended to worsen as V_A was increased from 3 to 5 ft/s.

However, in all treatments, at least ~7 out of every 10 fish successfully passed the EP diffuser and swam into the entrance channel within the 3.5-hour long trial, highlighting the general effectiveness of the novel AWS technology. In both years, lower velocities through the EP diffuser led to increased shad passage efficiency, though performance peaked for treatment T_2. This treatment condition represents an approximate six-fold increase in gross diffuser velocity relative to conventional auxiliary water systems.

In summary, lower auxiliary water velocities resulted in increased entrance efficiency and reduced entry time for shad in this study. While the possible effect of fish collection timing between years could not be accounted for, the overall entrance efficiency was greater than 70% across all treatments regardless of year. This high efficiency rate underscores the effectiveness of AWS technology in passing diadromous species.

Data supporting these conclusions can be obtained through the U.S. Geological Survey ScienceBase-Catalog (https://www.sciencebase.gov/) following publication of this article.

Table 1: Summary of the results based on the passive integrated transponder (PIT) telemetry data and Kaplan-Meier curve

Treatment	**T_1**	**T_2**	**T_3g**	**T_3**		**T_4**	**T_5**
Auxiliary Water Velocity, V_A (ft/s)	**1**	**2**	**3**	**3**	**3**	**4**	**5**
Entrance Gate	**No**	**No**	**Yes**	**No**	**No**	**No**	**No**
Year	**2021**	**2021**	**2021**	**2021**	**2019**	**2019**	**2019**
Number of Fish	198	197	155	75	196	158	200
Time to 50% Entry (minutes)*	1.47	1.53	35.6	13.1	57.7	76.6	87.5
Entrance Efficiency at Trial End (%)*	92.4 ± 4.7	95.0 ± 4.2	88.1 ± 6.7	91.0 ± 9.2	74.3 ± 6.9	72.8 ± 7.9	68.3 ± 7.4

*Time to 50% entry and entrance efficiency were calculated using a univariate, non-parametric Kaplan Meier curve fit

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Award Outputs

Technologies or Techniques

Entrance Palisade Diffuser

Publications

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Mulligan, K., A. Haro, B. Towler, B. Sojkowski. M. Rojas, and R. Palmer. Recent USGS Laboratory Studies Aimed at Improving Passage of American Shad. Connecticut River Research and Management Forum. Oral presentation. 8 August 2019. Turners Falls, MA

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