

Evaluation of Modular and Scalable Downstream Passage Systems for Silver American Eels

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Key Study Findings

The following are the primary findings from the results of each study component that was completed for the evaluation of the Klawe horizontal zig-zag and vertical silver eel bypass designs:

Laboratory Evaluation

- The laboratory evaluation of the two bypass designs, which was conducted in a large recirculating flume with a simulated turbine intake, demonstrated bypass efficiencies of 68% for the vertical system tested alone and 91% for both systems evaluated together when the intake bar spacing was 1-inch clear and a small-mesh perf-plate was placed over the lower 16 inches of the bar rack.
- The horizontal bypass system also produced a bypass efficiency of 75% when tested alone with 2-inch bar spacing on the intake rack and with the perf-plate overlay on the lower portion of rack.
- The estimated bypass efficiencies from the laboratory tests indicated both bypass systems had potential to provide acceptable levels of protection for silver eels when installed at an actual turbine intake.
- The CFD modeling demonstrated accelerations in flow around the bypass systems and into the bar racks with eddies and back flows on the downstream side of each bypass design.
- Despite the flow acceleration directly upstream of the bar racks, the channel velocity of 2.0 ft/s and the increase to velocities up to about 2.5 to 3.0 ft/s did not lead to impingement of eels and produced acceptable levels of bypass efficiency for some of the test conditions.
- With the narrower bar spacing (1-inch) and the perf-plate installed, test fish appeared to have more opportunity to search, locate, and enter the bypass openings. This was particularly evident for the vertical bypasses which were ineffective with the 2-inch bar spacing, but had a bypass efficiency of 68% with the 1-inch spacing.

Field Evaluation

- The field evaluation of the two eel bypass designs, which was conducted at a turbine intake at a small hydropower project in New Hampshire, did not demonstrate effective downstream passage for test fish released upstream of the intake in the project's power canal.
- CFD modeling indicated the turbine operating conditions that were evaluated produced flow velocities approaching the powerhouse intake that were too high (up to 4 ft/s) for eels to effectively avoid entrainment and impingement before locating a bypass opening for safe downstream passage.



- The CFD modeling also indicated a blockage over some portion of the lower bar rack (i.e., similar to what was tested in the flume with perf-plate) could not be used at the field site because it would have created even higher approach velocities and produced flow conditions downstream of the bar rack that could negatively impact turbine operation.
- Bypass efficiencies were estimated to be 0 to 33% for the range of turbine generation levels and the two bar spacings (1.13 and 3.00 inches) evaluated, with most bypassed eels using the horizontal zig-zag system.
- A large proportion of test fish (13 to 60%) moved upstream out of the power canal and did not interact with the turbine intake or bypass systems. These fish either remained upstream or passed downstream over the spillway. The loss of these fish to the evaluation of the bypass systems reduced the robustness of the efficiency estimates due to smaller than anticipated sample sizes.

Technology Application Assessment

- There are about 265 hydropower projects in the range of American Eel that will be undergoing FERC relicensing in the next 15 years, many of which could benefit from an affordable and effective eel diversion system that can reduce turbine entrainment and minimize impacts to project operation.
- The four case studies demonstrated that the two existing eel protection technology alternatives that comply with USFWS prescription requirements (i.e., 0.75-inch bar spacing on existing intake structure or installation of an angled rack with the same spacing, and both with approach flow velocities of 1.5 ft/s or less) are likely to be the most costly approaches.
- Targeted nightly shutdowns that are triggered by precipitation events could provide very high levels of protection for silver eels (potentially as high as 98% total project survival), as would shutdowns on every night of the migration season. However, although annual costs for this alternative would be low for each of the case study sites, it could be a very costly alternative over a 30 to 40 year FERC license term.
- The two eel bypass designs were typically the least expensive technology option, but also had the lowest estimated total project survival rates at each case study site. However, the eel bypass systems could potentially provide levels of bypass efficiency similar to the two narrow-spaced bar rack alternatives while using orders of magnitude less flow, if they are combined with 0.75-inch clear bar spacing.
- When considered with the laboratory and field testing results, the case study assessments suggest that the two eel bypass designs could potentially be effective at sites with relatively low approach velocities and narrow intake bar spacings (e.g., 0.75 inch clear openings), while using significantly less flow than more conventional bypass



systems. The cost savings of the lower bypass flow could be substantial over the course of a typical FERC license term (30 to 50 years).

Recommendations for Future Research

- Although neither of the two eel bypass systems evaluated as part of this research effort performed to a standard (i.e., bypass efficiencies exceeding at least 75%) that would allow them to be considered for immediate application at hydropower projects in the U.S., the results of laboratory and field testing indicate further development and testing of these technologies could lead to more effective designs.
- Potential modifications that could improve performance include larger openings, an increase in bypass flow, and improvement in hydraulic conditions around the bypass pipes (this may be more important to the vertical system than the horizontal design). Techniques that reduce entrainment and allow fish more time to search for the bypass openings, such as the use of a solid or small-mesh panel on the bottom of turbine intake bar racks, should also be examined in more detail to develop approaches that positively influence eel behavior without impacting turbine operation.
- CFD modeling and laboratory testing should both be used to develop and evaluate design enhancements and optimize each bypass system before any additional testing is conducted in the field.



Executive Summary

Implementation of effective downstream passage for silver-phase American Eel (*Anguilla rostrata*) at hydropower dams using methods that are economically feasible has been a challenge for many project owners. Due to the potential for high mortality rates during turbine passage, resource agencies have focused on mandatory prescriptions that prevent entrainment by physically excluding eels (i.e., narrow trash rack bar spacing) or eliminating turbines as a passage route (i.e., unit shutdowns at night when eel movement is greatest). Both of these options can significantly impact the economic viability of a project. Consequently, there is a need for alternative technologies that can provide safe and effective downstream passage for silver eels without having a major impact on the ability of a project to generate power during the eel downstream migration period. This need is of particular concern now because about 300 hydropower projects within the range of American Eel freshwater habitats are scheduled to be relicensed by the Federal Energy Regulatory Commission (FERC) in the next 15 years

To address the need for biologically and cost effective eel bypass systems, Alden Research Laboratory, Inc. (Alden) received an award from the U.S. Department of Energy (DOE) to conduct a biological evaluation of two new bypass designs developed specifically for silver eels. Both systems can be classified as modular and scalable and require very little flow compared to conventional bypass designs. The primary goals of this research project were to provide information and data on the biological performance and design and operation of the two bypass systems and to assess their potential application at hydropower projects within the range of American Eel in the US. To achieve these goals, Alden conducted laboratory and field evaluations of each bypass system and assessed the feasibility of application of the two technologies at a wide range of hydro projects, including what the expected operational impacts and costs will be relative to the current standards for providing downstream eel passage. Numerical hydraulic modeling was also conducted for a subset of the laboratory flume test conditions and for the intake channel and turbine intakes at the field study site.

Eel Bypass Designs

The two eel bypass systems that were evaluated for this study are designed to exploit behaviors exhibited by downstream migrating silver-phase eels (American and European species) during previous lab and field studies. One technology, developed by a German company (KLAWA), incorporates a series of horizontal pipes connected together in a zig-zag pattern installed on the river bottom just upstream of turbine intake bar racks. There are 2-inch diameter openings on the upstream and downstream sides of the piping for eels to enter, after which they are carried downstream in flow created by a siphon or from pumping. The other system (developed by Lakeside Engineering) consists of a straight vertical pipe with multiple openings similar in design and intake flow as the horizontal system. The vertical system is designed to take advantage of vertical movements exhibited by some silver eels when they encounter intake trash racks, which has been demonstrated during field studies.



Laboratory Evaluation

The laboratory evaluation of the two eel bypass designs was conducted in a large recirculating flume located on Alden's campus in Holden, Massachusetts. The goal of laboratory testing was to determine passage efficiency for each bypass design using near full-scale systems and a simulated hydro turbine intake with bar racks. Silver-phase American Eels were collected from a river in Maine during the fall out migration in 2018 and transported to Alden for testing. A PIT tag system, underwater video cameras, and a DIDSON acoustic camera were used to monitor eel movements and bypass use during each trial. Test conditions included an intake (channel) approach velocity of about 2 ft/s, 1 and 2-inch clear spacings on the bar rack, and the use of a perforated-plate panel placed on the lower 16 inches of the bar rack. The two bypass designs were tested alone and in combination and a set a trials was conducted with only the bar racks (i.e., baseline condition with no bypasses).

The first set of trials evaluated eel passage with both bypass systems operating and a 2-inch bar spacing on the simulated intake rack. Bypass efficiency for this test condition was about 40%. To reduce the potential for entrainment of eels in the lower portion of the water column, all subsequent tests were conducted with a 16-inch high perf-plate panel installed on the bottom of the upstream face of the bar rack. Following this modification, bypass efficiency for each system tested alone was 75% for the horizontal zig-zag design and about 14% for vertical design. The baseline (control) trial conducted without a bypass produced an entrainment rate of about 60%, which was similar to the percent of eels entrained (59%) during the trial with only the vertical bypass system. For the two sets of test conditions evaluated with the 1-inch bar rack spacing, bypass efficiency was 91% with both bypasses operating and about 68% with only the vertical bypass system. These efficiencies were significantly higher than those estimated for the 2-inch bar rack tests, indicating the narrower bar spacing was more effective at reducing entrainment and allowing test fish to locate bypass openings of both systems.

The CFD modeling indicated flow accelerated up to about 2.5 to 3.0 ft/s as it went around the bypass structures (vertical and horizontal) and approached the bar rack. Smaller regions of higher velocities were observed close to the vertical bypass systems. Lower velocities occurred downstream of each vertical conduit and the brush material placed on the bottom of the flume upstream of the horizontal bypass conduit. The perf-plate placed on the lower 16 inches of the bar rack did not substantially alter flow path or velocities at the bar rack due to the flow separation created by the brush material upstream. In the horizontal bypass, there were seven entrances in the 6-inch diameter conduit, which produced higher velocities inside the conduit compared to the vertical bypasses. Additionally, there was higher headloss through the pipe due to the bends of the zig-zag design. This causes a large pressure difference between the upstream and downstream ends of the pipe, resulting in a significant difference in flow rate among the openings of the horizontal bypass. The CFD model demonstrated that five of the openings had a flow fraction between 12% and 16% and two varied significantly from the theoretical average flow.

The results of the laboratory evaluation demonstrated relatively high bypass efficiencies for the horizontal zig-zag system tested with the 2-inch bar spacing (75%) and both systems combined



tested with the 1-inch bar spacing (91%). The use of the solid panel over the bottom 16 inches of the rack appeared to reduce entrainment and increased bypass use, particularly for the horizontal system. Additionally, more eels used the horizontal bypass than the vertical system when they were tested in combination. However, bypass efficiency was about 67% for the vertical system when tested alone with the 1-inch bar spacing. These results supported a determination to test both bypass systems during the field evaluation phase of the study.

Field Evaluation

The field evaluation of the two bypass designs was conducted at a small hydropower project in southern New Hampshire using silver American Eels collected from a Maine river during their spawning outmigration and tagged with acoustic telemetry transmitters. Similar to the laboratory evaluation, CFD modeling was conducted to characterize the hydraulic conditions tagged eels experienced in the vicinity of the bypass systems and intake structure following release into the turbine intake channel of the study site. The project where the field study was conducted has two Kaplan turbines, each rated for generation of 1.5 MW at a flow rate of 990 cfs. Prior to starting the field study, the Unit 1 turbine had been removed for repairs and was not returned to operation until after the bypass evaluation was complete. Consequently, the evaluation of the two bypass systems was conducted with only Unit 2 operating.

The vertical bypass system installed at the field site consisted of two vertical pipes and frame structures. One vertical bypass was located on the centerline of the Unit 1 turbine intake and the other was installed on the shore side wall adjacent to the Unit 2 intake. The Klawwa horizontal zig-zag bypass system was installed at the base of the trash racks across the full width of the intake structure. Acoustic telemetry and PIT tags were used to monitor test fish movements and passage during testing of the bypass systems with four combinations of clear bar spacing (1.13 and 3.00 inches) and turbine flow. The first three tests were conducted with the narrower bar spacing and turbine flows between about 200 and 600 cfs. The fourth test evaluated the larger bar spacing with a turbine flow of about 300 cfs.

Bypass efficiency ranged from 0% for the second release group (75% gate opening with 1-inch bar spacing) and the fourth release group (50% gate opening with 3-inch bar spacing) to 33.3% for the first release group (50% gate opening with 1-inch bar rack spacing). The entrainment rate of tagged eels ranged from 31% for the third release (45% gate opening, 1-inch bar spacing) to 82% for the second release. Throughout the study period, 10 tagged eels and 11 native eels used one of the bypasses. Of the 21 eels that were bypassed, 16 used the horizontal zigzag bypass and 5 used one of the vertical bypasses. Impingement of tagged and untagged (native) eels was observed throughout the study period. The highest number of impingements occurred at the 50% gate opening (Release 1) for native eels and the 75% gate opening (Release 2) for tagged eels. No eels were impinged during Release 4, which was with the 3-in bar rack. All eels, regardless of the passage route, were found throughout the water column. However, the highest densities of tagged fish were observed approximately 3 to 7 ft above the bottom. About 13 to 60% of tagged eels in each release were last detected by the hydrophone located upstream of the intake channel gate structure, indicating they either remained upstream of the project or passed downstream over the spillway. Although it was anticipated some of the



released fish might move upstream, the large percentage of tagged eels that left the intake canal during three of the four tests (about 42 to 60%) was higher than expected.

The CFD modeling of the field site simulated the intake channel flow conditions at 200 cfs (release 3), 300 cfs (releases 1, 4), and 600 cfs (release 2). The velocity profiles provided by the model were very uniform throughout the channel until flow was within a few feet of the Unit 2 intake where it began to accelerate. At the 200 and 300 cfs conditions, the velocity at the rack was below 2.5 ft/s over the entire area of the structure, which is lower than the velocity was approaching most of the bar rack in the flume testing. At 600 cfs turbine flow, the bar rack approach velocity was over 4.0 ft/s in some locations. Silver eels should be able to swim away from turbine intakes after encountering intake approach velocities of about 2.5 ft/s and less and this was demonstrated by the low number of impinged tagged eels for tests at the lower turbine loads. Conversely, high numbers of impinged native eels were observed at the higher turbine flows (300 and 600 cfs) when approach velocities exceeded 2.5 ft/s over a large portion of the intake rack area.

Technology Application Assessment

The objective of the technology application assessment was to evaluate the potential for the two eel bypass systems to be applied at hydropower projects in the US for passing silver eels safely downstream. The technology assessment included a review of FERC-licensed projects at which the bypass systems could be considered for application and several case studies evaluating the feasibility of available alternatives (including approaches accepted by the USFWS) based on biological performance and engineering and economic considerations.

Out of the 2,247 hydro projects in the US, approximately 873 are in the native range of the American Eel and over 250 sites have FERC licenses that expire by 2035. A dataset containing information on flow, head, generating capacity, and current downstream fish passage facilities was developed to determine which sites may need to address silver eel passage and, consequently, may benefit from the new eel bypass designs. The majority of these sites (64.6%) are considered small hydro (>5 MW).

Case study evaluations of downstream eel passage were conducted for four projects of varying sizes (with respect to generating and turbine flow capacities) and configurations. The goal of the case studies was to determine operational, cost, and biological benefits that may be realized with the new eel bypass systems when considered for a set of typical hydropower projects located within the range of American Eel. However, based on the results of the field evaluation conducted at Mine Falls (Section 4), bypass efficiency and total project survival rates for the new bypass designs are unlikely to be as high as they would be for approaches currently accepted by the USFWS (i.e., 0.75-inch clear spacing on bar racks and 1.5 ft/s or less intake approach velocities, or nightly turbine shutdowns during the entire annual eel migration period). Although USFWS sites require a maximum approach velocity of 1.5 ft/s for silver eels, there is evidence from lab and field studies that velocities up to 2.0 ft/s can provide adequate protection from impingement. It is possible that the new bypass systems could meet USFWS requirements for downstream eel passage if future design improvements lead to higher bypass



efficiencies or if the existing designs are installed in conjunction with bar rack clear spacings of 1 inch or less and with approach velocities less than 2 ft/s (i.e., to physically exclude eels from entrainment and eliminate impingement). The new bypass designs provide an economic advantage over conventional surface or submerged bypasses because they require significantly less flow (by one or more orders of magnitude) for operation.

Study Conclusions

The evaluation of the two bypass designs (vertical and horizontal zig-zag conduits with small entrance openings) developed specifically for downstream passage of silver eel at hydropower dams incorporated three study components (biological testing in the lab and field and CFD modeling of both test locations) to determine the efficacy of these technologies and the potential need for further development. The laboratory results indicated that the two systems, operated alone or in combination, had potential to effectively bypass silver eels at turbine intakes under certain design and operational conditions. These conditions included intake bar rack clear spacing of 1 inch (or less), approach velocities of 2 ft/s (or less), and the use of a solid panel over a portion of the lower bar rack (a 16 inch height was tested in the lab). The horizontal bypass system also was shown to provide effective passage (75% bypass efficiency) with a 2-inch clear bar spacing.

Based on the positive laboratory results, the field evaluation was conducted using similar design and operational conditions that were considered effective in the lab. Bypass efficiencies for all four test releases of tagged silver eels were low (0 to 33%). The ineffectiveness of the bypass systems at the field site was attributed primarily to high velocities at the turbine intake (up to about 4 ft/s based on CFD modeling) that made it difficult for eels to locate a bypass opening before becoming entrained or impinged. Additionally, for three of the four test releases about 40 to 60% of test fish were last detected in the impoundment, indicating they moved upstream out of the power canal and likely passed downstream over the spillway. This significantly reduced the effective number of tagged fish encountering the turbine intake and bypass systems and, consequently, limits the robustness of the bypass effectiveness results to some degree.

The technology application assessment demonstrated there are hundreds of projects that will likely need to address downstream passage of silver American Eels during FERC relicensings currently underway and that will be initiated in the next 10 to 15 years. The current standards and requirements for downstream eel passage prescribed by state and federal resource agencies, including 0.75-inch spaced bar racks to reduce entrainment and intake approach velocities less than 1.5 ft/s to prevent impingement, can be onerous and difficult to implement from operational and cost standpoints. The results of four case studies completed as part of the technology application assessment indicate that the two eel bypass systems evaluated for this study may not achieve acceptable levels of bypass efficiency and total downstream passage survival for silver eels, but the two systems would be less costly to implement mainly due to bypass flow requirements that can be one to two orders of magnitude less than conventional submerged and surface bypasses. Also, the field test site used for this study was not conducive to the use of the new bypass designs primarily due to the high velocities at the turbine intake.



Bypass efficiencies would likely be higher at projects with turbine intake approach velocities lower than 2 ft/s. However, some projects may need to install new or modified bar racks with narrower clear spacings (one inch or less).

The results of this study indicate there is potential for effective application of the two new eel bypass designs if specific intake rack bar spacings and approach velocity conditions are met. Also, CFD modeling of the hydraulic conditions at the bypass openings and in the conduits suggest that design modifications may be needed to optimize the designs to improve the detection of entrances by silver eels and increase the likelihood of entry and passage. With design modifications and field testing at sites that are more conducive to the application of these bypass systems, it may be determined that many hydropower projects could benefit from these technologies, primarily with respect to the reduced flow required for their operation.



1.0 Introduction

Downstream passage of silver-phase American Eel (*Anguilla rostrata*) is a major issue at hydro projects due to population declines in many river systems. Hydropower facilities can impact eel populations by causing migratory delays or mortality during passage through turbines. Providing downstream passage for silver eels can be logistically difficult and very costly for dam owners. The US Fish & Wildlife Service (USFWS) has developed relatively restrictive downstream passage criteria for protecting eels at hydro projects, including 0.75-inch clear bar spacing on intake trash racks and a maximum intake approach flow velocity of 1.5 ft/s (USFWS 2017). As an alternative to USFWS's bar spacing and approach velocity criteria, nightly turbine shutdowns during the entire annual migration period (August 15-December 15 in the Northeast) is also considered an acceptable method for protecting silver eels from turbine entrainment. Consequently, development of biologically effective eel bypass systems that need less flow and/or do not require very narrow bar spacing will provide significant economic benefits to dam owners.

With about 300 hydropower projects within the range of American Eel freshwater habitats to be relicensed by the Federal Energy Regulatory Commission in the next 15 years, there will be a significant need for biologically and cost effective bypass systems designed to protect silver eels during downstream migrations and to minimize impacts to power generation. Bypass systems that are modular and scalable should allow for broad application at hydropower projects of varying size (head and flow) and configurations (i.e., layout of spillways, gates, forebays, and intakes).

To address the need for more effective eel bypass systems that have less impact on power generation and that can be applied at a wide range of projects, Alden Research Laboratory, Inc. (Alden) received an award from the U.S. Department of Energy (DOE) to conduct a biological evaluation of two new bypass designs developed specifically for silver eels that can be classified as modular and scalable. The primary goals of this research project are to provide information and data on the biological performance and design and operation of the two bypass systems and to assess their potential application at hydropower projects within the range of American Eel in the US. To achieve these goals, Alden conducted laboratory and field evaluations of each bypass system and assessed the feasibility of application of the two technologies at a wide range of hydro projects, including what the expected operational impacts and costs will be relative to the current standards for providing downstream eel passage.

The initial technical scope of work developed for this study included the following three discrete components:

1. A laboratory evaluation of the biological and operational performance of the two bypass systems conducted with actively migrating silver eels;



2. A field evaluation of both bypass systems at a typical small hydro project to verify biological and operational performance and to further optimize the design of each system; and
3. A desktop study evaluating the cost and biological benefits from the use of the two bypass systems compared to conventional bypass systems (i.e., technical baseline) and an assessment of the potential application of each system at hydro projects that are or will be undergoing FERC relicensing over the next 20 years and will need to address eel passage.

In addition to these three study components, numerical hydraulic modeling (also referred to as computational fluid dynamics modeling, or CFD) was added as a fourth phase to the study. The CFD modeling was conducted for a subset of the laboratory flume test conditions and for the intake channel and turbine intakes at the field study site.



2.0 Bypass Design Descriptions

The two eel bypass systems that were evaluated for this study are modular and scalable and are designed to exploit behaviors exhibited by downstream migrating silver-phase eels (American and European species) during previous lab and field studies. One technology, developed by a German company (KLAWA), incorporates a series of horizontal pipes connected together in zig-zag pattern installed on the river bottom just upstream of turbine intake bar racks (Figure 2-1; <https://www.youtube.com/watch?v=rk2aC0Ho1og>). The other system is designed to take advantage of some of the same behavioral characteristics that were considered in the development of horizontal zig-zag bypass. However, its orientation is vertical rather than horizontal (Figure 2-2). The vertical orientation is important because field studies have shown silver eels will search throughout the water column for a downstream egress when they encounter bar racks rather than stay solely near the bottom (Brown et al. 2007).

The KLAWA zig-zag bypass pipe sections are placed at a 30-degree angle to each other and at each interior angle is a bypass port (i.e., entrance) on the upstream and downstream sides of the pipe (Figure 2-1). The structure is set horizontally across the base of a turbine intake and is plumbed via siphon or pump to exit over a dam or into a holding tank with 1 to 2 cfs bypass flow. A brush material is installed just upstream of the pipe to provide a refuge area (i.e., velocity break) between this material and the pipe to allow eels more opportunity to search for a bypass opening without being exposed to entrainment through turbine intake racks.

The vertical bypass system consists of a straight pipe with multiple entrance openings and can be positioned at one or both ends of an intake, or at positions in between depending on the intake width. If positioned away from a side wall, the vertical pipe has tangential plates oriented at right angles along the length of the pipe. A series of entrance ports in the pipe are located tangential to the side plates. Similar to the horizontal system, brushes can be installed along the leading edge of the side plates to create a refuge for eels. A siphon or pump is used to move bypass flow and eels through the central pipe downstream to a safe discharge location in a tailrace or below a spillway. To the best of our knowledge, a system like this has not been implemented at any projects in the U.S. or other countries. Some projects have installed standard bypass systems with entrances at multiple depths, but these systems have much larger openings and require higher flow rates than the vertical eel bypass system.

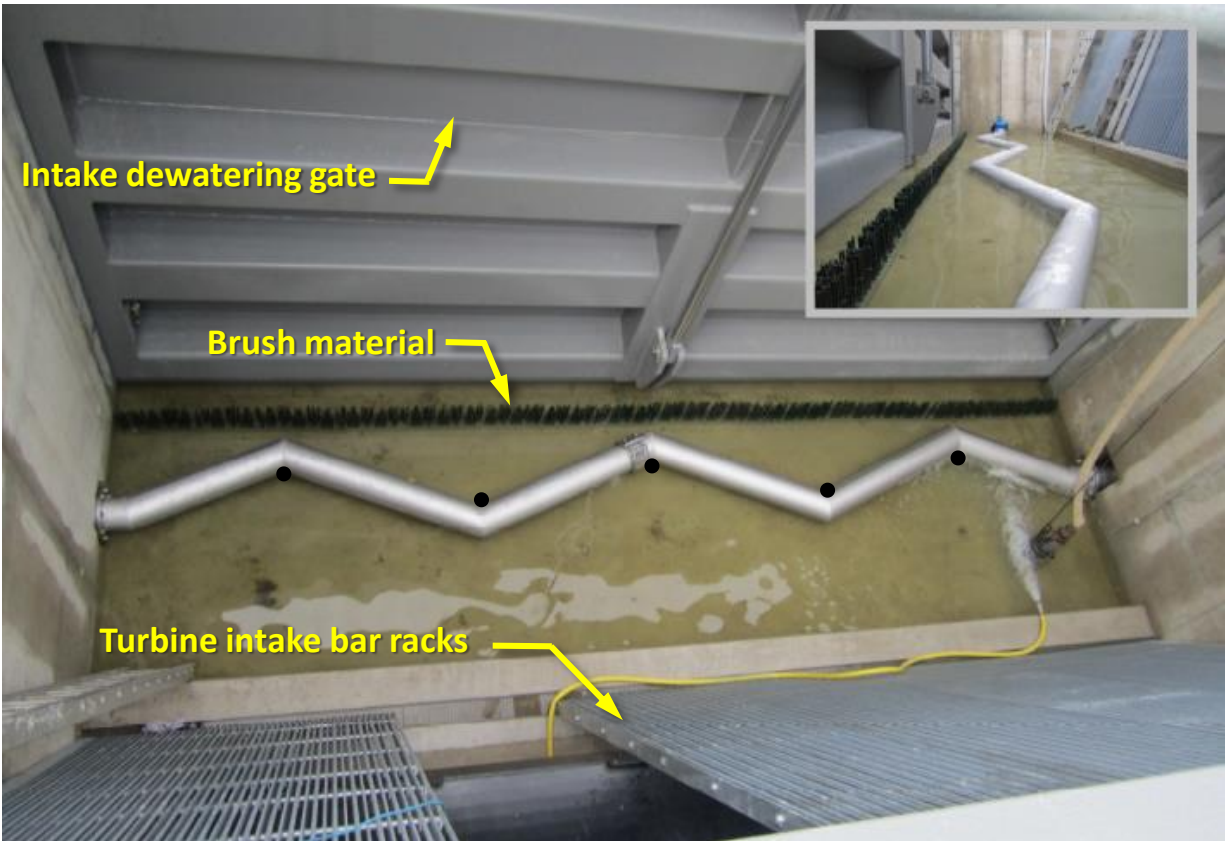


Figure 2-1. KLAWA horizontal zig-zag bypass system installed upstream of a hydropower intake (black circles indicate location of openings for eels to enter bypass pipe). (Source: KLAWA)

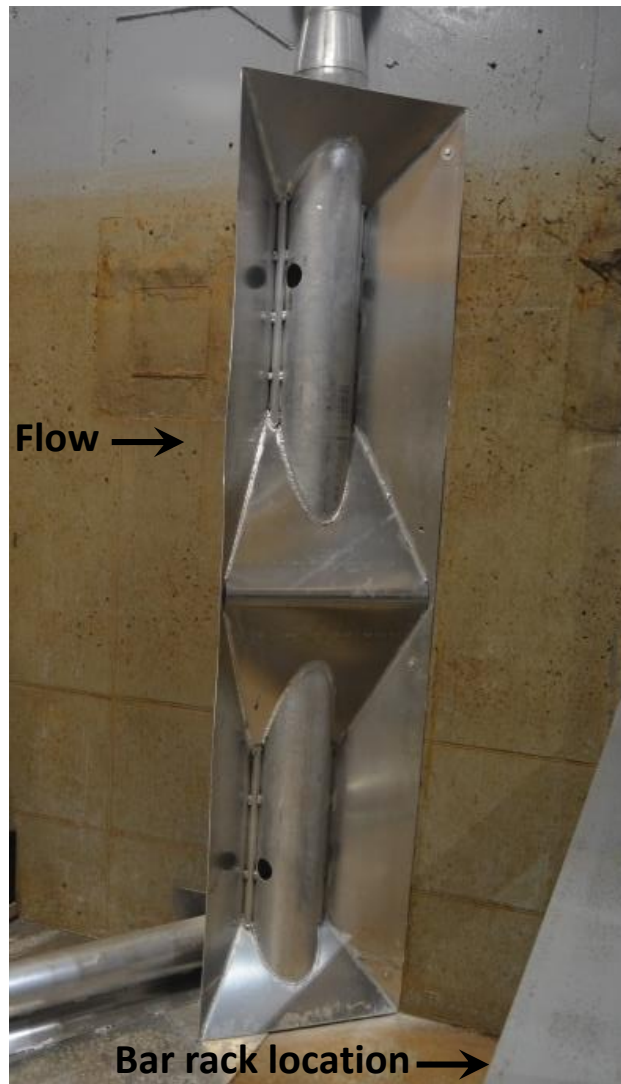


Figure 2-2. Vertical eel bypass system installed upstream of bar racks in the laboratory test facility.



3.0 Laboratory Evaluation

The laboratory evaluation of the two eel bypass designs was completed in the fall of 2018. The primary objectives for laboratory testing included the following: (1) complete an evaluation of each bypass system with silver American Eels to estimate bypass efficiencies and identify important behavioral aspects related to bypass discovery and use; and (2) provide design and operation recommendations for installation of each bypass system at the selected field site. In addition to testing with silver eels collected during their spawning outmigration to the Atlantic Ocean, CFD modeling was conducted to determine the hydraulic conditions experienced by fish during the laboratory evaluation of the two bypass systems.

3.1 Methods

3.1.1 Test Facility Design

Testing was conducted in a large re-circulating flume located in the Taft Fisheries Research and Test Facility building at Alden's campus in Holden, Massachusetts. The flume has 10-ft high walls and a test area that is about 80 ft in length and 20 ft wide. Flow is recirculated through the flume by two 5.5-ft diameter bow-thrusters (400 hp each) located at the downstream end of a lower channel beneath the test flume floor (i.e., flow passes vertically between the upper test channel and lower recirculation channel). The bow-thrusters are capable of pumping up to 500 cfs through the flume channel at a velocity of 3 ft/s. Turning vanes are located at both ends of the flume to straighten flow before it passes through the bow thrusters and prior to entering the upstream end of the flume. Fixed isolation screens are located at each end of the test channel to prevent fish from leaving the test area and potentially being entrained through the bow thrusters. The channel is equipped with a Cldon Ultrasonics LEFM[®] 800 Series 200 kHz flowmeter to measure water velocities and determine flow rates. Suspended solids and particulates are removed by a canister filtration system that has multiple 10-micron mesh bag filters. A UV filter is used to minimize the presence of pathogens.

The test facility configuration for the evaluation of the two bypass designs included the following (Figure 3-1 and Figure 3-2):

- A 20-ft wide bar rack structure (i.e., simulation of a turbine intake; tested with 1 and 2 inch clear bar spacing);
- Two full-depth (8 ft) vertical bypass systems;
- A KLAWA horizontal zig-zag bottom bypass system (full flume width);
- A bypass fish collection tank; and
- An acclimation and release pen located at the upstream end of the flume

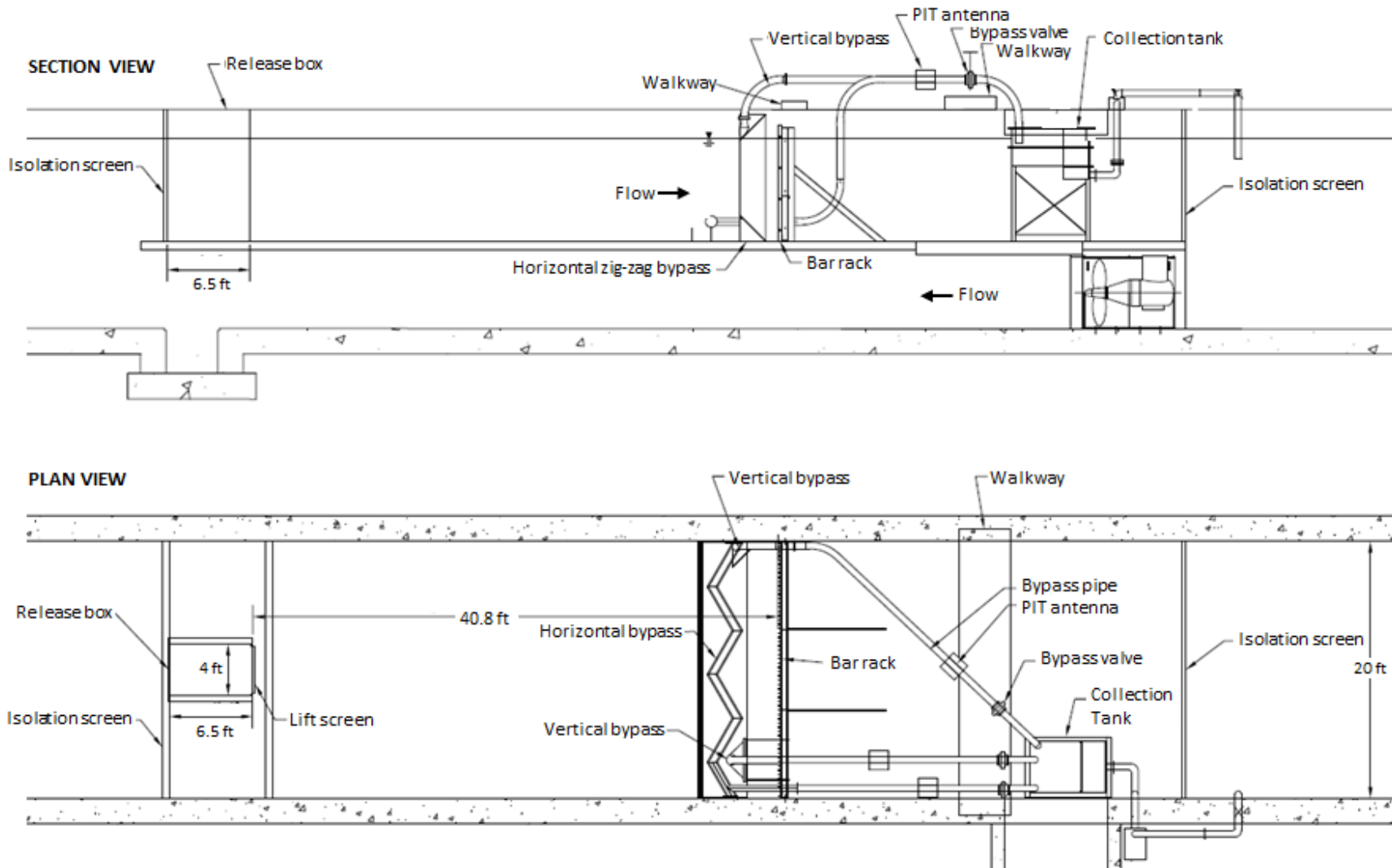


Figure 3-1. Test Facility design for the laboratory evaluation of two downstream eel bypass systems.

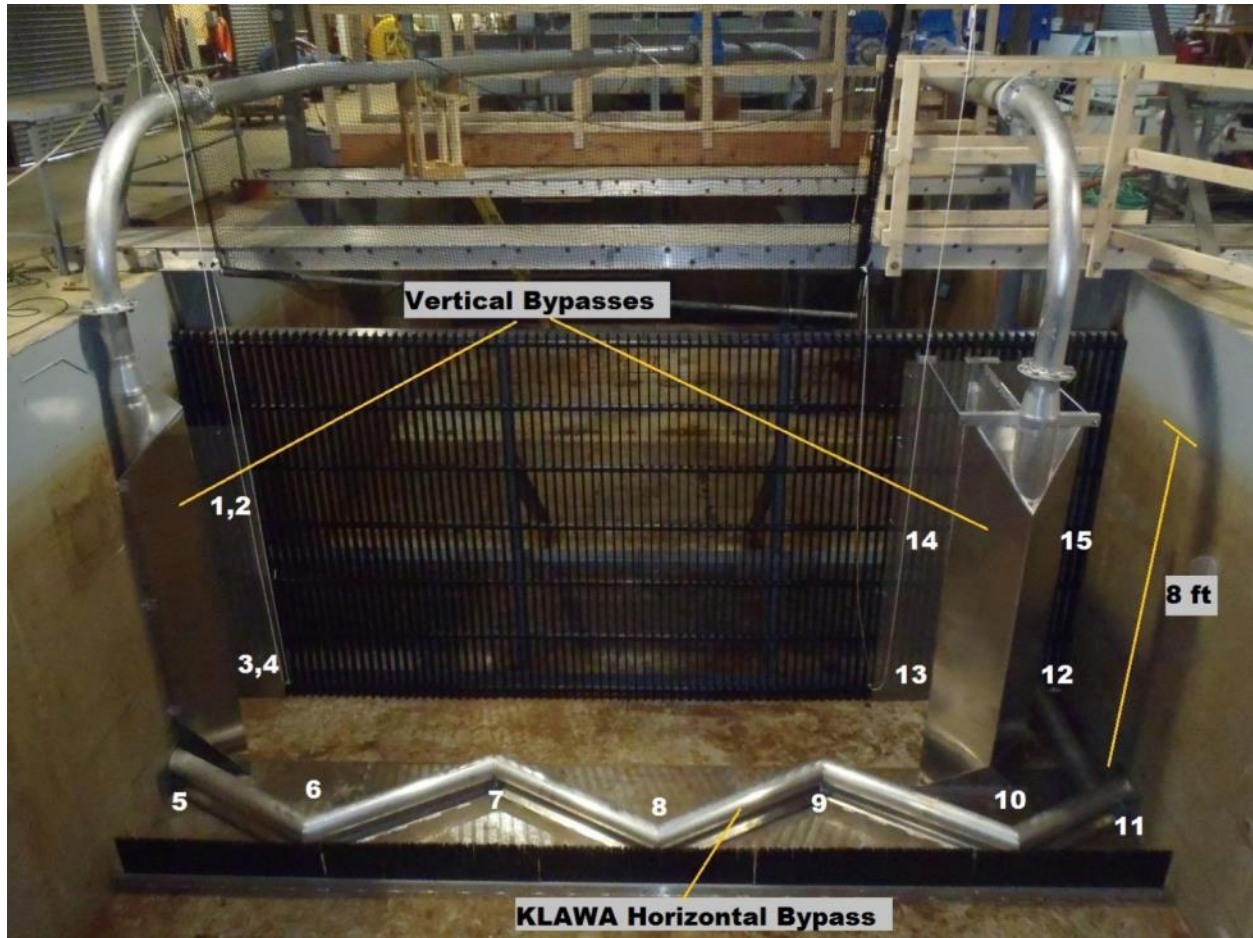


Figure 3-2. Laboratory test configuration with both bypass systems and the 2-inch clear spaced bar rack installed. Bypass entrances are labeled but not visible. Bottom perforated plate placed on the lower 16 inches of the bar rack for 1-inch bar rack trials is not present.

The submerged sections of the bypass conduits for both systems were 8 inches in diameter. Each conduit transitioned to 6-inch diameter conduits above water. The entrance ports were 2 inches in diameter. The approximate flow rates were 0.3 cfs through each vertical bypass pipe and 0.5 cfs through the horizontal zig-zag system. The acclimation pen was located in the center of the flume at the upstream end and was full depth (8 ft), 4.5 ft wide, and 6.6 ft long (in direction of flow). The downstream panel of the pen was mechanically lifted to allow test fish to voluntarily enter the flume and move downstream through the test area.

A Dual-Frequency Identification Sonar (DIDSON) acoustic camera was installed to monitor eels as they approached and interacted with the bar racks and bypass systems. Several underwater infrared cameras were mounted entrance ports of each bypass conduit to observe and record eel interactions with the openings. The number and placement of cameras varied between test configurations. A Passive Integrated Transponder (PIT) tag system (i.e., antennae and readers) was installed to record passage of eels (all of which had transponders injected into the gut cavity) through each bypass system prior to being discharged into a common collection tank.



After the first three trials, a 16-in perforated plate overlay was installed on the lower 16-inches of the bar rack in an attempt to reduce entrainment through the bar rack and increase the opportunity for bypass discovery. The vertical bypass systems were also modified by replacing a portion of the solid side panels with perforated plate prior to conducting the 1-inch bar rack trials. This modification was made in an attempt to reduce turbulence and eddies on the downstream side of the panels that appeared to be affecting eels based on video observations from the trials with the 2-inch bar spacing.

3.1.2 Eel Acquisition, Holding, and Tagging

Silver-phase American Eels used in the laboratory evaluation of the two bypass designs were obtained during the fall outmigration from two sources. Forty (40) eels were collected from the Holyoke Canal louver bypass sampler located at the Holyoke Hydroelectric Project on the Connecticut River in Massachusetts. Two-hundred (200) silver eels were collected from a sluice weir sampler at the Kelleyland Dam on the St. Croix River in Baileyville, Maine. Alden staff transported eels from both collection locations to Alden, where they remained in a fish holding facility located in a building adjacent to the test facility until the laboratory evaluation was completed. Using an eel silvering index methodology described by Durif et al. (2005), we determined that 227 of the eels obtained for testing were silver-phase adults and 12 were yellow-phase adults.

The holding facility has seven 420-gallon circular tanks and eighteen 235-gallon circular tanks. Each holding tank is supplied with a continuous flow of about 4 to 7 gpm. Solid waste products and particulates are removed with coarse and fine micron bag filters. Biofiltration and activated carbon systems are used to neutralize ammonia and reduce other impurities. An ultraviolet sterilization filter is used to minimize the presence of pathogens. The holding system also has a chiller and submersible heaters to maintain optimum temperatures throughout the year depending on the species being held. While eels were held in the system, temperature, dissolved oxygen, and pH were monitored on a daily basis and ammonia was measured several times per week. Towards the end of the experiment, temperatures dropped in fish holding to below 8°C for two days due to a malfunction with the heating system. The physical condition and behavior of eels were visually assessed daily to screen for signs of disease, fungus, and stress.

Two weeks prior to testing, Passive Integrated Transponders (PIT tags) were injected into the peritoneal cavity of each fish, which were also measured for length, weight, and eye diameter (Figure 3-3). The eye measurement was used to determine silvering stage as described by Durif et al. (2005). Head width was measured for 60 of the 238 eels. General physical condition and any pre-existing external injuries were recorded during the tagging process.



Figure 3-3. Examples of PIT tag insertion (top photo) and eye width measurement (bottom photo) performed with each test fish.

3.1.3 Bypass Efficiency Testing

The laboratory evaluation of the two eel bypass systems initially included the following test conditions:

- 2 inch clear bar rack slat spacing;
- 2 ft/s flume channel flow velocity;
- The two bypass systems evaluated separately and together; and
- Testing with the bar rack only (i.e., baseline condition).



After low bypass efficiencies were observed during the first set of trials conducted with both bypass systems evaluated together, perforated plate was placed on the lower 16 inches of the bar rack (across its full width) in an attempt to reduce entrainment and increase bypass use. The perf-plate appeared to improve bypass efficiency for the horizontal zig-zag system when tested alone, but not for the vertical systems. Consequently, testing with 1-inch clear spacing on the bar rack was added and included trials with both bypass systems together and the vertical systems only (Table 3-1). The approach (channel) flow velocity was maintained at 2 ft/s for all trials.

Because eels primarily migrate downstream during nighttime hours, all testing was conducted at night under complete darkness. Three replicate trials were conducted for each test condition using 30 eels per trial, with the exception of two trials for which 29 eels were evaluated (Table 3-1). For testing with the 2-inch bar spacing, naïve eels were used for the first two trials of a test condition. The third trial comprised 15 eels from each of the two previous trials. All eels evaluated with the 1-inch bar spacing had been tested during the trials with the 2-inch bar spacing. However, similar to trials with the 2-inch rack, the third trial conducted for each set of test conditions with the 1-inch rack were conducted with 15 eels from each of the first two trials.

At the start of each trial, the channel flow velocity was set at 0.5 ft/s and an eel test group was placed into the release pen. Eels were acclimated for 30 minutes and the channel velocity was slowly accelerated to 2 ft/s before raising the gate on the downstream side of the pen to allow eels to volitionally leave the pen and move downstream in the flume. Test durations were variable (4 to 6 hours) in the first set of 3 trials (i.e., tests with the horizontal zig-zag and vertical bypasses operated together with the 2-inch bar spacing), but were about 6 hours for trials conducted with all other test conditions (Table 3-1).

During each trial, eels were removed from the bypass collection tank and examined for injuries after being detected by one of the pit tag antennae. Video from the DIDSON acoustic camera and infrared cameras was recorded throughout the duration of each trial and monitored in real time to observe bypass events and general eel behavior (Figure 3-4). DIDSON images of the test area around the bypass entrances and bar rack were insufficient for observing eels (i.e., it was difficult to see fish in these areas). Consequently, DIDSON recordings were not analyzed for eel behavior or bypass use. IR videos were later reviewed to confirm bypass events and to record additional data on fish behavior in the vicinity of the bar rack and bypass entrances.

At the end of each trial, a 0.75-in mesh net was lowered over the upstream face of the bar rack to isolate fish and prevent movement through the rack in either direction before collection and enumeration. Once the flume was drained, all eels were collected using dip nets, enumerated by recovery location (upstream of rack, downstream of rack, and bypass collection tank), scanned for PIT tag code, visually assessed for external injuries, and returned to a tank in the holding facility. Any mortality that occurred during testing or within 96 hours from the completion of a trial was recorded.



Table 3-1. Test conditions for the laboratory evaluation of the two eel bypass systems. Perforated plate was placed on the lower 16 inches of the bar rack after the first set of three trials with both bypass systems operated together.

Test Day	Bypass Test Condition	Test Duration (hours)	Bar rack spacing (inches)	Replicate Trial	Number of Eels	Previously Tested Eels
1	vertical and horizontal	4	2	1	30	0
2	vertical and horizontal	5	2	2	30	0
3	vertical and horizontal	6	2	3	30	30
4	horizontal only	6	2	1	30	0
5	horizontal only	6	2	2	30	0
6	horizontal only	6	2	3	30	30
7	vertical only	6	2	1	30	0
8	vertical only	6	2	2	29	0
9	vertical only	6	2	3	30	30
10	baseline – no bypasses	6	2	1	30	0
11	baseline – no bypasses	6	2	2	29	0
12	baseline – no bypasses	6	2	3	30	30
13	vertical and horizontal	6	1	1	30	30
14	vertical and horizontal	6	1	2	30	30
15	vertical and horizontal	6	1	3	30	30
16	vertical only	6	1	1	30	30
17	vertical only	6	1	2	30	30
18	vertical only	6	1	3	30	30



Figure 3-4. Video image of an eel entering the peripheral entrance of the horizontal bypass.



3.1.4 Data Analysis

The primary metric for assessing the performance of the bypass systems with silver eel was bypass efficiency (B_E):

$$B_E = B_N / (B_N + E)$$

where B_N is the total number of eels recovered from the bypass collection tank during a trial and E is the number of eels entrained through the bar rack (i.e., the total number of eels recovered downstream of the bar rack at the end of a trial). Estimates of bypass efficiency were calculated for individual trials and using pooled-replicate data from the three trials compiled for each test condition. Trials from the combined horizontal and vertical bypass configuration with the 2-in bar rack were removed from statistical analyses due to the differences in test duration and absence of a 16-inch high perforated plate on the bottom of the rack. Results from trials conducted with the bar rack only (i.e., no bypass) served as a baseline condition (i.e., control) for entrainment.

For all statistical tests, an α level of 0.05 was used to determine statistical significance. A two-way ANOVA and post-hoc analysis of least square means with Tukey-adjusted p -values were used to test for significant differences in the frequency of eels bypassed among bypass configurations and bar rack spacings. Residuals were checked for normality and homogeneity using a Shapiro-Wilk normality test and a Levene's test, respectively. The same analyses were applied to determine if vertical bypass placement affected entrance frequency.

Eel length and temperature were examined for differences among the test condition with respect to bypass use and entrainment through the bar racks using a one-way ANOVA followed by a Tukey HSD test.

Underwater IR camera imaging and the PIT tag detection data were used to determine the following:

- Elapsed time until first encounters with a bypass entrance
- Elapsed time until bypass passage
- Frequency of approaches (defined by volitional movement) to bypass entrances
- Acceptance or rejection of an entrance
- Orientation during bypass entrance approach (head or tail first)

A two-proportions z-test with continuity correction was used to determine if entry success differed between peripheral (outer edge) and central entrances in the horizontal zig-zag bypass. This assumed that the success rate of eels that attempted to enter the horizontal bypass was independent of bar rack spacing and presence of a vertical bypass in the flume.

A non-parametric Wilcoxon rank-sum test was performed to determine if the frequency of entry attempts differed between the horizontal zig-zag and vertical bypasses. We combined



observations under the assumption that each bar rack spacing was observed in similar enough proportions for the horizontal (43% for 1 inch spacing) and vertical (57% for 1 inch spacing) bypasses to avoid bias.

3.1.5 Computational Fluid Dynamics (CFD) Analysis of Test Facility Hydraulic Conditions

The CFD simulations of the flume test facility were conducted to determine flow patterns approaching and in the vicinity of the bypass systems and bar racks. The flow domain (i.e., test facility configuration) was recreated in 3D CAD format and meshed to create the solution space for the CFD model. The flume model was meshed with a combination of hexahedral and tetrahedral elements.

The commercially-available CFD software ANSYS-Fluent v19.0 was used to run the flume simulations. Turbulence was simulated using the two-equation k-omega SST model with a continuity equation and momentum equation in each of the three principal axes. The flow was assumed to be isothermal with constant properties (density and viscosity) corresponding to the average water temperature during flume testing.

A CFD simulation of the flume test conditions was created beginning 20 ft (one flume width) upstream of the bar rack. A uniform velocity profile was applied with an approach velocity of 2 ft/s (i.e., the channel velocity used for flume testing), which produced a flow rate of 320 cfs. A volume flow rate of 0.3 cfs exiting the domain was set for each of the vertical bypasses and a flow rate of 0.5 cfs was set for the horizontal bypass.

The bar rack was simulated as a porous media with an inertial loss coefficient of 0.9. This resistance corresponds to bar slats that are 0.5 inches thick and 3.5 inches long with a 1 inch clear spacing between bars. Additionally, for test conditions that included the perforated plate overlay on the lower 16 inches of the bar rack and behind the centered vertical bypass, a 60% open area perforated plate was used with a loss coefficient of two.

The CFD model was used to determine the flow split to all the entrance holes in the vertical and horizontal bypasses. The flow split is determined by the pressure difference between the local areas inside and outside of the holes, which means that the flow split is dependent on both the flow patterns inside and outside bypass piping.

3.2 Results

The laboratory evaluation of the two eel bypass systems was conducted from October 18 to November 29. Test fish ranged from 350 to 1,175 mm in length with an overall mean of 782 mm. Mean length by test condition ranged from 760 to 805 mm (Figure 3-5). Length was not significantly different among test groups evaluated with the different test conditions (ANOVA, α -level = 0.05). During the 6-week testing period, water temperature in the flume ranged from 7.4 to 14.6 °C and was significantly different among testing configurations (ANOVA, α -level = 0.05), except between test with the horizontal bypass alone and vertical bypasses with the 2-inch bar racks (Figure 3-6). Assessment of physical condition demonstrated that injury rates for eels evaluated with each test configuration were very low (less than 2.5% by recovery location



for all trials and test conditions combined; Table 3-2). Observed injuries were likely pre-existing or due to handling and testing rather than bypass use or entrainment.

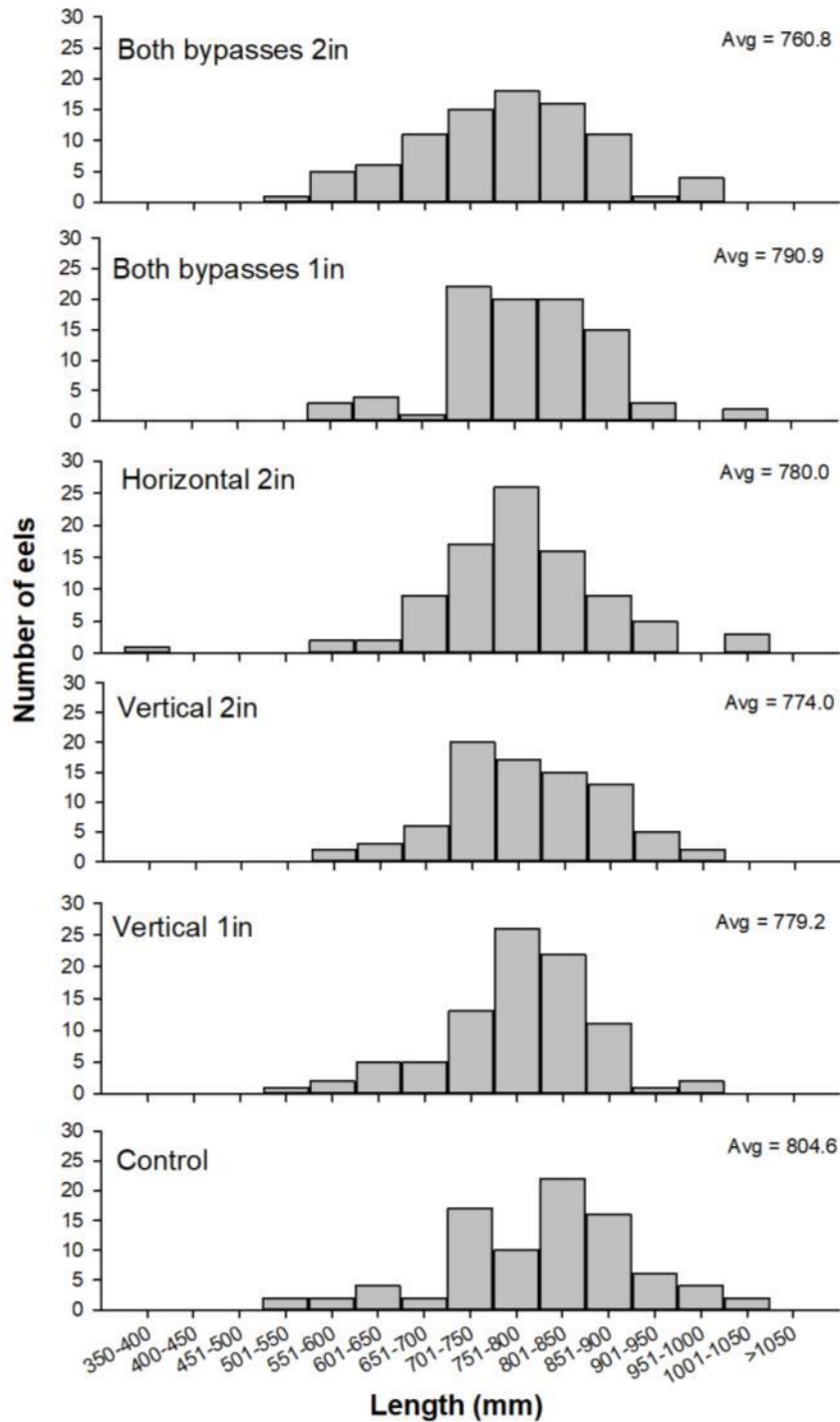


Figure 3-5. Length frequency for eels tested by bypass configuration (bypasses tested and bar rack spacing).

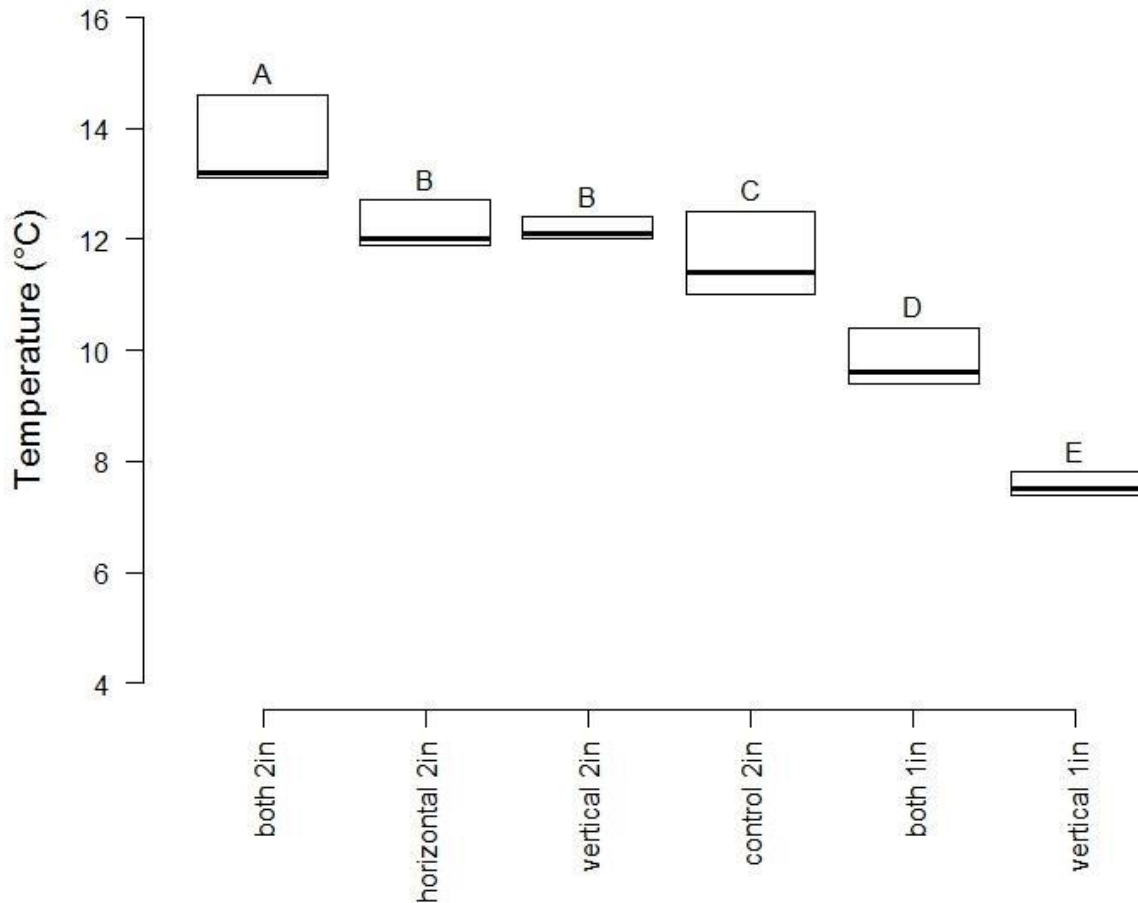


Figure 3-6. Flume water temperature ranges for trials conducted with each test configuration (bypasses and rack spacing; presented in order of testing). Test conditions without a letter in common had statistically significant differences in temperature.

Table 3-2. Percent of test fish with external injuries by recovery location (data from all trials and test conditions combined).

Passage Route/ Recovery Location at End of Trial	Hemorrhages (%)	Lacerations (%)	Total (%)
Horizontal bypass	1.6	0.8	2.4
Vertical bypass	0.0	0.0	0.0
Entrained (2-inch rack)	1.1	0.0	1.1
Entrained (1-inch rack)	1.1	0.5	1.6
Upstream	0.7	0.0	0.7
Total	1.3	0.1	1.7



3.2.1 Bypass Efficiency

For the initial set of trials that were conducted with both bypass systems, a 2-inch bar spacing, and no perf-plate overlay on the lower 16 inches of the bar rack, the entrainment rate (percentage of all fish released) was about 39% and bypass efficiency was 40.4% (Table 3-3). A third of the 90 fish released for this set of conditions remained upstream of the bar racks for the duration of the trials, and two fish could not be located. Following these initial trials, the perf-plate overlay was installed over the lower 16 inches of the 2-inch bar rack as a means to further reduce entrainment (i.e., physically exclude eels near the bottom). Following installation of the perf-plate, each bypass design was tested separately. Entrainment was lower (18%) and bypass efficiency higher (75%) for the trials with just the horizontal zig-zag bypass (Table 3-3). For the evaluation of just the vertical bypasses, entrainment was significantly higher (60.7%) than it was for the two previous configurations and bypass efficiency was significantly lower (14.3%) (Table 3-3). The total number of fish that remained upstream during tests with each bypass system evaluated separately was similar to tests with the two systems evaluated together with the 2-inch bar rack (Table 3-3). The entrainment rate for the evaluation of the 2-inch bar rack without either bypass system operating was about 59% and the number of fish that remained upstream was higher (36) compared to tests with the bypass systems tested together and separately (Table 3-3). These results demonstrated that the vertical bypasses did not reduce entrainment from the baseline condition (i.e., bar rack only) and only provided marginal benefits as an alternative downstream passage route.

After reducing the clear bar spacing on the rack to one inch, entrainment decreased and bypass efficiency increased significantly for tests with both bypass systems together and the vertical bypasses alone (these tests also included the perf-plate overlay on the lower 16 inches of the bar rack) (Table 3-3). Also, fewer eels remained upstream at the end of each trial with the 1-inch bar rack, particularly when both bypass systems were tested together (Table 3-3). Additionally, similar to tests with the 2-inch bar rack, most bypassed eels (about 85%) used the horizontal zig-zag system during 1-inch bar rack trials conducted with both bypass designs.

Eels that were entrained through the 1-inch bar rack had head widths less than or equal to about 1.2 times the 1-inch bar spacing (i.e., eels with measured head widths of 1.2 inches or less were physically capable of passing through the 1-inch clear bar spacing). A lower percentage of eels moved downstream (i.e., were bypassed or entrained) when using previously tested eels during the third trial of each test condition evaluated with the 2-inch bar rack (Figure 3-7). A similar pattern was observed for trials with the 1-inch rack, for which all test fish had been evaluated previously and the third trial comprised 15 fish from each of the first two trials of a test condition.



Table 3-3. Summary of bypass and entrainment data by test condition.

Test Condition	16-inch Perf-Plate Overlay on Lower Rack	Number Released	Number Entrained	Number Horizontal Bypass	Number Vertical Bypass	Number Recovered Upstream of Bar Rack	End of Test Location Unknown	Percentage Entrained ¹	Bypass Efficiency ² ±95% CI (%)
Both bypass systems	No	90	34	19	4	30	2	39.1	40.4 ± 12.8
Horizontal zig-zag bypass	Yes	90	16	48	--	26	0	17.8	75.0 ± 10.6
Vertical bypasses	Yes	89	54	--	9	26	0	60.7	14.3 ± 8.7
No bypass (baseline)	No	89	52	--	--	36	1	59.1	--
Both bypasses	Yes	90	7	60	11	12	0	7.8	91.0 ± 6.3
Vertical bypasses	Yes	90	21	--	44	25	0	23.3	67.7 ± 11.4

¹ Percentage entrained is the number of eels entrained divided by the total recovered from all locations (bypassed + entrained + upstream).

² Bypass efficiency is the number of eels bypassed divided by the total recovered from downstream locations (bypassed + entrained).

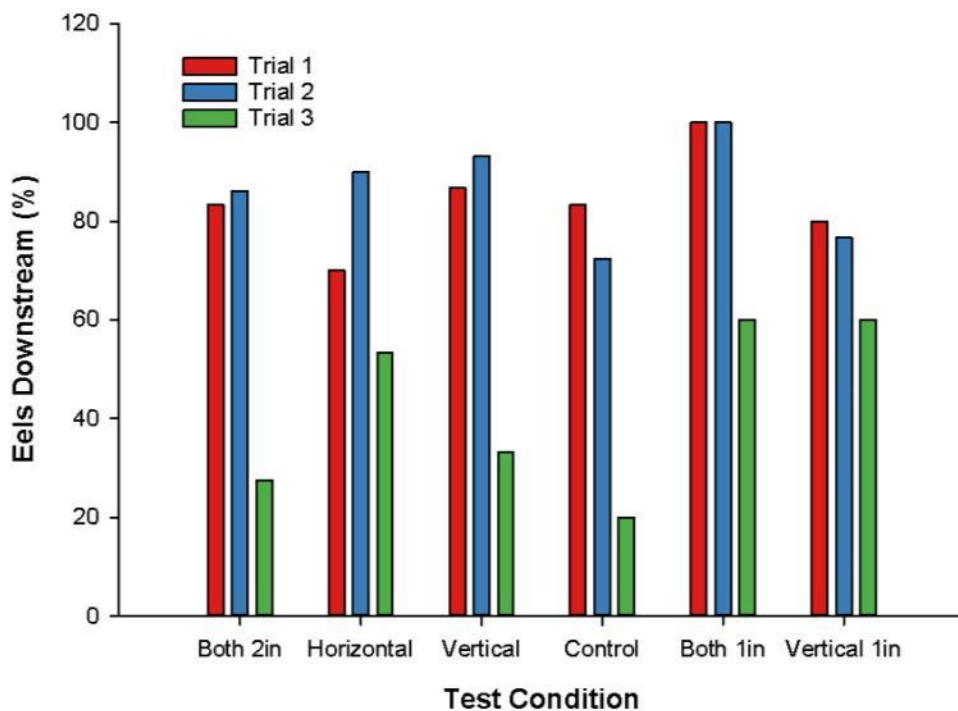


Figure 3-7. Downstream movement (entrained or bypassed) of eels by test condition (bypass type and bar rack spacing). For tests with the 2-inch bar rack, the first two trials with each test condition were conducted with naïve eels (i.e., not previously tested) and third trial comprised 15 fish from each of the first two trials. All fish evaluated with the 1-inch bar rack had been previously tested with the 2-inch bar rack, but the same pattern of using 15 fish from each of the first two trials was repeated.

Bypass configuration (ANOVA, $p = 0.004$) and bar rack spacing (ANOVA, $p = 0.007$) both had a statistically significant effect on bypass frequency. Specifically, post-hoc analysis indicated that the 1-inch bar rack produced significantly higher bypass frequency than the 2-inch rack, and the horizontal zig-zag bypass passed significantly more eels than the vertical bypasses (Table 3-4). Both bypasses in tandem passed considerably more eels than the vertical bypasses alone, but statistical significance (at an α -level of 0.05) was not detected when these conditions were compared due to limited power from the experimental design which did not include comparable testing of both bypasses with a 2-inch rack (i.e., the evaluation of both bypasses together with the 2-inch rack was the only test condition that did not include the 16-inch perforate overlay on the lower rack).



Table 3-4. Post-hoc comparison of means analyzing differences in bypass frequency within two significant main-effect factor variables: bypass configurations and bar rack spacing. Asterisks indicate statistical significance at an α -level of 0.05

Comparison	Degrees of Freedom	Tukey-adjusted p -value
1-inch rack vs. 2-inch rack	8	0.007*
Horizontal vs. Both	8	0.666
Horizontal vs. Vertical	8	0.009*
Both vs. Vertical	8	0.054

The location of the vertical bypasses also influenced bypass use for tests that included the vertical design. The vertical bypass located more towards the center of the rack bypassed significantly more eels than the bypass secured to the flume wall on one end of the bar rack (ANOVA, $p = 0.017$). The lower frequency of use for the vertical bypass positioned against the wall may have been due to flow turbulence and an apparent vortex on the downstream side of the panel attached to the bypass conduit. Video observations indicated that these conditions were difficult for eels to negotiate and caused fish that encountered them to be “tossed” around.

When tracking the passage history of individual eels across multiple trials and test conditions, the percentage of eels that used the horizontal bypass or vertical bypass at least once 37.1% and 23.6%, respectively (Table 3-5). The percentage of eels that remained upstream during at least one trial and were entrained during another was also relatively high (32.5%). Only 4.2% of test fish used both the horizontal and vertical bypasses across multiple trials. The percentage of eels that were bypassed during one or more trials and either were entrained or remained upstream during others was 25.3 and 21.5%, respectively. The variability in outcomes for individual fish across multiple trials demonstrates the lack of predictability in how eels will respond when presented with the same or similar conditions when encountering a bar rack and searching for a downstream passage route.

The average time for the first eel to successfully use a bypass after release was less than 9 minutes, except for the trials with the vertical bypasses and 2-inch bar spacing which had an average time of about 145 minutes before an eel was bypassed (Table 3-6). The much longer time before a bypass event for this test condition was likely due to fish being entrained more readily with the wider bar spacing and not having a bottom bypass option. Over 50% of bypass events occurred within the first 80 minutes following release (Figure 3-8) and more than 90% occurred within 240 minutes. The cumulative rate of bypass use was similar for the two bypass designs (Figure 3-8).



Table 3-5. Individual eel bypass history by number and percent of eels that used each bypass, were entrained, or remained upstream. Some categories are not mutually exclusive and eels were tested either two or three times.

Bypass Use/Recovery Location	Number of Eels	Percent of Total (237)
Horizontal and Vertical Bypass	10	4.2
Horizontal Bypass	88	37.1
Vertical Bypass	56	23.6
Bypassed and Entrained	60	25.3
Bypassed and Upstream	51	21.5
Bypassed Twice	56	23.6
Always Bypassed	30	12.7
Upstream and Entrained	77	32.5

Table 3-6. Mean elapsed time until first bypassed eel.

Bar Rack Spacing (inches)	Bypass Configuration	Mean Elapsed Time (minutes)
2	Both bypass systems	3.2
	horizontal zig-zag bypass only	4.1
	Vertical bypass only	145.1
1	Vertical bypass only	6.3
	Both bypass systems	8.7

3.2.2 Behavioral Analysis

A subset of the 15 bypass openings (7 on the horizontal conduit and 4 on each of the vertical conduits) were monitored with underwater video cameras during each trial. The cameras were repositioned several times so that coverage was provided for each bypass opening for multiple trials. Behavioral observations were grouped by bypass location (i.e., horizontal openings near the flume walls and away from the walls; vertical openings in the lower and upper conduit sections adjacent to the flume wall and closer to the middle of the flume). Video observations of test fish behavior near monitored bypass openings revealed that about 42% of approaches to an opening resulted in an attempt to enter (Table 3-7). Of those that attempted to enter, the overall success rate was 36.7%. All successful entries were completed by eels entering head first (Table 3-8). Tail first entrance attempts appeared to produce slight startle and/or avoidance reactions, which typically triggered an escape response away from an opening. A similar escape response was sometimes exhibited for head first entry attempts. Unlike the tail first attempts, eels did not always swim away from a bypass opening after an initial startle reaction when approaching head first.

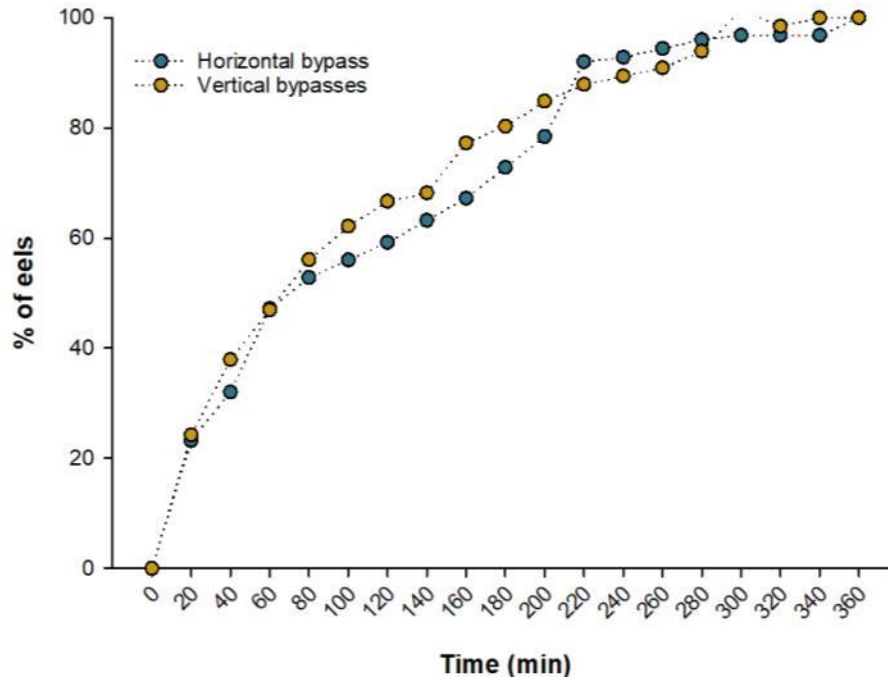


Figure 3-8. Cumulative time to bypass passage for eels that used each bypass system (data from all test conditions combined).

Table 3-7. Observed eel behaviors when fish approached and encountered bypass openings (data from all test conditions combined). Camera locations are categorized by bypass design, upstream (US) or downstream (DS) facing opening on the horizontal system, adjacent to or away from the wall (mid flume) and top or bottom openings on the vertical systems.

Bypass Opening Camera Location	Number of Trials with Camera	Approaches to Bypass Opening	Approaches per Trial	No Interest	Entry Attempt Outcomes				Entry Attempts ¹ (%)	Successful Entries ² (%)
					Reject Head First	Enter Head First	Reject Tail First	Enter Tail First		
Horizontal-All	29	418	14.4	235	95	70	18	0	43.8	38.3
US - Mid	9	102	11.3	61	18	22	1	0	40.2	53.7
DS - Mid	8	178	22.3	113	28	27	10	0	36.5	41.5
Wall - Right	6	102	17.0	41	43	13	5	0	59.8	21.3
Wall - Left	6	36	6.0	20	6	8	2	0	44.4	50.0
Vertical - All	31	166	5.4	98	37	22	9	0	41.0	32.4
Mid - Top	5	9	1.8	6	2	1	0	0	33.3	33.3
Mid - Bottom	11	100	9.1	51	25	16	8	0	49.0	32.7
Wall - Top	11	40	3.6	25	10	4	1	0	37.5	26.7
Wall - Bottom	4	17	4.3	16	0	1	0	0	5.9	100.0
Totals	60	584	9.7	333	132	92	27	0	43.0	36.7

¹ Total number of entry attempts divided by total approaches.

² Total successful entries divided by total entry attempts.



Table 3-8. Observed bypass entry success rates by orientation.

Eel Position	Entry Attempts	Entry (%)
Head First	224	41.1
Tail First	27	0.0
Overall	251	36.7

The horizontal zig-zag bypass had significantly greater (Wilcoxon rank-sum, $p < 0.001$) entry attempts per bypass entrance (5.7) than the vertical bypasses (1.9). Although not statistically significant (Wilcoxon rank-sum, $p = 0.110$), the lower entrances of the vertical bypass had more entry attempts per observed trial (2.8) than the top entrances (1.1). The peripheral bypass openings on the horizontal bypass had significantly fewer successful entry rates (30%) than the centrally located entrances (51.6%) (two-proportions z-test, $p = 0.009$) (Table 3-9). Eels that entered the peripheral holes were observed to have more frequent escape responses. Some eels were observed swimming within the bypass for 30 minutes or more and possibly utilizing low pressure areas at the peripheral ends of the bypass.

The first observation of an eel was noticeably later for the third trial of each set of test conditions (i.e., previously-tested eels from the first two trials) across all bypass configurations. In the control configuration, for which there were no bypass structures in the flume to rest behind, the first observation of an eel averaged 32 minutes longer from release compared to test conditions with one or both bypass systems (Table 3-10).

Table 3-9. Observed head-first bypass entry attempts and success rates.

Bypass Opening Camera Location	Number of Trials with Camera	Entry Attempts	Entry Attempts/Trial	Entry (%)	Entries/Trial
Horizontal Bypass	29	165	5.7	42.4	2.4
Middle	17	95	5.6	51.6	2.9
Wall	12	70	5.8	30.0	1.8
Vertical Bypasses	31	59	1.9	37.3	0.7
Left Bottom	4	1	0.3	29.4	1.3
Right Bottom	11	41	3.7	40.5	1.5
Left Top	5	3	0.6	24.3	3.4
Right Top	11	14	1.3	50.0	2.5

Table 3-10. Mean elapsed time before observed bar rack encounter in control trials.

	Naïve eels	Experienced eels
Mean (min)	0.95	33.8
SD (min)	0.35	29.6
Cameras (n)	10	4



3.2.3 CFD Modeling Results

As the channel flow approaches the bar rack and encounters the vertical bypasses, separation zones are created by the bypass conduit deflector plates. These separation zones produce a relatively weak reversed flow moving back towards the bypass openings (Figure 3-9). The reversed flow behind the deflector plates of the vertical bypass located away from the walls is stronger than the reversed flow behind the deflector of the bypass attached to the flume wall.

As the flow approaches the bar rack along the floor of the flume, it encounters the array of stiff brushes located just upstream of the horizontal bypass. The brush material forces the flow to move up and over the horizontal bypass conduit. This creates a large, strong recirculation zone that flows back upstream along the floor from the bar rack to the horizontal bypass. This zone of reversed flow is substantially larger and stronger than those behind the vertical bypass deflector plates, most likely because the brush material and horizontal bypass are further upstream compared to the vertical bypasses.

The CFD modeling included evaluations of the hydraulic conditions with and without the perforated-plate on the low 16 inches of the bar rack to examine any potential effects of this blockage that could influence eel behavior and bypass use. The flow separation produced by the brush material resulted in the flow approaching the lower portion of the bar rack to pass over the perforated-plate at a depth similar to the condition without the perforated-plate. Consequently, the flow patterns upstream of the lower portion of the bar rack with and without the perforated-plate were not substantially different (Figure 3-10 and Figure 3-11). The similarity in flow conditions with and without the perforated-plate indicates the 16-inch high blockage was effective as a physical barrier for reducing entrainment.

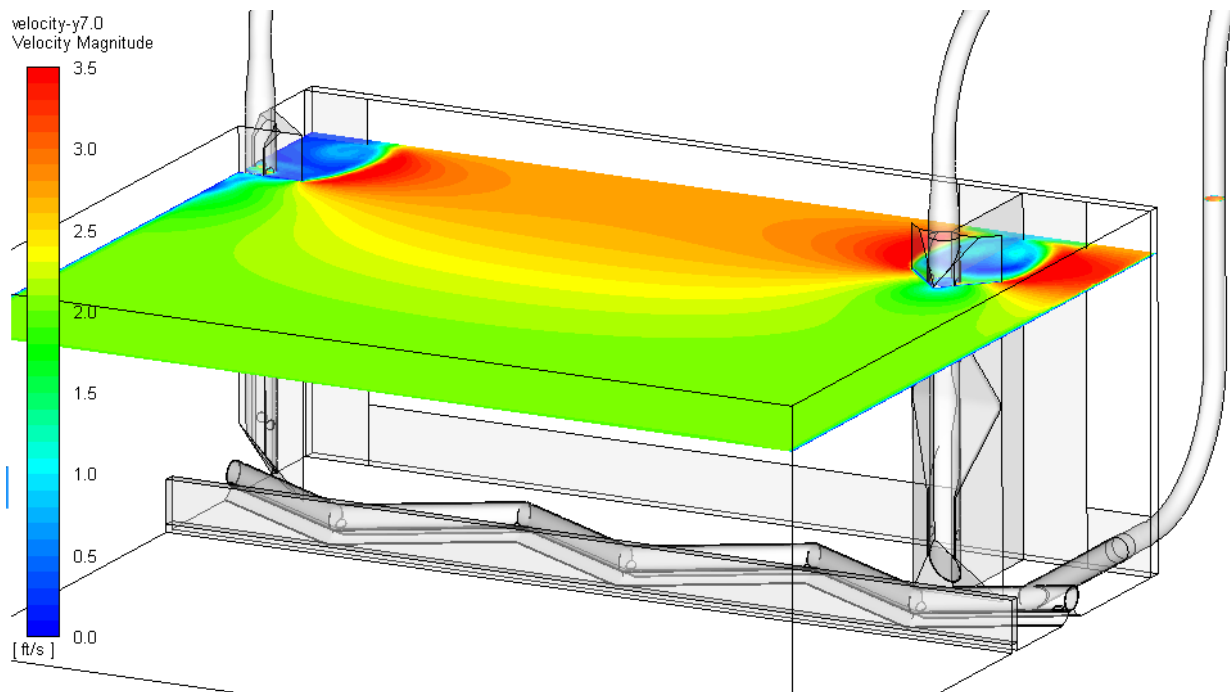


Figure 3-9. Velocity around the vertical bypass deflector plates (ft/s)

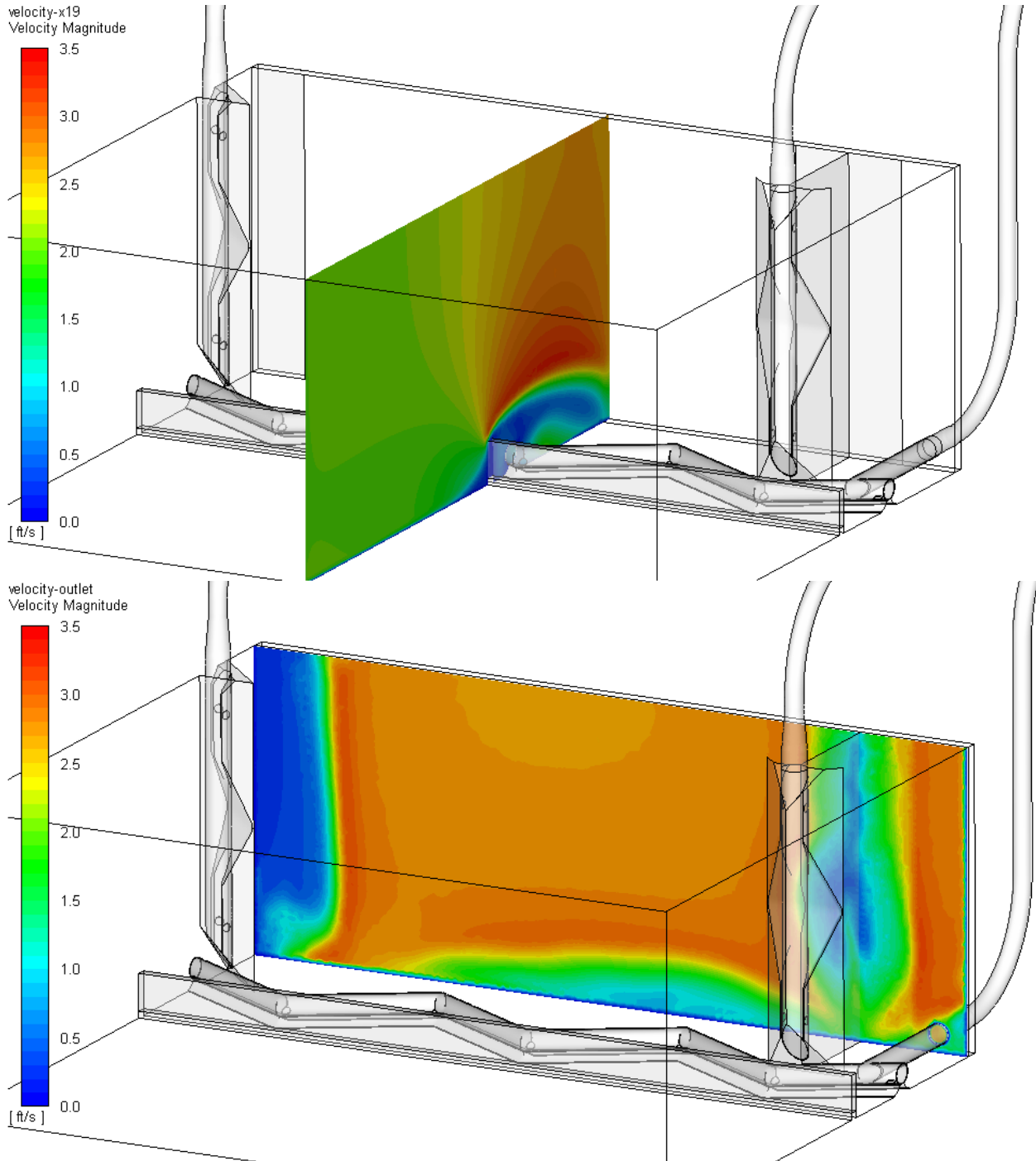


Figure 3-10. Velocity approaching bar rack without perforated-plate overlay on lower 16 inches of bar rack.

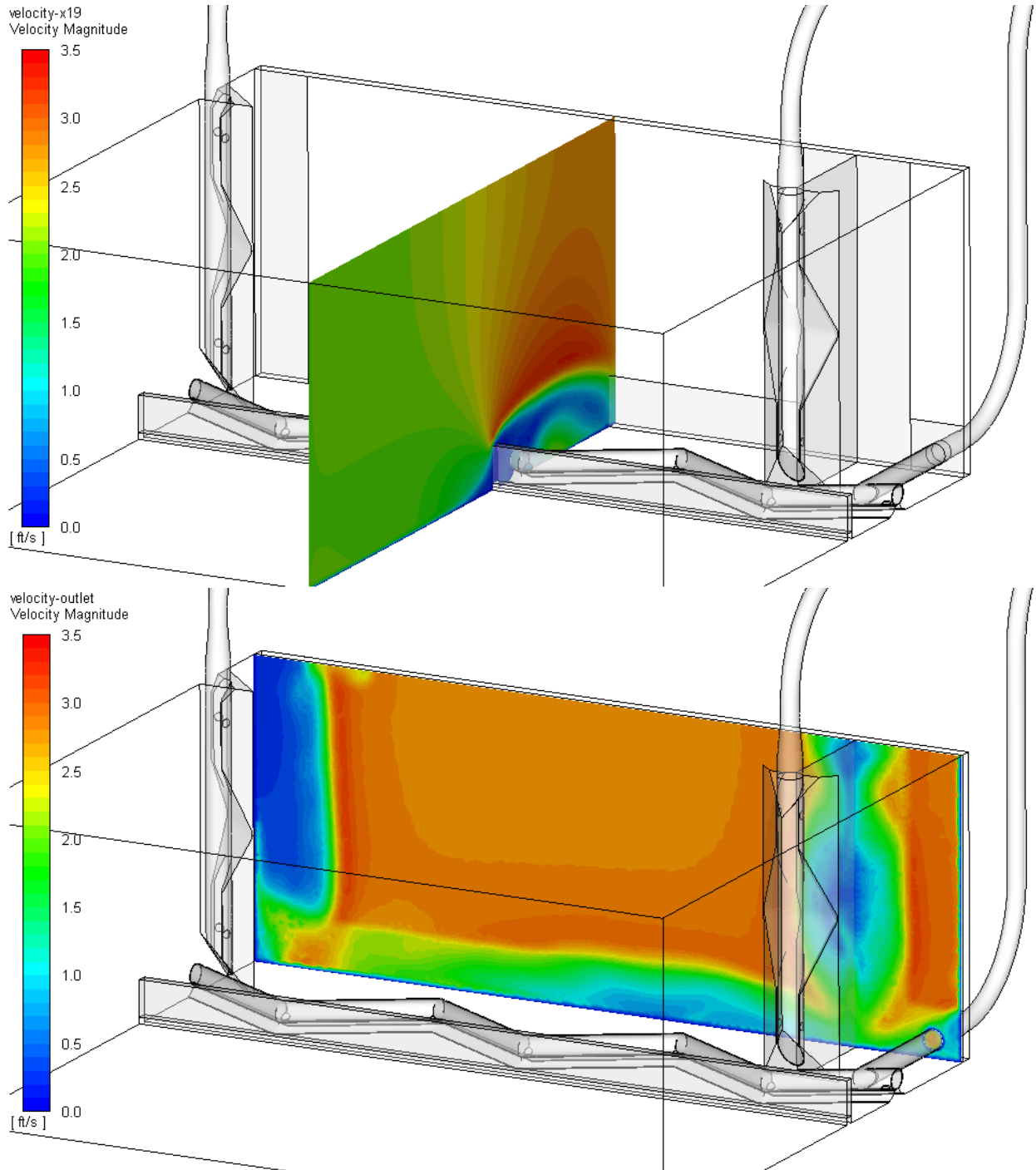


Figure 3-11. Velocity approaching bar rack with perforated-plate on lower 16-inches of bar rack.

All bypass entrance openings were the same diameter (2.63 inches) and the flow into each bypass was intended to maintain a constant average velocity of about 2 ft/s through the entrances. In both vertical bypass systems, there were four entrances in each of the 6-inch diameter conduits, so the flow split evenly between all 4 entrances.



In the horizontal bypass, there were seven entrances in the 6-inch diameter conduit, which produced higher velocities inside the conduit compared to the vertical bypasses. Additionally, there was higher head loss through the pipe due to the bends of the zig-zag design. This causes a large pressure difference between the upstream and downstream ends of the pipe, resulting in a significant difference in flow rate among the openings of the horizontal bypass. With a uniform flow split, each of the seven entrances would receive about a 14% share of the intake flow. The CFD model demonstrated that five of the openings had a flow fraction between 12% and 16% and two varied significantly from the theoretical average flow. Entrance 7 only had 5% of the horizontal bypass flow and entrance 10 had 24% (Figure 3-12).

3.3 Laboratory Evaluation Conclusions and Discussion

The KLAWA horizontal zig-zag bypass system had significantly greater bypass efficiencies than the vertical bypass systems, but the combination of both bypasses operating together produced the highest bypass efficiencies with the 16-inch high perforated-plate on the lower portion of the bar rack. Bypass efficiency was relatively high for the horizontal zig-zag bypass with 2-in bar rack spacing (75%) and for both bypasses with 1-in spacing (91%). Reduction of bar spacing from 2 to 1-in significantly improves bypass efficiency by reducing entrainment. The horizontal zig-zag bypass appears more efficient than the vertical bypasses alone; however, the combination of both vertical and horizontal zig-zag bypasses resulted in the highest bypass efficiency. Had the 16-in bottom perforated plate been installed for the initial testing of both bypasses with 2-in spacing, it is believed that similar high bypass efficiency would have been achieved. Mid-depth and bottom bypasses have been shown to be more effective. A study in France found three to four times more eels using a bottom bypass than ones near the surface (Gossett et al. 2005). The University of Kassel in Germany, which developed the KLAWA horizontal zig-zag system, found greater than 90% of the eels entered the bypass within 40 minutes in laboratory testing with a 0.5-in bar rack spacing (Hassingier and Hübner 2009). However, available field data have demonstrated that eels typically will search vertically and horizontally along a trash rack looking for an outlet before entering a bypass system or passing through trash rack bar openings and through a turbine (Gosset et al. 2005, Brown et al. 2007) suggesting that the use of both vertical and horizontal zig-zag bypasses combined would allow access to a bypass for those eels searching vertically along the trash rack.

There have been very few advancements and developments in bypass systems for eels in the past. Development of an airlift bypass system for silver eels which uses rising air bubbles to draw and pass flow through a bypass pipe had an attraction efficiency of 76.2% with 85.9% of the attracted eels successfully entering the airlift (Baker et al. 2019, Haro et al. 2016). The airlift system uses a bottom entrance based on the assumption that eels tend to approach intakes deeper in the water column. However, with respect to eel behavior and passage efficiency, the airlift system does not necessarily offer any biological advantages to conventional bypass designs that use gravity flow (surface bypasses) or siphons (submerged bypasses). That is, the airlift system only provides a bottom entrance location, which limits the opportunity for discovery by eels that are searching throughout the water column for a downstream egress route.

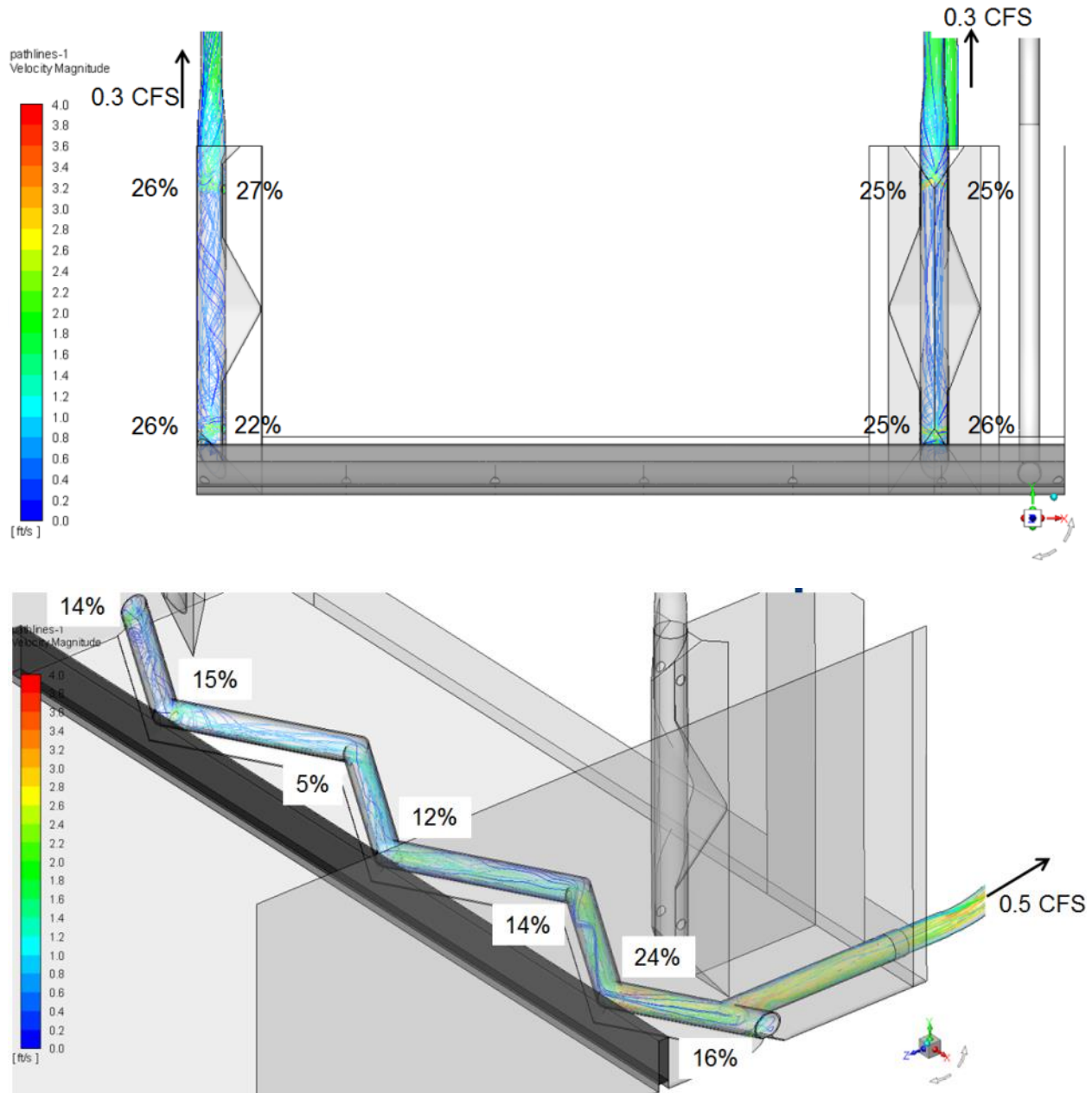


Figure 3-12. Flow split to the various openings in the vertical (top) and horizontal (bottom) bypasses

Overall, the majority of eels that used a bypass did so within the first hour with the exception of the vertical bypass with the 2-in bar rack spacing. Indicating that it may take longer for eels to find the vertical bypass entrances compared to the horizontal zig-zag. However, when the smaller bar rack was introduced, limiting the number of eels that could move downstream through the rack (entrained) and potentially increasing vertical searching, eels found the vertical bypass entrances sooner. There was no clear pattern in individual eel movement between trials, but experienced eels did seem to avoid moving downstream and would take longer to appear on video near the bypasses when compared to naive eels. This finding stresses



the importance of using naïve eels to avoid behavioral changes. However, the experimental design accounted for this by ensuring that eels in the first two trials of each configuration were naïve or had not been exposed to testing in over a month. This deviation may indicate some sort of behavioral avoidance or learning from previous experiences and may indicate changes in bypass efficiency in systems with successive bypass systems at multiple sites.

A number of important behaviors were observed by video analysis. Most notably, the horizontal zig-zag bypass had greater entry attempts per observed bypass entrance than the vertical bypasses. This difference is likely explained by the demersal behavior of eels observed while moving about in the flume. The peripheral entrance holes in the horizontal zig-zag bypass had less successful entry rates than the centrally located entrances. Eels that entered the peripheral holes were observed to have more frequent escape responses, perhaps initiated by differences in entrance shape or flow velocity. The vertical bypass cameras, especially those focused on the bypass secured to the wall, observed eels being tossed around in eddies or vortices for sometimes up to multiple minutes. The addition of perforated plate on the leading edge of the vertical bypasses did not seem to alter these eddies. These unique vortices may explain the lower bypass efficiency and number of entrance attempts seen for the vertical bypass.

Modifications based on the laboratory results, such as reducing eddies and adjusting peripheral entrances, could further increase bypass efficiency in the future. The vertical and horizontal zig-zag bypass designs take advantage of known eel behaviors at hydro turbine intakes, including bottom-orientation and searching throughout the water column and side-to-side when bar racks are encountered. Both bypass systems provide multiple entrances over the length of each system, increasing the opportunity for discovery of a bypass entrance and passage efficiency.



4.0 Field Evaluation

The relatively high bypass efficiencies observed during laboratory testing with the one inch clear spacing on the bar rack indicated that the two eel bypass designs had potential for effective application at hydropower projects. However, because laboratory testing cannot fully replicate field conditions or behavior of fish in their natural environment, field testing is required to validate the laboratory results and assess whether design and operational modifications may be needed to optimize performance. The field evaluation of the two eel bypass designs was conducted in the fall of 2019 at a small hydropower project using silver American Eels collected from a Maine river during their spawning outmigration and tagged with acoustic telemetry transmitters. Similar to the laboratory evaluation, CFD modeling was conducted to characterize the hydraulic conditions tagged eels experienced in the vicinity of the bypass systems and intake structure following release into the turbine intake channel of the study site.

4.1 Study Approach and Methods

4.1.1 Study Site

The field evaluation of the two downstream eel bypass systems was conducted at the Mine Falls Hydroelectric Project located on the Nashua River in Nashua, New Hampshire (Figure 4-1). The MFHP is owned by the city of Nashua and is operated by Essex Hydro. The project is operated as a run-of-river facility and consists of a 132-ft long spillway, three spillway sluices (one with a gate and two with stoplogs), a headgate structure, a power canal (forebay), an intake structure, and a powerhouse with two Kaplan turbines (Figure 4-2). The forebay channel is about 167 ft long with a width of 22 ft over the first 62 ft of its length downstream of the head gate structure, after which it gradually widens to maximum width of 36 ft at the trash racks. The depth of the channel also gradually increases from upstream to downstream due to the floor sloping downward as it approaches the intake. Depending on flow, depth at the upstream end of the channel is about 18 to 20 ft and at the intake it is about 20 to 22 ft. There is a bulkhead above turbine intakes that extends about 8 ft from the intake deck to the top of the trash racks (Figure 4-3). The trash racks have 3-in clear bar spacing. The project has two vertical Kaplan turbines, each with a generation capacity of 1,500 kW and a hydraulic capacity of about 990 cfs. Currently, downstream passage is accessible through a surface weir located at the waste gate on the riverside channel wall adjacent to the intake structure (Figure 4-2, Figure 4-3).

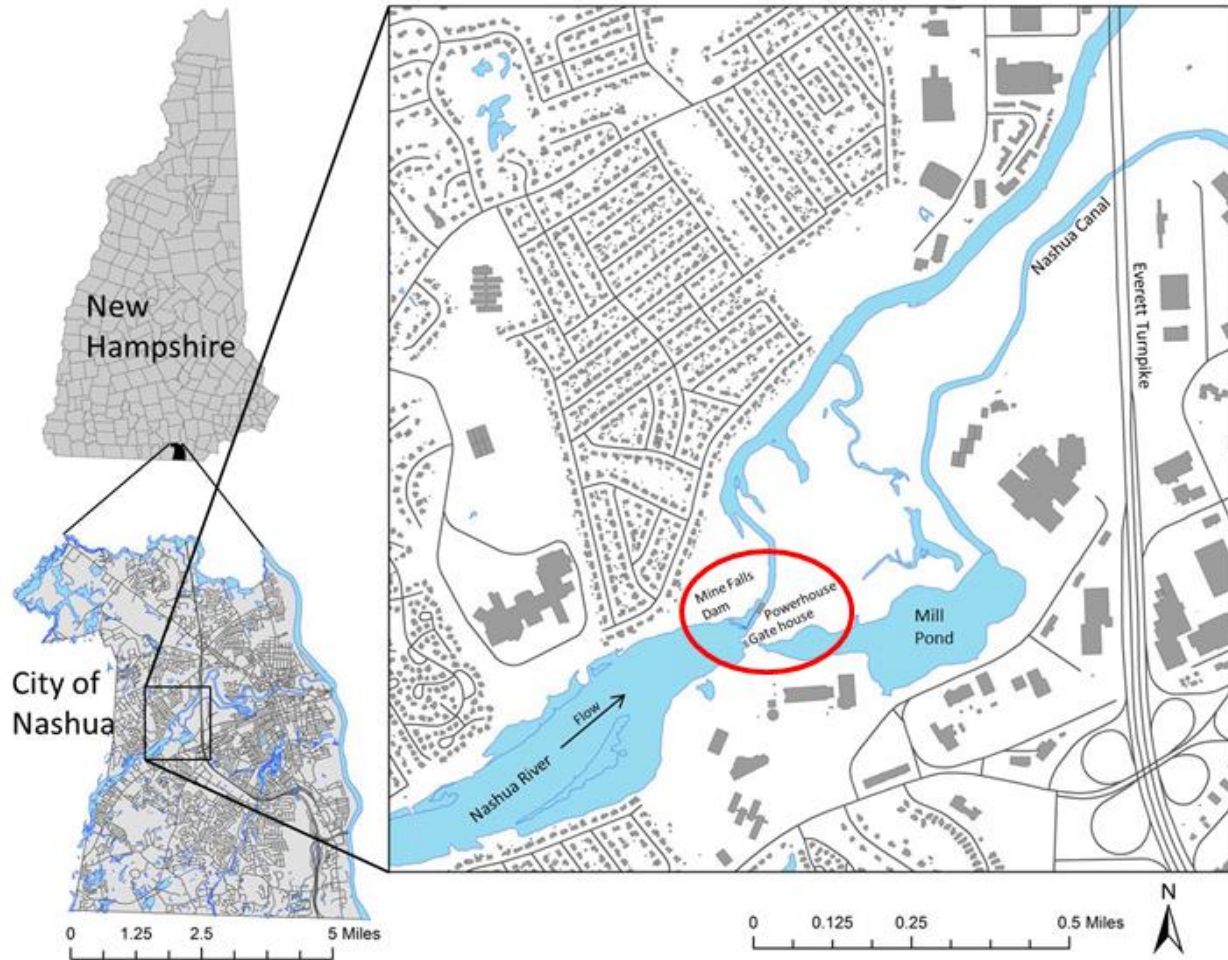


Figure 4-1. Location of the Mine Falls Hydroelectric Project. (Source: City of Nashua, Pre-Application Document)

4.1.2 Unit 1 Outage during Study Period

Due to a damaged runner that had to be repaired, Unit 1 was offline during the entire study period of the field evaluation. With only Unit 2 operational, the study could be not conducted under normal generating conditions for the project. The Unit 1 outage did not affect the ability to effectively evaluate the biological and operational performance of the eel bypass systems, but the study results may not accurately reflect performance metrics specific to the Mine Falls application when both units are operating. To avoid any negative impacts to Unit 2 operation (as demonstrated by CFD modeling of the power canal), the initially proposed configuration of the two bypass systems was not adjusted due to the Unit 1 outage (potential modifications investigated included moving the Unit 1 vertical bypass to the nose pier between the intakes of the two units or the center of the Unit 2 bar rack). Therefore, the vertical system installed on the center of the Unit 1 rack and the portion of the horizontal system at the base of the Unit 1 intake did not have any turbine flow passing by them.



Figure 4-2. Mine Falls Project configuration (inset photo shows dewatered forebay channel with turbine intake at downstream end).



Figure 4-3. Mine Falls turbine intake and surface bypass.



4.1.3 Design and Installation of Bypass Systems

Installation of the bypass systems at Mine Falls occurred in mid to late September of 2019. The vertical bypass system consisted of two vertical pipes and frame structures. One vertical bypass was located on the centerline of the Unit 1 turbine intake (river side unit) and the other was installed on the shore side wall (Figure 4-4 and Figure 4-5). The Klawa horizontal zig-zag bypass system was installed at the base of the trash racks (Figure 4-4 and Figure 4-5). Conduits transporting eels that entered each system discharged into one of two collection tanks (one for the vertical systems and one for the horizontal system) located in the upstream fish passage facility exit flume on the right (shore) side of the powerhouse (Figure 4-4).

The vertical bypass centered on the Unit 1 intake had 10 openings for eels to enter along its length, five on either side of the perforated plate panel that extends from the pipe centerline to the bar rack. Flow through the 10 openings totaled about 0.6 cfs. The vertical bypass installed on the shore side channel wall had six openings along its length, withdrawing about 0.3 cfs of total flow. The horizontal zig-zag bypass had 11 openings (5 on the upstream side of the pipe and 6 on the downstream side) withdrawing a total of about 0.6 cfs.

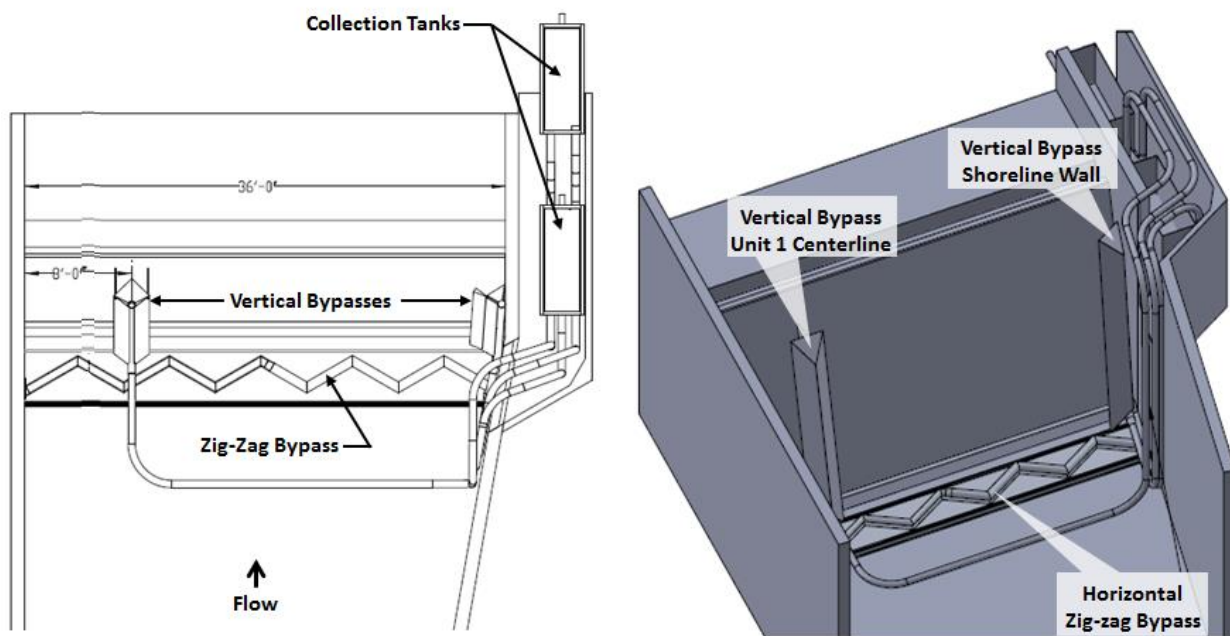


Figure 4-4. Design and location of vertical and horizontal bypasses installed at the Mine Falls Project.



Figure 4-5. Installation of the two eel bypass systems at Mine Falls.

In addition to the installation of the two bypass systems, the bar spacing on the trash racks was reduced to 1.13 inches (clear) at the Unit 2 intake to more closely match the spacing that produced the best results during the laboratory study (i.e., 1 inch clear). The existing bar spacing for Unit 1 was not reduced because no flow was entering through this intake with the unit out of service and the intakes to each unit are separated by the nose pier with no openings that would allow flow (or fish) to pass from the Unit 1 intake to the Unit 2 intake. Testing was also conducted with the existing 3-inch clear bar spacing to determine whether bar spacings larger than 1 inch clear may be sufficient for achieving high bypass efficiencies.

The reduced bar spacing (1.13 inches) was accomplished with slip bar grading placed over the existing bar rack structure when the bypass systems were installed. After testing with this narrower spacing was completed, the overlay was removed for testing with the existing 3-inch bar spacing. Consideration was also given to adding finer bar spacing (e.g., 0.5 inches) to a portion of the lower trash rack based on the findings from the laboratory evaluation conducted with perf-plate placed on the bottom 16 inches of the racks in test flume. However, CFD modeling of the Mine Falls intake with 0.5-inch bar spacing over the lower 16 inches of the Mine Falls trash racks indicated there would likely be significant negative effects on flow entering the turbine intakes, and velocities approaching the wider spacing above would



increase. Such conditions could increase the potential for impingement and entrainment of eels and, therefore, it was determined that the bar spacing should be the same across the entire depth of the trash rack (i.e., at the Unit 2 intake).

During the latter part of the field evaluation that included the third and fourth releases of tagged eels, debris build up became increased considerably and the bypasses were occasionally flushed with air to clear debris in the pipes and around the bypass openings. This procedure was not done consistently and only occurred on days when large amounts of leaf debris were seen in the collection tanks.

4.1.4 Eel Acquisition, Holding, and Tagging

Silver American Eels used in the field evaluation were collected in September 2019 from a sluice weir sampler at a hydropower dam on the St. Croix River in Maine. The eels that were captured for the study were actively migrating downstream to the ocean. Alden staff transported the eels from the collection site to fish holding tanks installed at Mine Falls, where they were held until tagged and released for the bypass evaluation. One hundred ninety-nine (199) eels were acquired for the field evaluation.

At least 48 hours prior to each release, 24mm HTI acoustic telemetry tags (Figure 4-6) were surgically implanted into 185 test fish. Passive integrated transponders (PIT tags) were also injected into the peritoneal cavity of these fish and into the remaining 14 eels (Figure 4-6). Fish length, weight, head width, and eye measurements were recorded for each individual eel tagged. The eye measurement was used to determine silvering stage as described by Durif et al. (2005). General physical condition and any external injuries were also recorded during the tagging process.

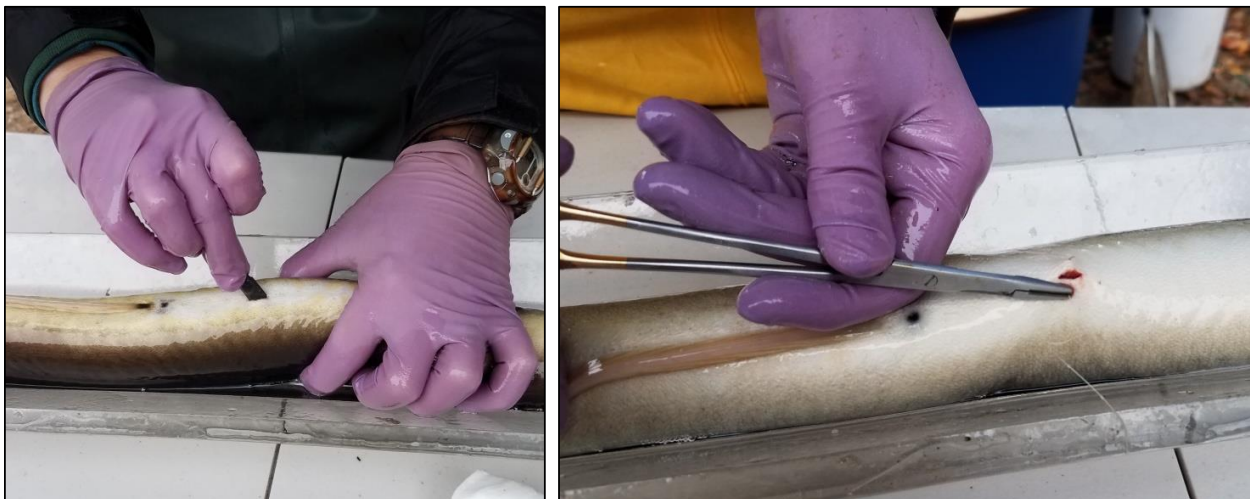


Figure 4-6. Surgical implantation of an acoustic tag into a test eel.



4.1.5 Testing Methods and Experimental Design

The field evaluation of the two eel bypass systems was designed to estimate bypass efficiencies for selected test conditions and to provide information on silver eel behavior as they approach and interact with the turbine intakes and bypass systems. The study methods and experimental design, as described below, were developed to provide the necessary data and information for making a determination of biological performance of the two bypass systems with respect to application of these technologies at a wide range of hydropower projects.

4.1.6 Test Conditions and Evaluation Procedures

The test conditions for the field evaluation of the two bypass systems included two clear bar rack spacings (1.13 and 3.00 inches) and multiple turbine gate openings (Table 4-1). The gate openings initially targeted for testing were 50 and 100%, each to be tested with both bar rack spacings. However, the actual gate openings tested were dependent on available river flow and debris loading, which impacted head loss and how much flow could be passed through Unit 2. Additionally, based on observed impingements at the highest gate opening tested (about 75%) during the second release of test fish, it was decided to limit the gate opening to no more than 50% for the third and fourth release groups. These constraints resulted in gate openings of approximately 40 to 75% being evaluated during the field evaluation (Table 4-1). Maintaining the gate opening at a specified level for each test was attempted for at least 48 hours after tagged eels were released, but flow and debris conditions often resulted in deviations from the targeted opening during this period. A decision was also made to test the wider spacing with only one release group because of the low bypass efficiencies observed during testing with the narrower spacing during the first two releases.

Three releases of 45 tagged eels were conducted with the 1.13-inch bar spacing and one with 64 tagged eels with the 3-inch spacing (Table 4-1). Both vertical bypasses and the horizontal zig-zag bypass were operating for all releases. All test fish were released in the center of the forebay channel between 8 and 8:30 pm. The release location was about 20 ft downstream of the forebay channel intake structure (approximately 120 ft upstream of the turbine intakes). Eels were released through a 20-ft long, 6-inch diameter PVC pipe approximately 5 ft below the water surface. Releases for each test condition were separated by at least three nights and usually occurred during or shortly after rain events that led to rising river flows.

Table 4-1. Test conditions for each of the four releases of tagged silver eels at Mine Falls.

Release	Acoustic and PIT Tagged Eels	Eels with PIT Tags Only	Bar Rack Spacing (inches)	Approximate Unit 2 Gate Opening (%)	Average Unit Gate Opening (%)	Unit 2 Flow (cfs)
1	45	--	1.13	50	51.2	288-422
2	45	--	1.13	75	79.0	300-647
3	45	--	1.13	40	34.4	171-202
4	50	14	3.00	50	58.6	163-540



The acoustic telemetry system and the bypass PIT tag antennae were monitor for tagged eels continuously from the release of the first test group until one week after the last group was released. Videos from the underwater conventional cameras and the DIDSON acoustic camera recorded continuously to monitor both native and tagged eels from one week before the first release until one week after the last release.

All eels recovered from the bypass collection tanks, which were checked on a daily basis, were scanned for acoustic and PIT tags. Any untagged eels (i.e., natural outmigrants from upstream river reaches) recovered from the collection tanks during the study period were measured, weighed, and examined for physical condition using the same procedures used for the tagged fish. All eels recovered from the bypass collection tanks were released downstream after being evaluated.

4.1.7 Eel Tracking and Monitoring

Eel behavior and downstream passage was monitored during the field evaluation of the two bypass systems using the following techniques:

- 3D acoustic telemetry system for positional tracking of tagged eels in the forebay channel.
- PIT tag system with an antenna in each bypass conduit to detect passage of tagged eels prior to collection.
- Underwater video cameras placed at several bypass openings to observe eel behavior during discovery of and interaction with openings (e.g., entry, attempted entry, rejection, entry followed by exit).
- A DIDSON acoustic camera to observe eels as they approach and interact with the intake structure and bypass systems.

An HTI 3D acoustic telemetry system was installed at the study site and included surface and bottom mounted model 590 hydrophones at four locations in the downstream half of the forebay channel with a total of nine hydrophones (Figure 4-7). These hydrophones provided tag detection data for 3D positioning of eels as they moved downstream and approached and moved around in the vicinity of the turbine intake and bypass systems. The acoustic tag detection data allowed spatial and temporal tracks to be developed for each tagged fish. A hydrophone was also installed on the pier nose between the entrance to the intake canal and the adjacent spill gate (Figure 4-7). Any tagged eels leaving the canal in the upstream direction were detected by this hydrophone. The acoustic telemetry system receiver was located in an office space adjacent to the powerhouse.



Figure 4-7. Location of acoustic hydrophones and DIDSON installed at the Mine Falls Project.

A PIT system was used to monitor tagged eel passage through each of the three bypass conduits prior to entry into the collection tanks. PIT tag antennae were installed in the conduits between where they rise above the water surface and the collection tanks. The receiver used to record detections was located in the powerhouse office space.

Underwater video cameras were placed at several of the openings on each bypass system to observe eels encountering and interacting with the openings (Figure 4-8). The DIDSON camera was located on the shore side of the intake canal about 20 ft upstream of the turbine intake bar racks (Figure 4-7). The coverage of the DIDSON camera was focused on the lower part of the water column where most eels were expected to be when they approached the intake.

Throughout the project there were instances when a particular eel monitoring system shut down or did not record. The following are the times when some of the operation data were not recorded:

- The DIDSON camera was not recording for the first 32 hours after the first release.
- The DIDSON camera stopped recording for 15 continuous hours on November 4 and 5.
- The four hydrophones closest to the turbine intake stopped recording for 3 hours on the morning of November 1.
- Underwater video cameras 7 and 8 malfunctioned during the study produce any vide that useable for eel behavior observations.

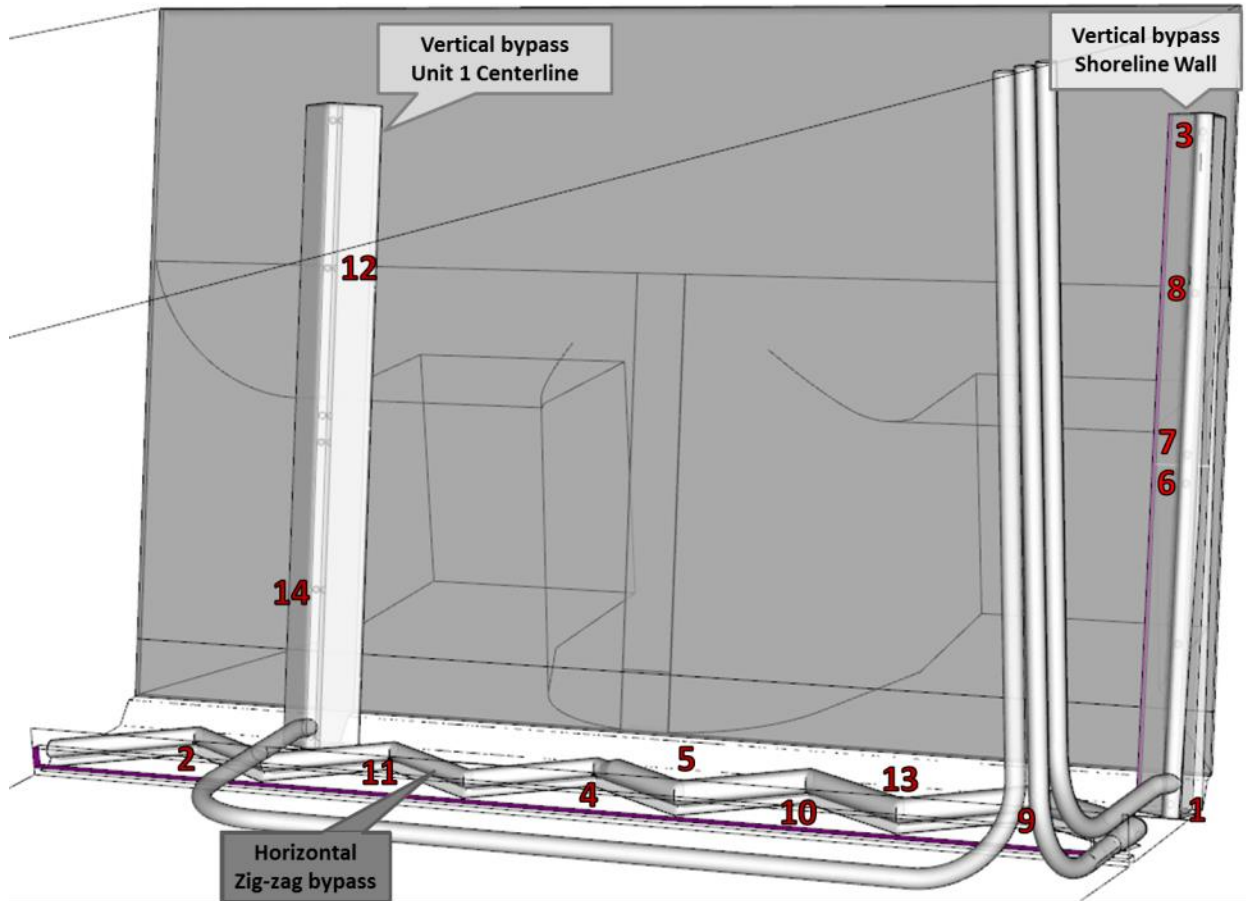


Figure 4-8. Underwater video camera number and location (in red) on horizontal and vertical bypasses; purple lines show the location of the brush material.

4.1.8 Data Analysis

The primary metric for assessing the performance of the bypass systems with silver eels was bypass efficiency (B_E), which was calculated using the following equation:

$$B_E = B_N / (B_N + E)$$

where B_N is the total number of tagged eels recovered from the bypass collection tanks following a release and E is the number of eels entrained through the turbines during a specified period following release. The duration of test periods was at least 24 hours following the release of a test group, but typically lasted three days if unit operation did not change for extended periods of time and some tagged eels remained upstream for a longer period. Any tagged eels that were not detected in the bypass or recovered from one of the collection tanks and that did not leave the intake canal in the upstream direction (i.e., the last detection was on the hydrophone located at the entrance to the canal) or through a small opening of the surface bypass gate (as determined by a last detection on a hydrophone near this bypass), were assumed to have been entrained through the turbine. The acoustic tracking data were also used to provide verification of turbine passage based on the last detection location (i.e., at the



bar racks). Estimates of bypass efficiency were calculated for each set of test conditions (combination of rack spacing and turbine flow). Acoustic telemetry data were also analyzed for temporal and spatial patterns associated with downstream passage and bypass use.

DIDSON images were reviewed for two nights following a release. The hours of review included 8 pm to 6 am the night of the release and 6 pm to 6 am of the following night. Images were analyzed for swim direction, last location observed, and general behavior.

Underwater video camera footage was reviewed for two nights following a release and any known times when eels entered one of the bypass systems based on PIT tag detection data. The hours of review included 7 pm to 7am the night of and the night following each release. Video footage was analyzed for swim direction, frequency of approaches to bypass entrances, and behavioral observations.

Specific metrics that were evaluated using video footage and the acoustic telemetry data included the following:

- Preferences for different areas of the intake channel as fish move downstream (for example, tendency to follow either the shoreside or riverside walls).
- Preferences for different depths within the intake channel during downstream movement and at the intake.
- Elapsed time from release until first encounter with a bypass opening.
- Frequency of approaches to bypass entrances, acceptance or rejection of entrance.
- Preferences for vertical or horizontal bypass system and specific bypass openings.
- Orientation during bypass entrance approach (head or tail first).

Raw acoustic tag detection files were initially batch processed using HTI's Mark Tags™ software. The software automatically attempts to isolate tag signals from background noise. More detailed processing was performed by technicians and consisted of verifying each tag detection in each hourly file and removing invalid detections. Additionally, within hourly files with a passage event (entrainment or bypass), technicians manually isolated tag signals from background noise and multi-path signals to improve 3D tracking abilities. The final dataset was then processed in HTI's Acoustic Tag™ software to produce 3D tracks of eel movement within the detection array.

In order to compare tracks among releases and passage routes, location bin densities were developed with the acoustic tracking data. Bin densities show the proportion of individual tags (i.e., each tagged eel) that occurred in the area covered by each bin. Bins were created by overlaying the detection array with a grid of 1 ft by 1 ft squares and each tag presence in each bin was recorded only once. Using bin densities normalizes the dataset and highlights the use of space by the population and preventing individual eels that spent large amounts of time in specific locations from distorting or overwhelming the data set. The density scales used were set to be relative to each other by either release group or passage route depending on the



figure. The dataset within each grouping (release or route), with the greatest range of proportions of tagged eels present was used to set the scale for the remainder of the grouping so that comparisons within groups were proportional to each other rather than set individually for each subset of data.

Residence times were calculated by grouping detections of individual fish within the array that occurred within 5 minutes of each other and assigning a first and last detection date and time. If a fish was absent from a receiver for more than 5 minutes, a new residence period was assigned.

4.1.9 Computational Fluid Dynamics (CFD) Analysis of Field Test Site

CFD simulations of the field test site were conducted to determine flow patterns approaching and in the vicinity of the bypass systems and bar racks. The flow domain (i.e., the forebay) was recreated in 3D CAD format and meshed to create the solution space for the CFD model. The model was meshed with a combination of hexahedral and tetrahedral elements.

The commercially-available CFD software ANSYS-Fluent v19.0 was used to run the simulations of the intake channel. Turbulence was simulated using the two-equation k-omega SST model with a continuity equation and momentum equation in each of the three principal axes. The flow was assumed to be isothermal with constant properties (density and viscosity) corresponding to the average water temperature during field testing.

A CFD simulation of the intake channel flow conditions was created, beginning at the head gates and terminating at the turbine inlets. A uniform flow inlet at the head gates was imposed. The flow to the turbines varied over the course of the field study, so three different flow rates (200, 300, and 600 cfs), which represent average values for the 4 releases, were simulated.

Although the bypass designs were intended to operate with both turbines online, Unit 1 was offline for maintenance for the duration of the test program. Therefore, flow was only passed through Unit 2 in the CFD model simulations. The volume flow rate to each of the bypasses was set to have 0.05 cfs per opening.

4.2 Results

The American Eels acquired for testing (199 total) ranged from 625 to 1,043 mm in length with an overall mean of 800 mm. There was no significant difference in total length among the four release groups (ANOVA, $f = 0.27$, $df = 3$, $p = 0.85$) (Figure 4-9).

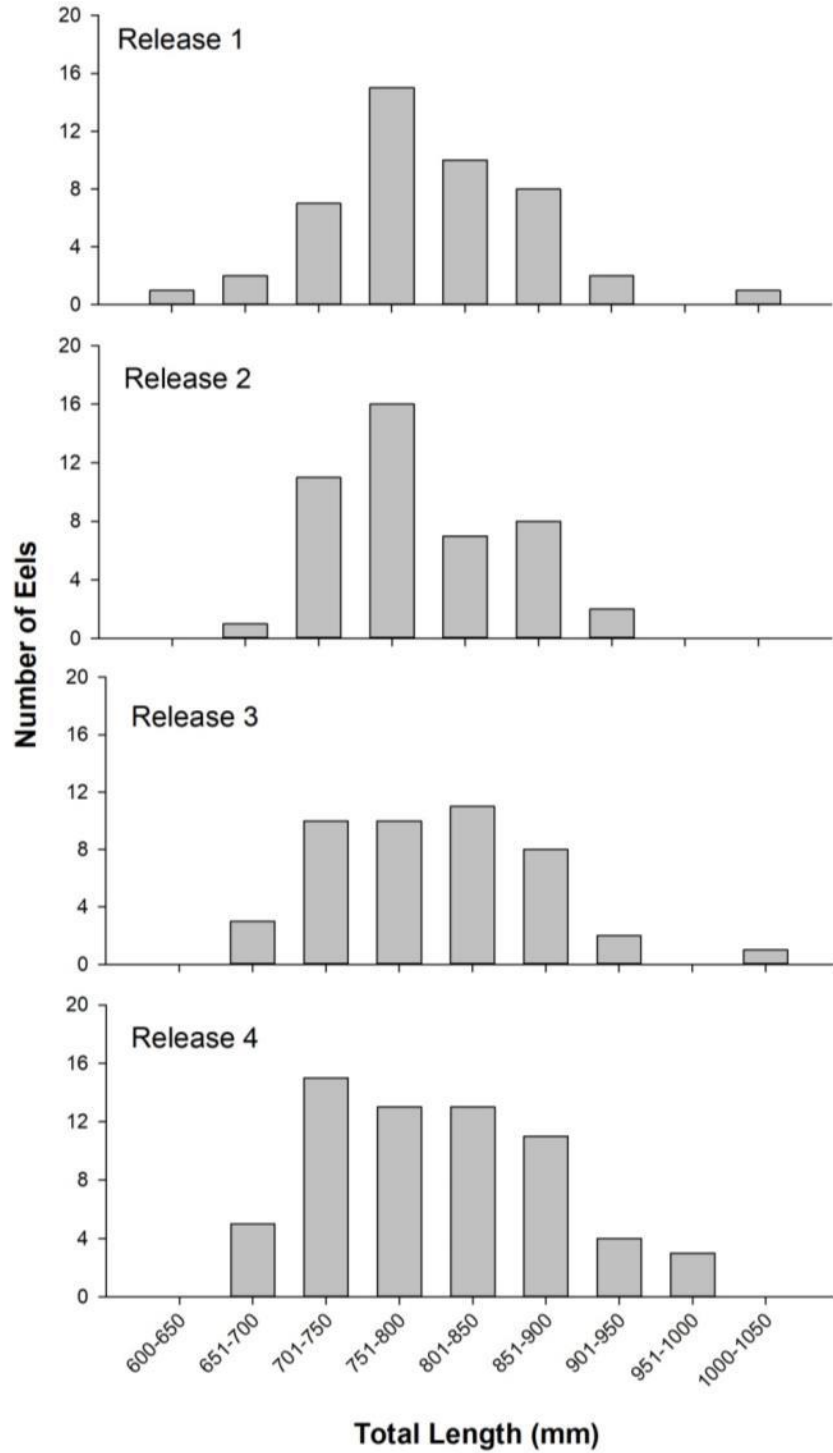


Figure 4-9. Length frequency of test fish by release group.



Nashua River flow during the study was obtained from the USGS gauge 01096500 at East Pepperell, Massachusetts. River flow during the study period ranged from 57 to 802 cfs with an average of 414 cfs (Figure 4-10). Mean flow through the Mine Falls Project over the course of the study was 297 cfs. The highest flows through the plant (646 cfs) occurred after the second release of tagged eels (75% gate opening test condition; Figure 4-10). Due to equipment issues at the project, there were multiple hours when the plant was offline and no flow went through the intake after some of the test releases (Table 4-2). The temperature recorded at an upriver location ranged from 3.8 to 15.8°C for the duration of the study, with a mean of 10.7°C (Figure 4-10).

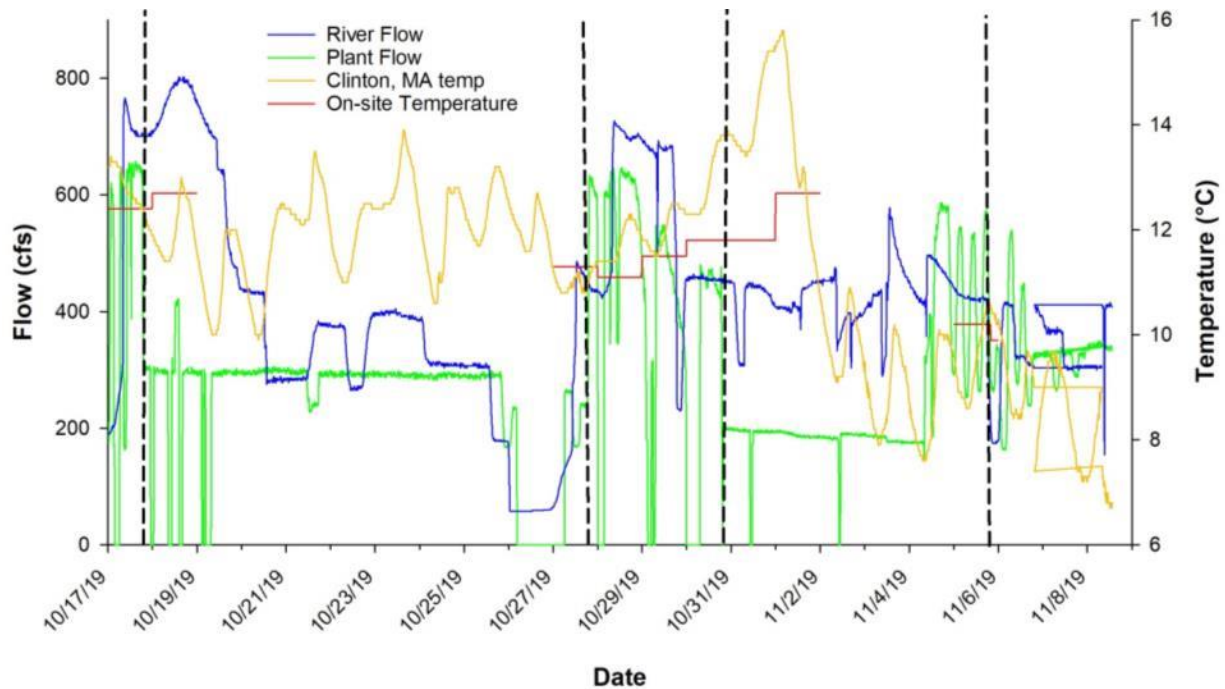


Figure 4-10. Flow for the Nashua River at Pepperell and Mine Falls Project during the duration of the American Eel bypass study. Temperature for the Nashua River, from the nearest upriver site in Clinton Massachusetts, is shown in orange.

Table 4-2. Number of hours Unit 2 was offline during the three day period after each release.

Release	Evening	Day	Total
1	5.5	3.5	9.0
2	10.0	1.0	11.0
3	0.0	1.0	1.0
4	0.0	0.0	0.0



4.2.1 Bypass Efficiency, Turbine Entrainment, and Impingement

Bypass efficiency ranged from 0% for the second release group (75% gate opening with 1-inch bar spacing) and the fourth release group (50% gate opening with 3-inch bar spacing) to 33.3% for the first release group (50% gate opening with 1-inch bar rack spacing) (Table 4-3). The entrainment rate of tagged eels ranged from 31% for the third release (45% gate opening, 1-inch bar spacing) to 82% for the second release (Table 4-3). Throughout the study period, 10 tagged eels and 11 native eels used one of the bypasses. Of the 21 eels that were bypassed, 16 used the horizontal zigzag bypass and 5 used one of the vertical bypasses (Table 4-4).

Impingement of tagged and untagged (native) eels was observed throughout the study period. The highest number of impingements occurred at the 50% gate opening (Release 1) for native eels and the 75% gate opening (Release 2) for tagged eels (Figure 4-11). The unknown eels were found impinged on the 1-in bar rack when it was removed and therefore it was unknown what release they came from or if they were native or tagged. No eels were impinged during Release 4, which was with the 3-in bar rack.

About 13 to 60% of tagged eels in each release were last detected by the hydrophone located upstream of the intake channel gate structure, indicating they either remained upstream of the project or passed downstream over the spillway. Although it was anticipated some of the released fish might move upstream, the large percentage of tagged eels that left the intake canal during three of the four tests (about 42 to 60%) was higher than expected. Higher velocities in the intake channel due to the wider turbine wicket gate opening evaluated for the second release likely resulted in fewer released fish (about 13%) leaving the canal in the upstream direction compared to the other three tests.

4.2.2 Eel Movement and Acoustic Data

The number of tagged eels detected by the hydrophones decreased considerably within several hours following each release (Figure 4-12). All tagged eels from the Release 4 moved out of the study area (hydrophone coverage) within one week, whereas Release 2 eels remained in the system up to 18 days after release (Figure 4-12). For all releases, the majority of eels in the system were active during nighttime hours, with very few eels observed from 7am to 2pm (Figure 4-13). The average residence time for all releases and locations was 236 minutes (approximately 4 hours). The average residence time was the longest for eels that used the bypass and shortest for eels that moved upstream (Table 4-5). The quickest an eel moved through the system was 6 minutes, this occurred for both upstream passage and entrainment. The longest an eel was seen in the system was (approximately 23 hours and this eel eventually was entrained (Table 4-5).



Table 4-3. Summary of the fate of tagged eels following release into the Mine Falls intake channel.

Release	Bar Spacing (inches)	Gate Opening (%)	Number Released	Entrained	Upstream	Bypassed	Surface Bypass	No Detection	Percent Entrained	Percent Upstream	Bypass Efficiency ¹ (%)
1	1.13	50	45	16	19	8	2	1	35.6	42.2	33.3
2	1.13	75	45	37	6	0	0	2	82.2	13.3	0.0
3	1.13	40	45	14	27	2	2	0	31.1	60.0	12.5
4	3.00	50	50	22	28	0	0	0	44.0	56.0	0.0

¹ Bypass efficiency was calculated by dividing the number eels bypassed by the total that passed downstream through the turbine and the bypasses combined.

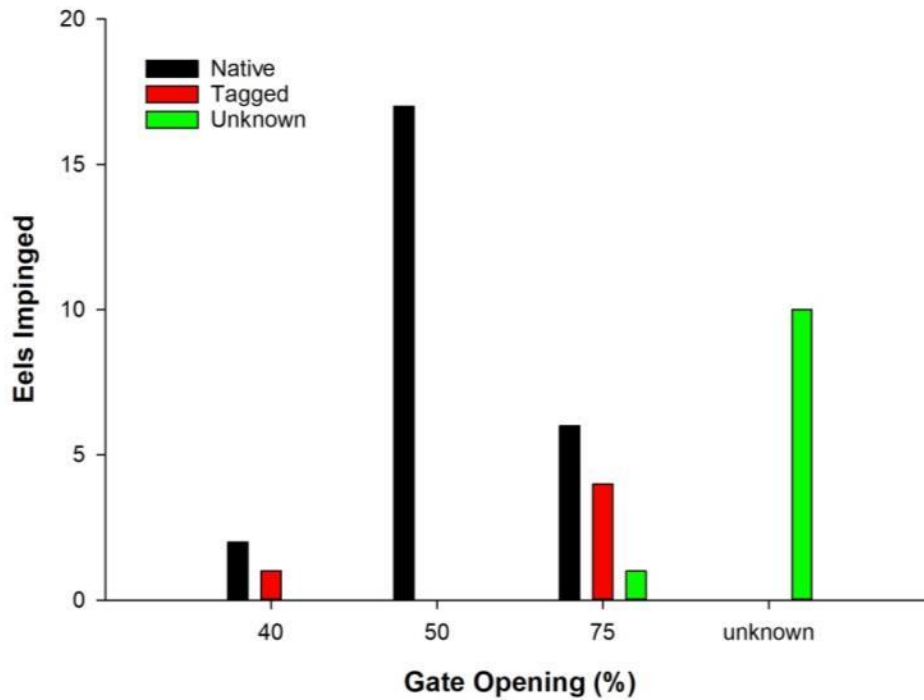


Figure 4-11. Number of impinged eels at each gate opening.

Table 4-4. Number of bypassed eels by date, test conditions (gate opening and bar rack spacing), and bypass system.

Date	Unit Gate Openings (%)	Bar Rack spacing	Bypass System	Number of Tagged Eels	Number of Native Eels
10/9/2019	offline	1.13	Vertical	0	2
10/16/2019	100	1.13	Horizontal	0	1
10/17/2019	50	1.13	Horizontal	2	0
10/17/2019	50	1.13	Vertical	1	0
10/18/2019	50	1.13	Horizontal	2	2
10/18/2019	50	1.13	Vertical	0	2
10/20/2019	50	1.13	Horizontal	1	0
10/21/2019	50	1.13	Horizontal	2	2
10/24/2019	50	1.13	Horizontal	0	1
10/25/2019	50	1.13	Horizontal	0	1
10/31/2019	45	1.13	Vertical	1	0
11/1/2019	45	1.13	Horizontal	1	0

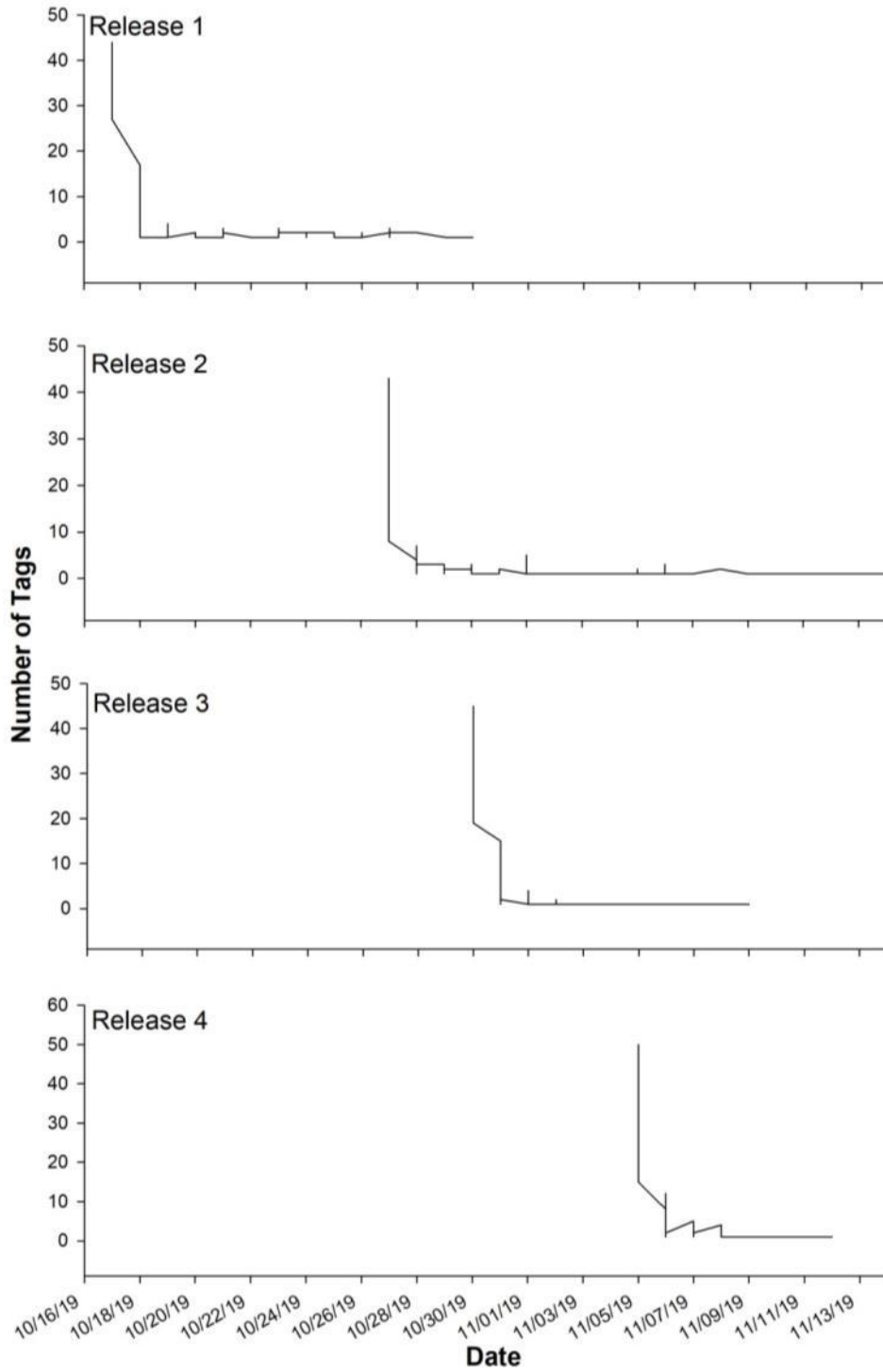


Figure 4-12. Number of tagged eels detected in the range of the hydrophones by day and release group.

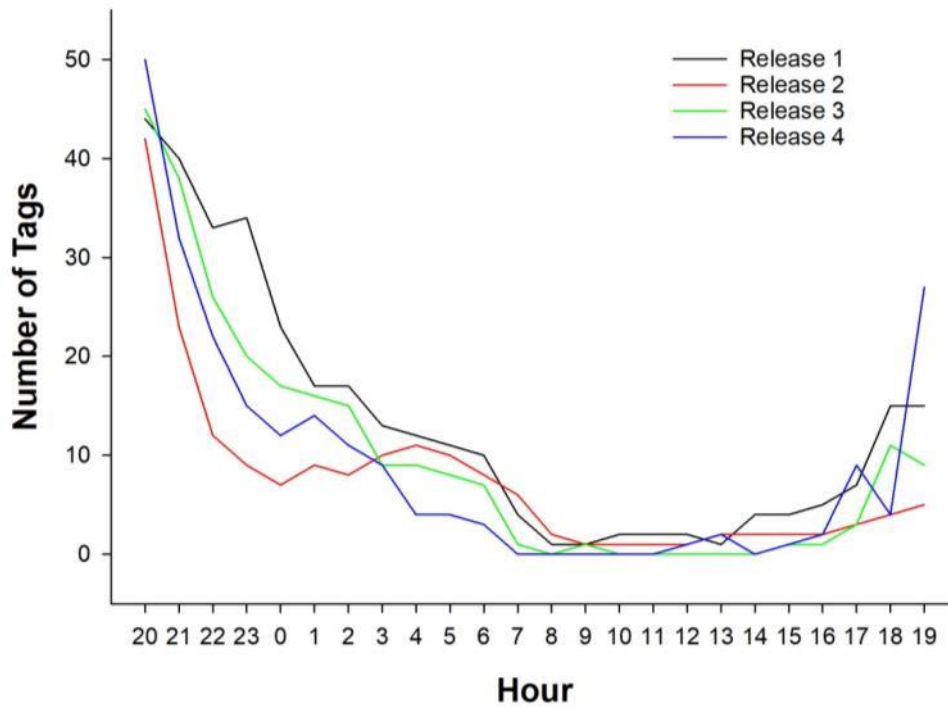


Figure 4-13. Number of tags found in the system by hour of the day for all releases.

Entrained eels had the highest densities at the intake for release groups 2, 3, and 4. Release group 1 fish that were entrained demonstrated a pattern of movement encompassing more of the intake channel (Figure 4-14). Eels that moved upstream into the impoundment were detected throughout the intake channel, with the highest tag detection densities in the upstream area. However, in Release 3 a large number of eels were found near the bypass and intake. Bypassed eels were found throughout the intake channel but had the highest densities near the bypasses (Figure 4-14). Examples of individual tracks are provided in Appendix A.

All eels, regardless of the passage route, were found throughout the water column with higher densities approximately 3 to 7 ft above the bottom. The lowest densities were observed near the surface (Figure 4-15). A higher percentage of eels were detected near the bottom of the channel for all passage routes up to 12 hours after release. Entrained eels continued this pattern up to 48 hours post release. However, eels that were bypassed or moved upstream had more variable depth profiles as time increased (Figure 4-16).



Table 4-5. Mean, minimum, and maximum residence time in the intake channel by release group and passage location.

Passage Location	Release 1			Release 2			Release 3			Release 4			All Releases		
	Mean (min)	Min (min)	Max (min)	Mean (min)	Min (min)	Max (min)	Mean (min)	Min (min)	Max (min)	Mean (min)	Min (min)	Max (min)	Mean (min)	Min (min)	Max (min)
Surface bypass	217	74	360	--	--	--	261	188	333	--	--	--	239	74	360
Eel bypass	260	48	721	--	--	--	218	93	3430	--	--	--	252	48	721
Entrained	307	21	871	160	6	1407	125	33	3620	76	18	187	159	6	1407
Upstream	175	6	783	94	20	277	105	15	511	99	9	642	119	6	783
All Locations	237	6	871	518	6	1407	123	15	511	89	9	642	236	6	1407

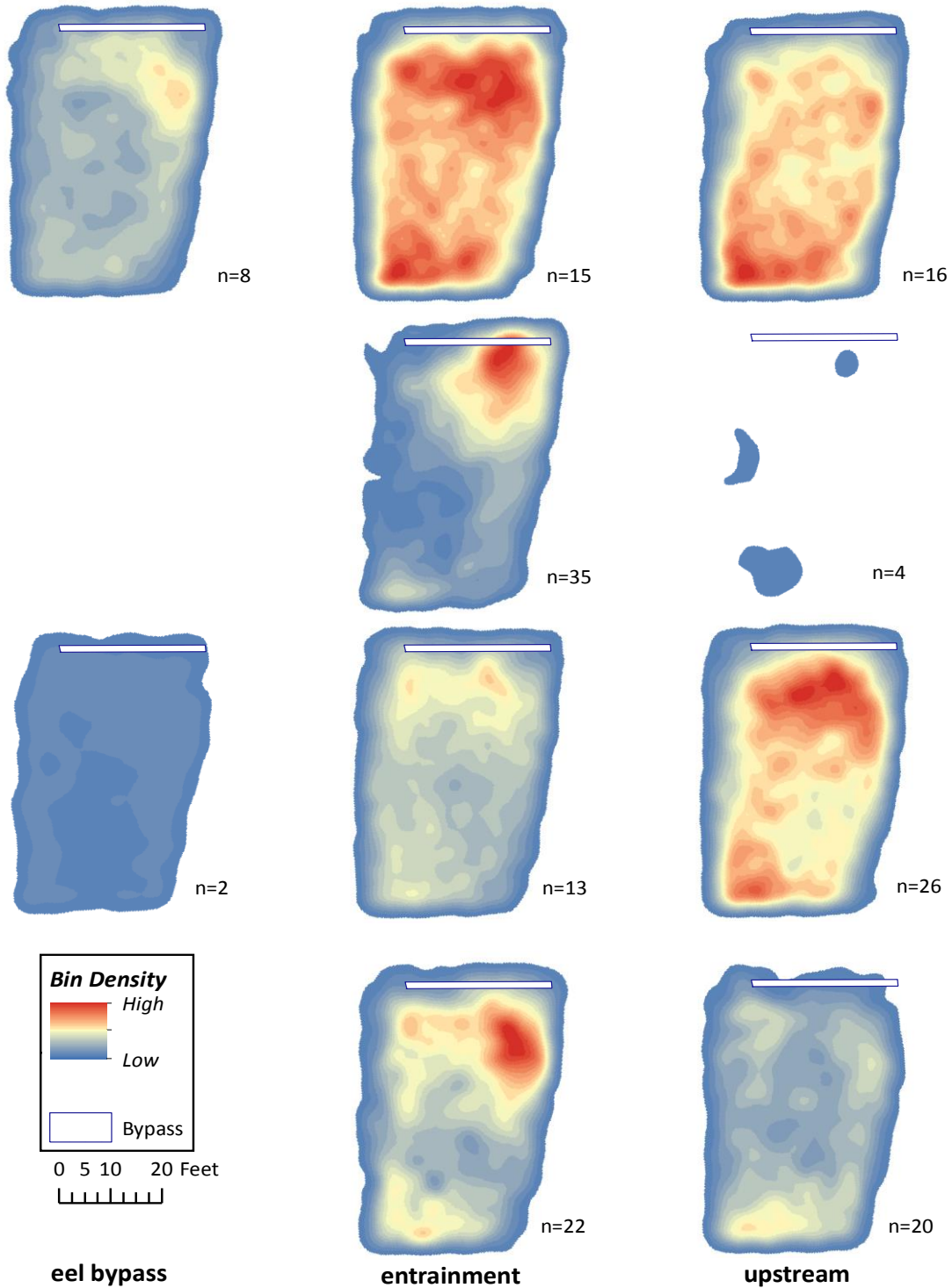


Figure 4-14. Bin densities of tagged eel detections by release group and passage route (all depths combined). The turbine intakes are depicted by the bar at the top of each image with the flow direction from bottom to the top. No bypass events occurred with release 2 and 4 eels.

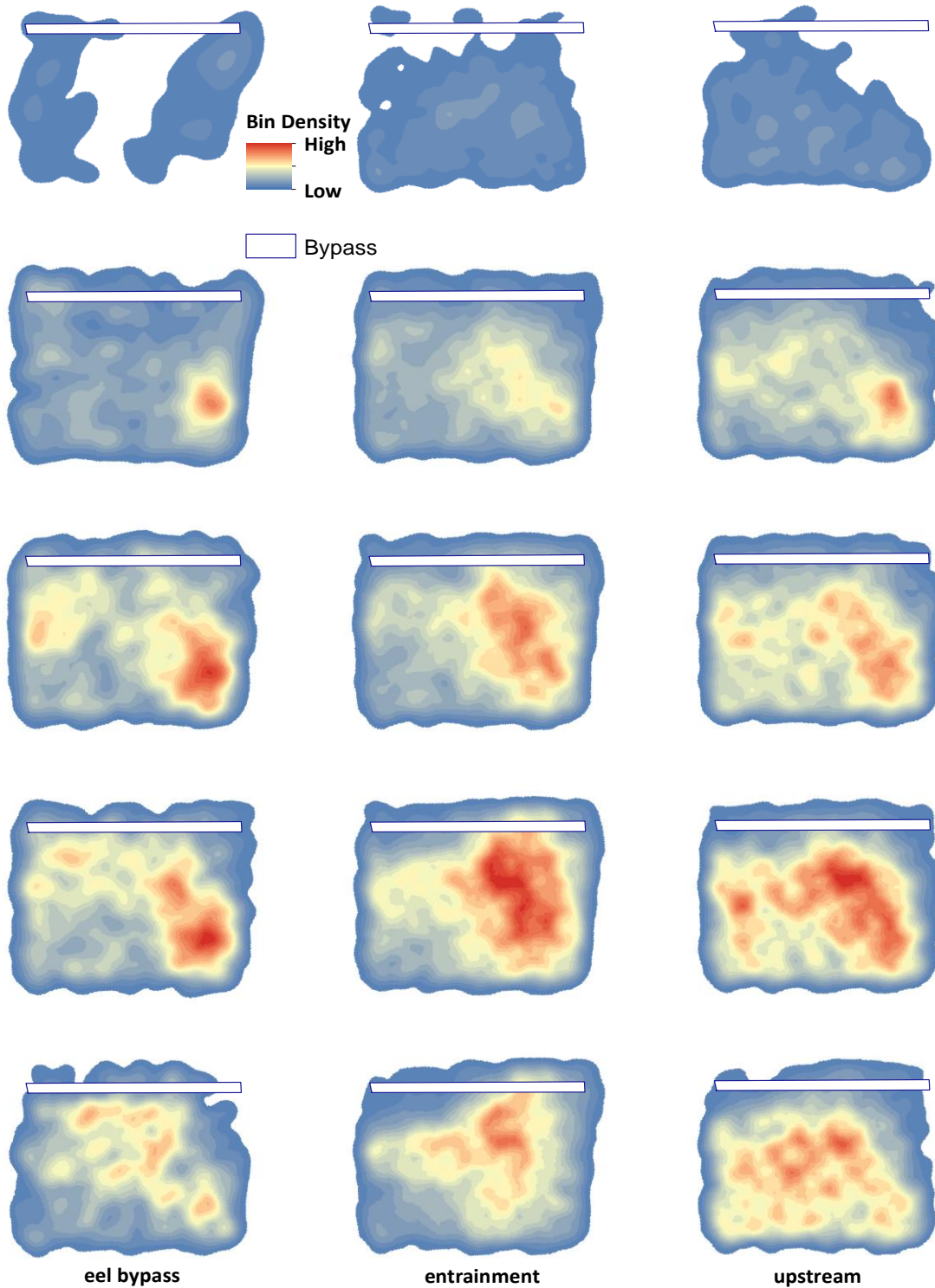


Figure 4-15. Bin densities of tagged eel detections by passage route and depth for all release groups combined, where 0 is the intake channel bottom. The turbine intakes are depicted by the bar at the top of each image with the flow direction from bottom to the top. No bypass events occurred with release 2 and 4 eels.

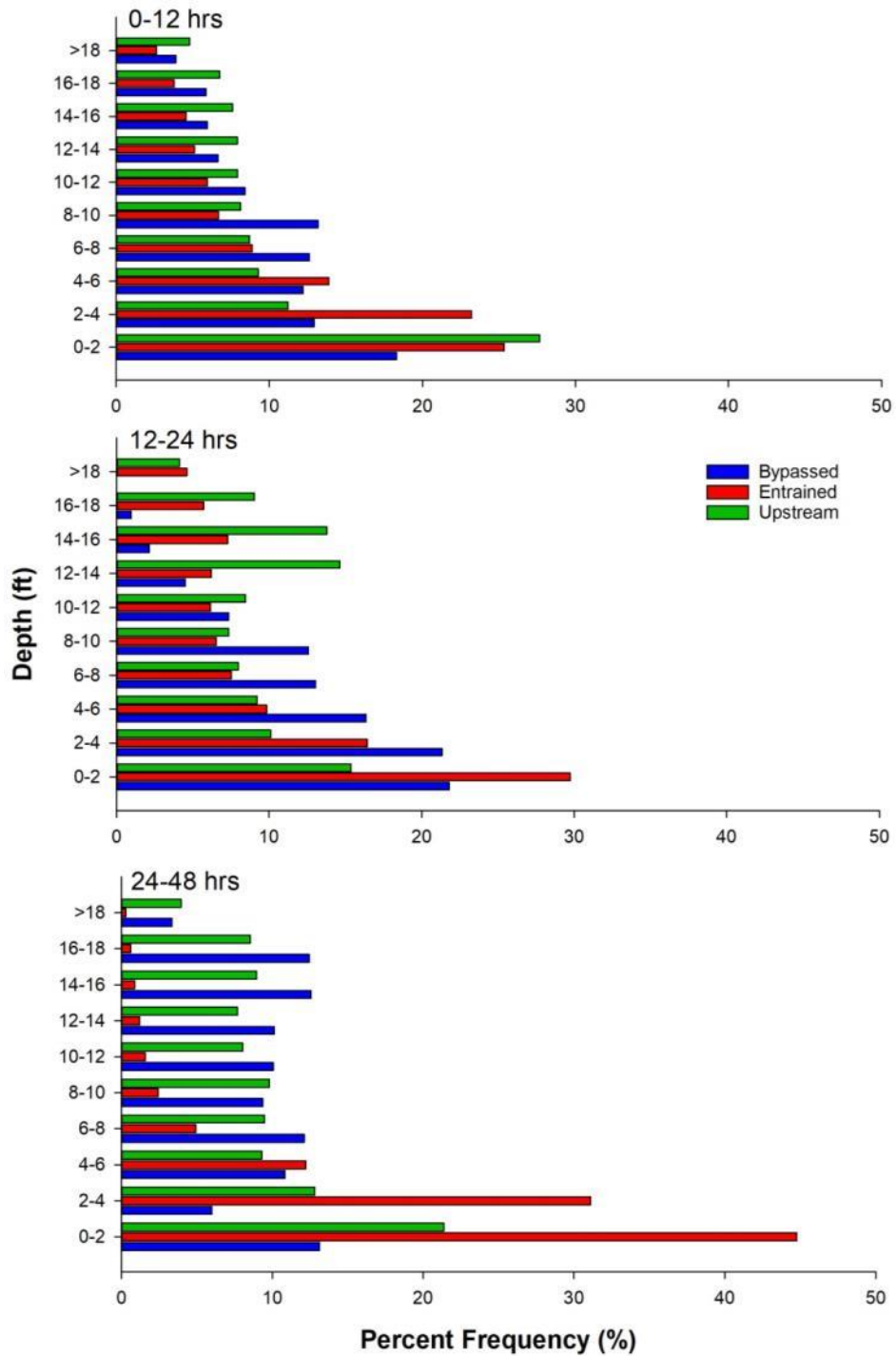


Figure 4-16. Percent frequency of tagged eels by depth and passage route for all releases combined, where 0 is the bottom of the channel.



4.2.3 Video and DIDSON Behavioral Observations

Underwater video cameras 1, 2, and 3 (see Figure 4-8 for camera locations) were typically covered with debris during the project period, thus making it difficult to observe if any eels were present near the bypass entrances associated with these cameras. The highest number of eel encounters on camera occurred at the horizontal zig-zag bypass entrances, particularly at camera locations 5, 10 and 13, which were directly in front of the Unit 2 turbine (Figure 4-17). No eels were observed at the Unit 1 centerline vertical bypass (cameras 12 and 14), and at the vertical bypass on the shoreline wall eels were only observed on camera 6. Camera data for the vertical bypass on the shoreline wall was limited, as cameras 7 and 8 malfunctioned during the project and were excluded from the analysis, and cameras 1 and 3 were typically debris-loaded and thus often difficult to see the bypass entrances.

For releases 1 and 4, eels were first observed on camera within 10 minutes of the release time. Release 2 and 3 eels were first observed on camera within 20 and 30 minutes, respectively, of release time (Figure 4-18). It is important to note that since some cameras were not functioning properly and not all bypass entrances were monitored by cameras, that eels may have encountered the bypass system and entrances sooner than was observed from video footage. The average time that observed eels spent on camera (i.e., in the immediate vicinity of a bypass entrance) was the shortest for Release 1 with an average of 10 seconds, and the longest was Release 4 with an average of 183 seconds (Table 4-6).

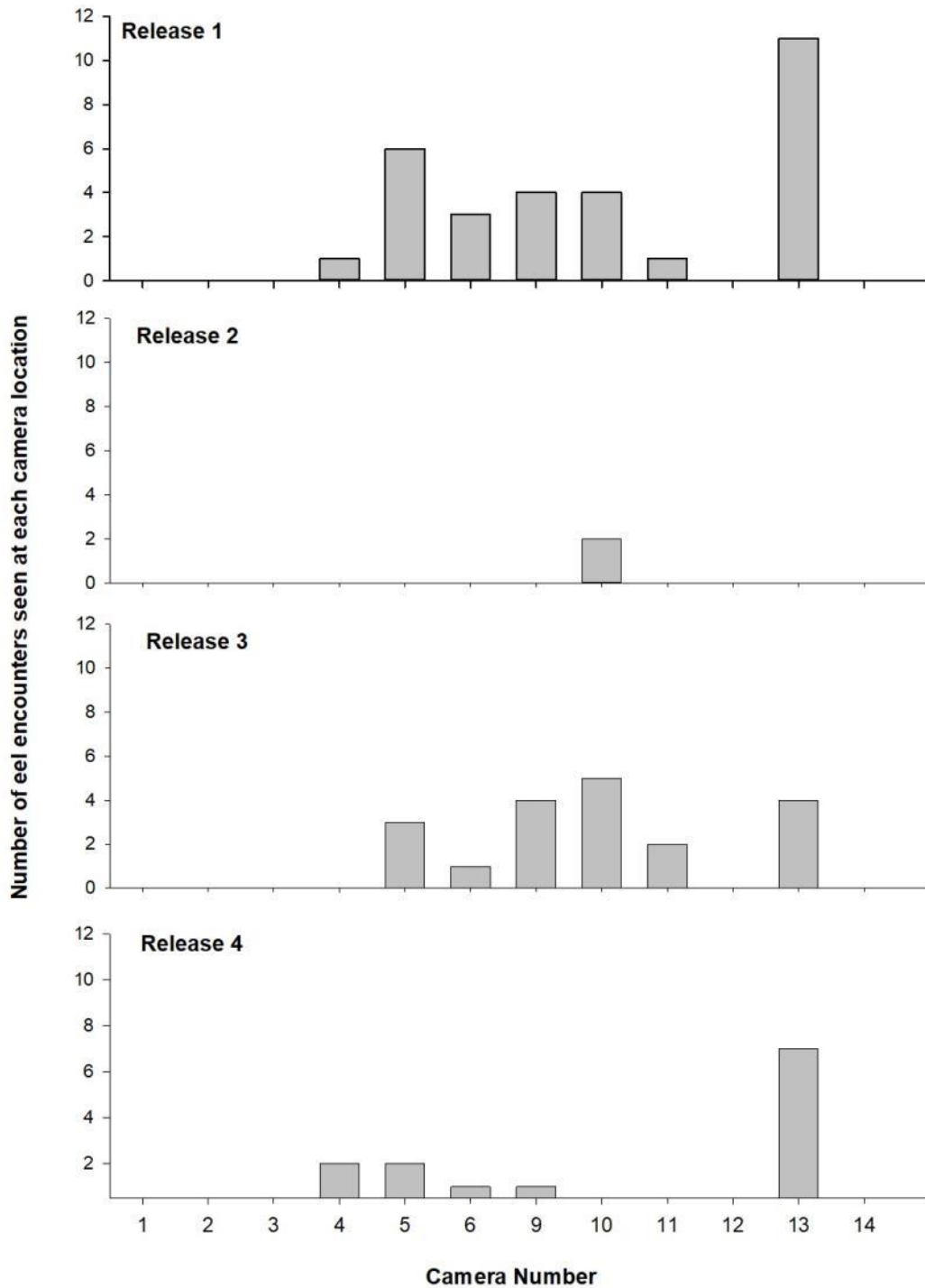


Figure 4-17. Number of eel encounters observed at each underwater video camera location (see Figure 4-8 for bypass opening locations of each camera).

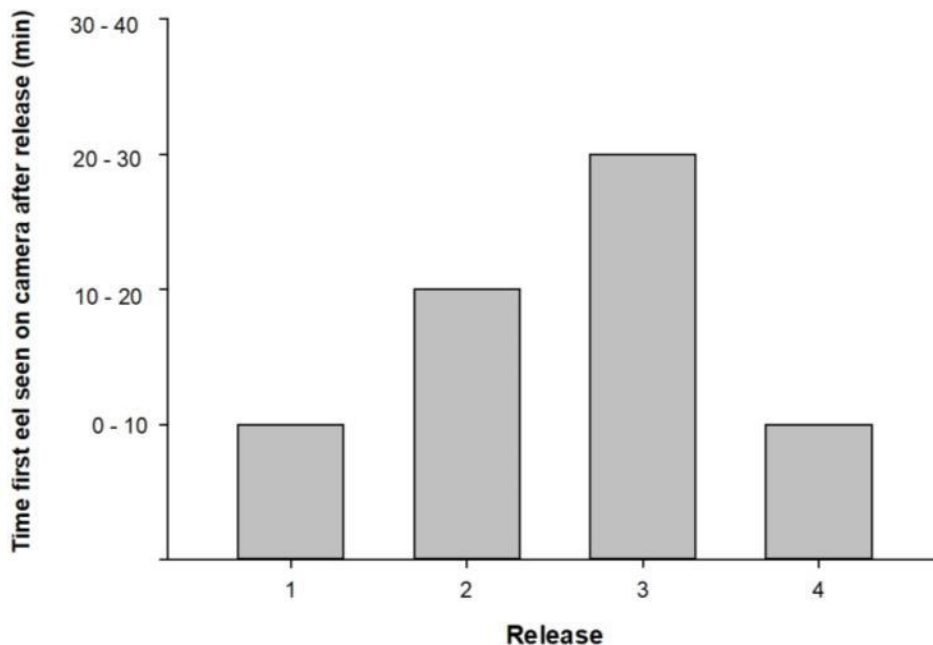


Figure 4-18. Time from release when first eel is observed on an underwater video camera.

Table 4-6. Average time observed eels spent in view of a camera.

Release Number	Average total time in camera view (seconds)
1	10
2	183
3	19
4	80
Total	32

There were only a few eels observed approaching and attempting to enter the bypass openings, with Release 2 having no observed approach behavior (Table 4-7). Approaches were defined as searching behavior in the bypass entrance area and/or immediate swimming towards the bypass entrance. Once an approach was observed, behavior was then characterized by attempts to enter, what orientation (head or tail first) an eel attempted to enter, or if the eel showed no interest in the bypass entrance. Only one observed eel had a tail-first attempt into a bypass entrance and this was likely inadvertent as it appeared that the eel’s tail got pulled into the bypass as it was swimming by, after which the eel immediately made attempts to exit the bypass and then swam away. The majority of observed eels were seen displaying no distinct behavior associated with the bypasses as they swam quickly past the camera view. Other notable eel encounters included those that swam towards the camera or towards a bypass opening (Table 4-8).



Table 4-7. Frequency of observed approaches to bypass openings and subsequent attempts, acceptance, or rejection of opening.

Release	Approaches	Attempts head first	Rejected head first	Entered head first	Attempts tail first	Rejected tail first	Entered tail first	Exited	No interest
1	8	2	0	2	1	1	0	0	5
2	0	0	0	0	0	0	0	0	-
3	1	1	1	0	0	0	0	0	-
4	3	2	1	1	0	0	0	1	1
Total	12	5	2	3	1	1	0	1	5

Table 4-8. Eel behavioral observations determined from underwater video recordings.

Behavior	Release 1	Release 2	Release 3	Release 4	Total
Head first bypass entrance attempt and rejection			1		1
Tail first bypass entrance attempt and rejection	1				1
Entered bypass	2				2
Entered and exited bypass				1	1
Searching behavior in/around bypass opening	5			1	6
Swims across quickly (no specific behavior)	12	1	8	7	28
Swims in front of camera, hangs out, swims away	1	1	1		3
Swims towards bypass	2		4	2	8
Swims towards camera	4		4	2	10
Swims towards camera, then towards bypass	1		1		2
Swims up vertical wall of bypass	2				2
Total	30	2	19	13	64



The majority of eels observed in DIDSON images were found moving upstream compared to downstream or perpendicular to the flow (Table 4-9). Overall, there were more eel encounters on the DIDSON in Release 3 compared to all other releases. Whereas a large proportion of eels seen on the DIDSON images swam quickly through the camera view without any specific behaviors, many eels were seen either disappearing near the bypass or swimming up towards the bypass, swimming around by the bypass and then swimming back upstream (Table 4-10). The most common last location recorded by the DIDSON throughout all releases was around mid-depth upstream of the bypass (Table 4-11).

4.2.4 CFD Results

The flow entering the forebay comes in through a rectangular channel that widens as the east wall begins to flare out. The channel also becomes deeper after the head gate and continues to increase towards the bar rack. This expansion in the area causes the flow to slow down approaching the turbines. Because Unit 1 was out of service during the testing, flow only passed through Unit 2. The turbine inlets are near the bottom of the channel, so the zone where the flow accelerates into the operating turbine was isolated to the bottom right corner of the channel.

The forebay was simulated at 200 cfs (release 3), 300 cfs (releases 1, 4), and 600 cfs (release 2). The velocity contours are taken at four elevations: 2.5 ft, 7.5 ft, 12.5 ft, and 17.5 ft above the channel floor, just upstream of the bar rack. The velocity profiles are very uniform throughout the channel, other than the few feet upstream of the Unit 2 intake where the flow is accelerating into the turbine (Figure 4-19). The velocity at the bar racks is a function of flow rate, and is an important parameter for the survivability of eels that encounter the rack. During the 200 cfs and 300 cfs conditions, the velocity through the rack is below 2.5 ft/s everywhere, which is lower than the velocity through most of the bar rack in the flume testing. During the second release, the flow was up over 600 cfs at times, and in the 600 cfs case, the bar rack velocity was over 4.0 ft/s in places (Figure 4-20).

Table 4-9. Swimming direction of eels observed in DIDSON images.

Swim Direction	Release 1	Release 2	Release 3	Release 4	Total
Downstream	8	2	51	21	82
Downstream/perpendicular to flow	-	-	2	1	3
Downstream/upstream	13	1	21	7	42
Downstream/upstream/downstream	-	-	1	-	1
Perpendicular to flow	5	-	11	21	37
Perpendicular to flow/downstream	-	-	-	2	2
Perpendicular to flow/upstream	-	-	5	3	8
Upstream	17	4	96	36	153
Upstream/downstream	--	-	2	1	3
Upstream/downstream/upstream	-	-	1	-	1
Upstream/perpendicular to flow	1	-	3	2	6
Total	44	7	193	94	338



Table 4-10. Eel behavior recorded from DIDSON images.

Behavior	Release	Release	Release	Release	Total
	1	2	3	4	
Disappears near bypass	1	-	25	9	35
Fighting flow to swim upstream	1	2	2	10	15
Milling about	1	-	-	-	1
Swims downstream then turned around and swims back upstream	2	1	1	-	4
Swims towards intake	-	-	2	-	2
Swims along trash rack, then swims upstream	1	-	1	-	2
Swims along brush	-	1	3	2	6
Swims along the trash rack	-	-	-	2	2
Swims downstream then turns around to swims back upstream, then disappears near bypass	-	-	1	-	1
Swims downstream then turns to swim perpendicular to the flow over the brush	-	-	1	-	1
Swims toward trash rack then turned around and swims back upstream	-	-	2	2	4
Swims towards bypass, hangout there, then disappears near bypass	-	-	4	8	12
Swims towards bypass, hangout there, then swims back upstream	11	-	27	3	41
Swims towards bypass, hangout there, then swims towards the trash rack	1	-	3	3	7
Swims across quickly (no specific behavior)	26	3	121	55	205
Total	44	7	193	94	338



Table 4-11. Last observed location of eels on DIDSON image.

Exit Location	Release 1	Release 2	Release 3	Release 4	Total
Mid depth upstream of bypass	32	2	103	35	172
Near brush	8	5	40	21	74
Near bypass	3	-	43	27	73
Near intake	1	-	7	11	19
Total	44	7	193	94	338

There are a few notable geometric differences between the field installation and the installation that was tested in the Alden flume. One is the channel expansion mentioned above, which causes the flow to slow down after the head gate. Another difference is that in the field installation the bottom of the bar rack is elevated 8-inches above the floor of the flume, on top of a sloped section (Figure 4-21). The elevated bar rack discourages the formation of the reversed flow along the floor from the bar rack to the horizontal bypass, which was present in the flume test.

The entrance holes that are far away from the active turbine inlet change very little as the channel flow rate changes. The flow rate, through the entrance holes that are directly in front of the active turbine, changes significantly as the channel flow increases (Figure 4-22). This is because the local pressure outside the holes changes significantly as a function of the local velocity. In general, as the channel flow increases, the flow through the entrance holes directly in front of the turbine decreases.

4.3 Discussion

Silver eel bypass efficiencies for the two bypass systems were low for all releases. The highest efficiency achieved was about 33%, which occurred during the first release when turbine flow was lowest. Also, tagged eels only used the bypasses at the lower flow configurations with the 1-in bar spacing overlay. Eels move through either upstream or downstream quickly with an average residence time in the study area of approximately four hours. Eels were detected throughout the water column, but at the intake the highest densities were observed in the lowest 10 ft. Previous field studies of silver eels approaching and passing downstream at hydropower projects have indicated they have tendency to be near the bottom but will search throughout the water column when they encounter turbine intakes. However, there is some evidence of preference for mid or bottom bypasses.

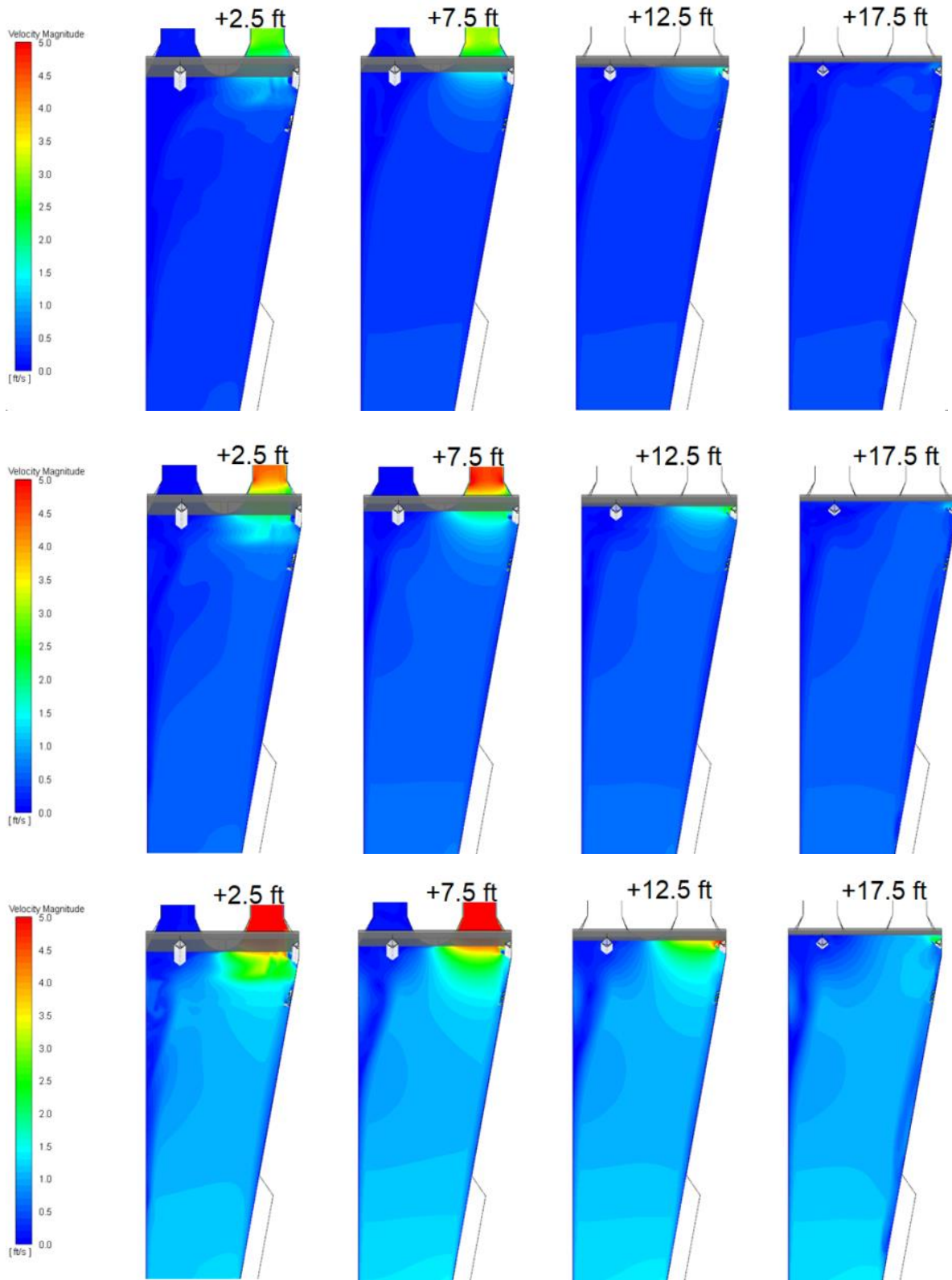


Figure 4-19. Velocity at different intake channel elevations for 200 cfs (top), 300 cfs (center), and 600 cfs (bottom).

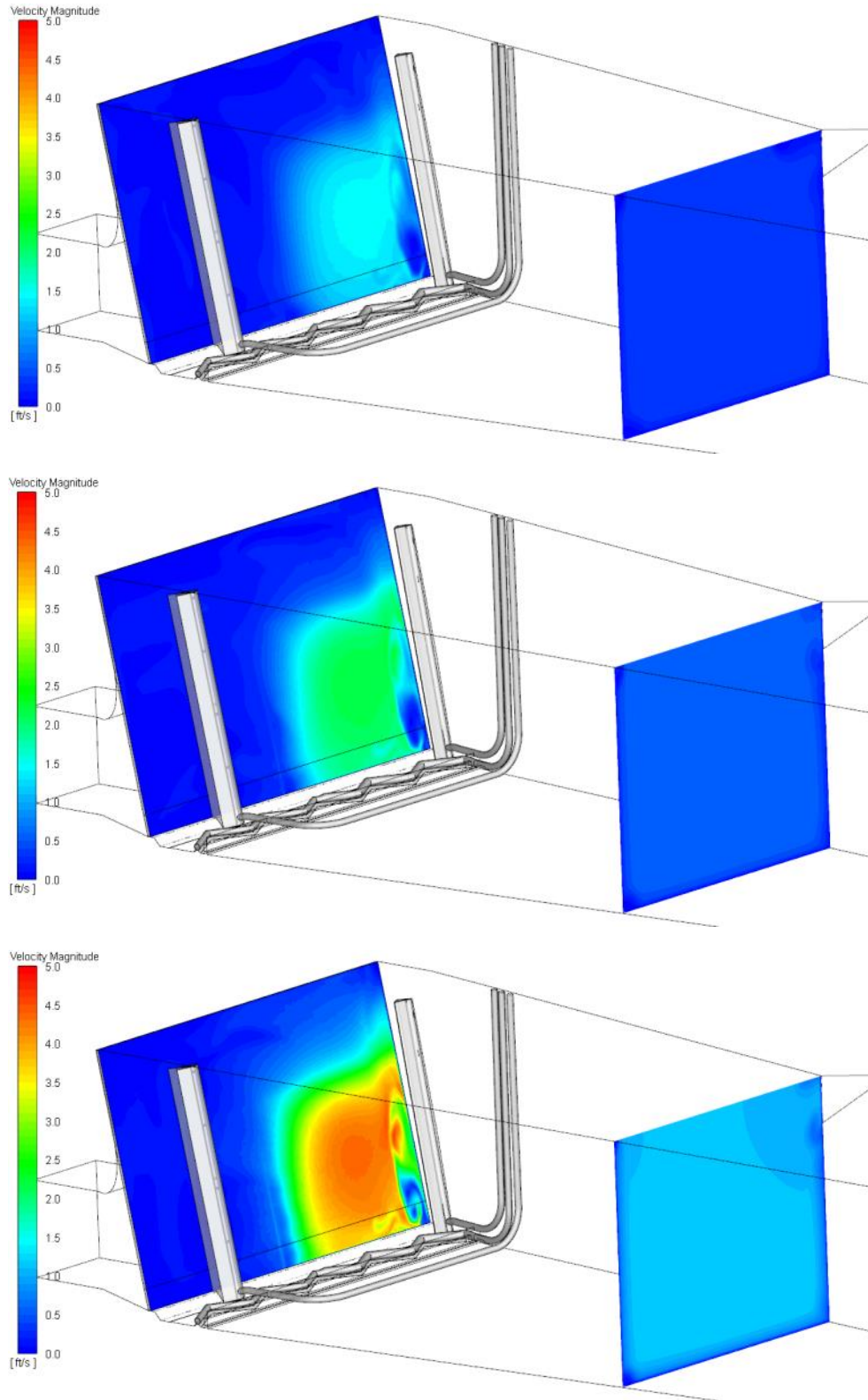


Figure 4-20. Velocity through bar rack at 200 cfs (top), 300 cfs (middle), and 600 cfs (bottom).

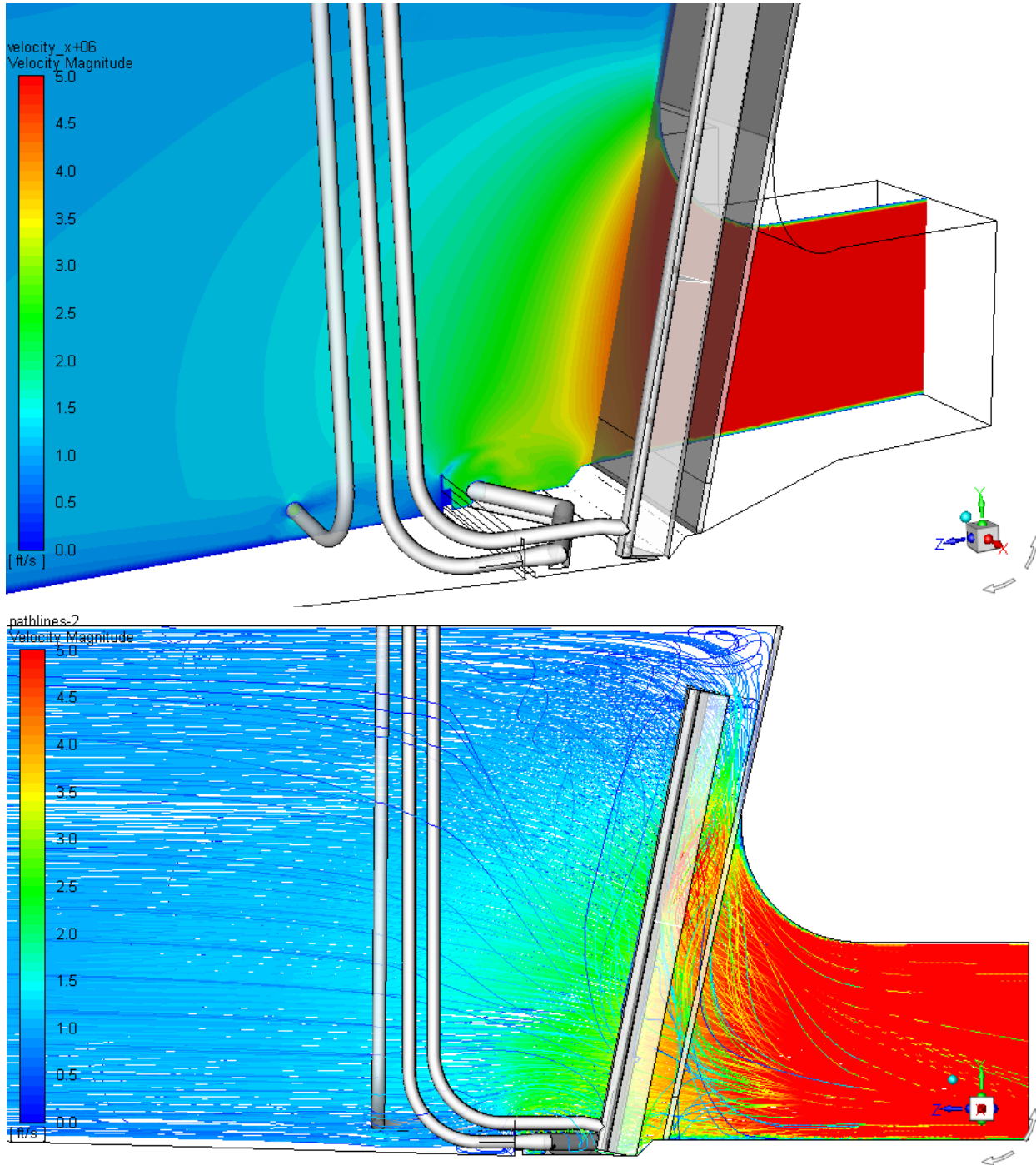


Figure 4-21. Contours and Pathlines of Velocity (ft/s) entering Turbine No.2 (flow = 600 cfs).

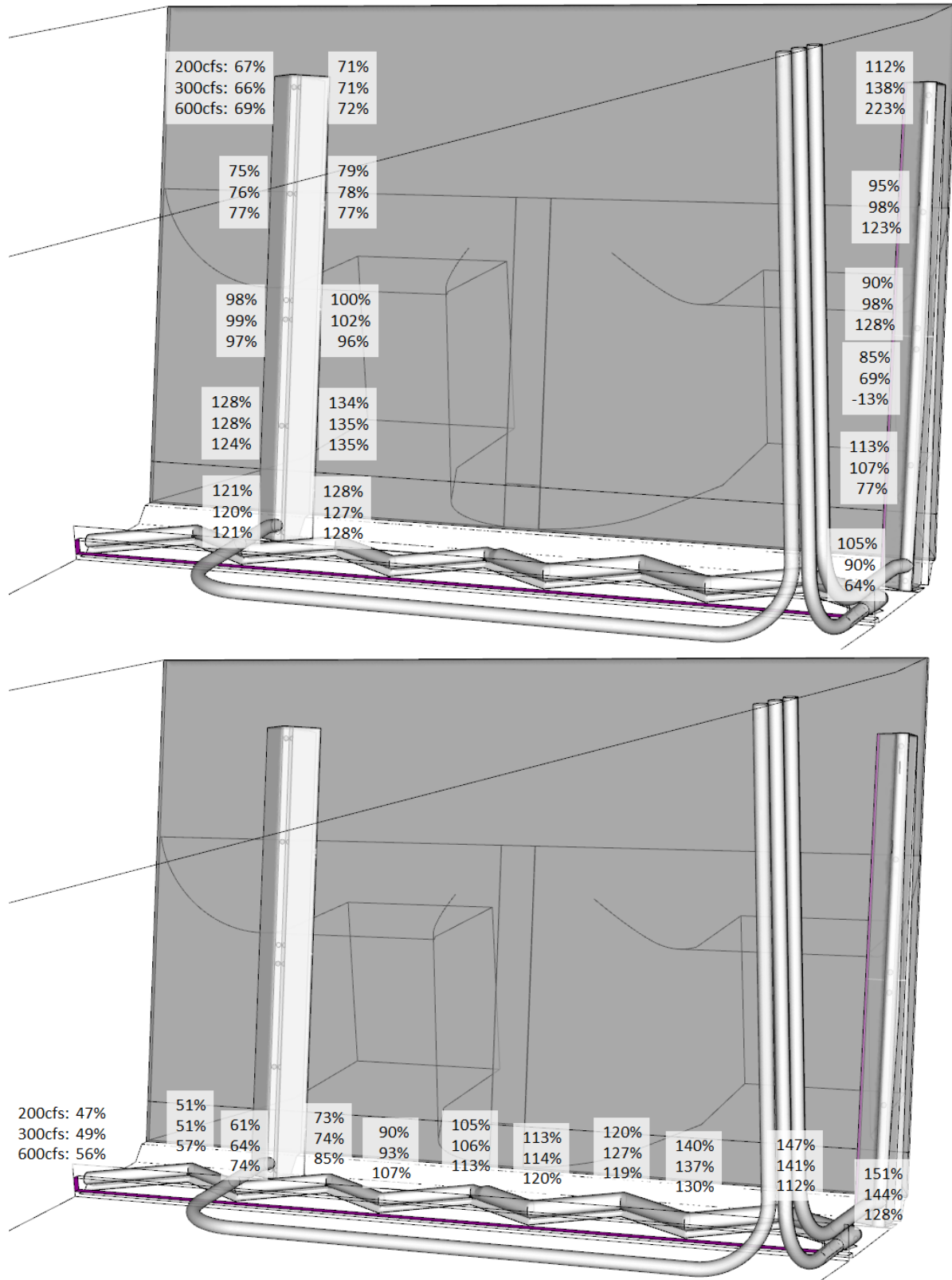


Figure 4-22. Flow split to vertical and horizontal bypass holes for each flow rate.



Differences in lab and field results have been previously demonstrated for the horizontal zig-zag bypass. A study conducted at the University of Kassel in Germany reported over 90% of the test eels were bypassed within 40 minutes during laboratory testing (Hassinger and Hübner 2009). The laboratory portion of our study also produced high bypass efficiencies with both bypasses tested together, ranging from about 40% with 2-inch clear spaced bar rack and 91% with 1-inch spacing. Although the KLAWA zig-zag system has been installed at some projects in Europe, there has been little to no testing on the efficiency at those sites. The results of one study conducted at a hydropower facility in Bavaria, Germany, reported downstream passage of 1,323 silver eels through an undershot gate but none were observed passing through a zig-zag system installed at the site (Egg et al. 2017). In 2017, a horizontal zig-zag was installed at Eel Weir Dam in Windham, Maine. Video surveillance recorded 40 silver eels passing through this bypass system over a two month period (Sappi and AES 2018).

The two bypass systems did not perform as well as expected in the field based on the laboratory results. This could be due to multiple factors that influenced eel behavior in the field. Entrainment was over 85% for tagged eels released at Mine Falls and no eels used the bypasses for the releases that had the highest turbine discharge. This suggests the tagged eels were attracted primarily to the turbine intake and unable to search for a safe bypass route and avoid entrainment at the high approach velocities. The two eel bypass systems we evaluated are designed to use relatively low flow and, therefore, do not provide strong attraction cues (i.e., a zone of influence) relative to the turbine flow. These systems are designed to intercept eels that are searching for an outlet after encountering bar racks; if velocities are too high, entrainment or impingement is more likely to occur before a bypass route can be located. It is possible that higher bypass efficiencies may occur at projects with more appropriate hydraulic conditions for reducing entrainment and allowing downstream migrants to locate bypass openings.

Migrating silver eels have been shown to travel downstream in the lower portion of the water column. The horizontal zig-zag system is designed to take advantage of the benthic preference of eels. However, when encountering turbine intakes, silver eels have been observed searching vertically for downstream passage routes. At Mine Falls, tagged eels were detected in greater abundance in the lower part of the water column, but presence in the upper portion was also observed and increased with time (particularly after 12 hours from release). The vertical bypasses were developed to provide outlets for eels higher in the water column. However, at Mine Falls, only two of the 11 bypassed eels used the vertical bypasses. One of the turbines at Mine Falls was offline for the complete duration of the study and may have affected the efficiency of the vertical bypass installed on the center of the bar rack of that intake. Without flow to this intake, eels were most likely not attracted to that side of the channel and, therefore, were less likely to encounter the vertical bypass and/or that side of the horizontal bypass. This was verified by a lack of eels observed on the cameras eels located on the centerline vertical bypass and the camera on that side of the horizontal bypass. CFD results determined that the highest flow percentages occurred at the horizontal bypasses entrances in front of the operation unit (entrance holes 5, 10, and 13). These entrances were also where the highest number of eels was observed during the review of video recordings.



CFD modeling results demonstrated that during the lower flow conditions (i.e., less turbine flow), the velocity approaching the bar rack was below 2.5 ft/s. Eels should be able to swim away from the rack after encountering it at these velocities and this was demonstrated by the low number of impinged tagged eels for these test conditions. However, high numbers of impinged native eels were observed at the higher turbine flow of 300 cfs. During the second release (600 cfs), the bar rack velocity was over 4.0 ft/s and for which tagged eel impingement was greatest.

Eels moved through out of the test area more quickly during the last two releases compared to the first two releases, which may have been due to a drop in water temperature and periods of increased flow. The observed migration temperatures are variable among the literature; however, the range is very similar for both the European and American eel. Vollestad et al. (1986) observed European Eel (*Anguilla Anguilla*) migrations occurring in temperatures ranging from 9 to 18°C, and Barbin et al. (1998) found migrations to occur from 9.6 to 17.6°C for American eel in Maine. Temperature at Mine Falls during the last two releases was very close to the lower portion of the observed ranged for eel migration and may have affected how quickly eels were moving through the system and potentially why larger numbers of eels moved upstream in those releases.

Debris buildup on and around the bypasses was a potential issue later in the study and may have affected bypass use. The bypass systems were designed to be cleared of debris using an air burst system, which was implemented several times during the study period. However, there was still the potential for debris to reduce access to some of the bypass entrances as this process was not carried out on a daily basis. It may be beneficial to have a more consistent cleaning regiment for any future installations of these bypass systems.

Overall, eel movement was variable in length of time spent in the test area and with respect to depth for all releases. The field evaluation of the two bypass systems at Mine Falls provided additional insights into the behaviors of silver American Eels when migrating downstream past a hydropower facility. However, additional studies need to be conducted to fully understand the performance of these bypass system at hydropower dams where site configuration and hydraulic conditions may lead to higher bypass efficiencies. Also, due to the low flow requirements compared to conventional bypasses, these eel bypass designs may be preferred at projects where bar rack spacing is sufficiently small to prevent entrainment and approach velocities are low enough to prevent impingement. Whereas bypass efficiency was lower than expected at Mine Falls based on the results of the laboratory evaluation, the performance of these bypass designs is likely site specific to some extent and with some modifications (e.g., larger openings, more bypass flow) either design could be more effective at other sites throughout the range of American Eel in the U.S.



5.0 Technology Application Assessment

Mortality of silver eels passing downstream at hydropower dams is a major issue that is typically addressed by state and federal resource agencies and project owners during the federal licensing process for hydroelectric facilities. The Federal Energy Regulatory Commission (FERC) regulates and issues licenses for the operation of non-federal hydropower facilities in the US. As of 2017, there were 2,247 operating hydropower facilities with a combined generating capacity of about 80 GW (Samu et al. 2017). FERC licenses are issued for a period of 30 to 50 years depending on the project. A large number of projects are currently being relicensed or will be over the next 15 years. Most of these relicensings are for small hydroelectric projects located on river systems in the Eastern US that are home to multiple migratory fish species (e.g., American Shad, Blueback Herring, Alewife, and American Eel). To protect these species and support ongoing restoration efforts, safe and effective upstream and downstream passage is often required by state and federal resource agencies as part of the FERC licensing process (through Clean Water Act Section 401 permits issued by states and/or mandatory fish passage prescription authority of the US Fish & Wildlife Service or National Marine Fisheries Service). Many of the projects undergoing relicensing now and in the coming years will be required to install new or upgrade existing upstream and downstream fish passage facilities. Upstream passage for American Eel elvers is fairly simple and relatively inexpensive to implement. However, because of their large size and unique behaviors, implementing downstream passage facilities for silver eels has been more difficult for project owners with respect to biological performance and cost. Consequently, there is a need for new technologies and approaches for passing silver eels downstream safely, effectively, and economically.

The current technology baseline/standard for silver eel downstream passage at US hydro projects (i.e., USFWS prescription requirements) includes the application of the following: (1) one or more bypasses (either surface, mid, and/or bottom locations) with gravity or siphon flow that is at least 3 to 5% of rated turbine discharge (all units combined); (2) 0.75-inch clear trash rack bar spacing; and (3) intake approach velocities of about 1.5 ft/s or less. A USFWS accepted alternative to this technology-based approach is nightly generation shutdowns during the established silver eel downstream migration period of August 1 to December 15 (varies slightly by state/region). Both of these approaches can result in significant negative impacts to the economic viability of hydropower projects.

The objective of the technology application assessment was to evaluate the potential for the two bypass systems to be applied at hydropower projects in the US for passing silver eels safely downstream. The technology assessment includes a review of FERC-licensed projects at which the bypass systems could be considered for application and several case studies evaluating the feasibility of available alternatives (including approaches accepted by the USFWS) based on biological performance and engineering and economic considerations.



5.1 Eel Migration

American Eel (*Anguilla rostrata*) are a catadromous species that spawn in the Sargasso Sea. The catadromous life history includes a period of rearing and maturation in freshwater systems before adult fish migrate to the ocean to spawn. After hatching, the larvae make their way into estuaries and rivers where they will stay until they reach maturity. In the fall (mid-August to late October), yellow-phase eels will transform (morphologically and physiologically) into mature silver eels for downstream migration (Brujij and Durif 2009). The large majority of migrations tend to be at night (Haro et al. 2000a; Brown et al. 2009; Calles et al. 2013), in periods of new moon (Lowe 1952), and during or after large rainfall events (Boubée et al. 2001; Dufif et al. 2002; Boubée and Williams 2006; Carr and Whoriskey 2008).

Many studies have evaluated eel downstream migrations and the factors that influence these movements. Field data and experiments over a 10 year period in Norway discovered that downstream migrations of European Eel were highly correlated with temperature and river discharge (Vøllestad et al. 1986). This study demonstrated increased downstream movement with low water temperatures and high river discharge. Few eels were detected migrating if temperatures were below 4°C or above 18°C. Increasing water discharge also increased migration speed, indicating eels were transported by currents. Brujij and Durif (2009) suggested there may be up to six factors that affect downstream migration of silver eels: (1) temperature, (2) photoperiod, (3) moonlight, (4) river discharge, (5) rain (atmospheric pressure), and (6) turbidity. However, many of these factors are linked together and may influence one another.

Numerous studies have investigated the effects of hydropower dams and impoundments on the emigration of diadromous species. Annually, mature silver eels with enough lipid storage will stop feeding and undertake their spawning migration to the Sargasso Sea (Palstra et al. 2009). During the migration out of freshwater systems, eels approaching hydropower stations have been shown to circle and move in and out of a forebay multiple times. It may take an eel several days to pass downstream of a hydro project (Brown et al. 2009). Drouineau et al. (2017) found that obstacles (hydropower stations) produced significant decreases in the distance traveled per day. Besson et al. (2016) found 75% of tagged European Eels were delayed in downstream migration in the Frémur River due to two reservoirs and dams and Bolland et al. (2018) found 76.7% retreated upstream after encountering an intake screen. Delays in migration caused by physical barriers, including hydropower dams, may decrease body reserves, increase spawning migration mortality, and decrease spawning success (Acou et al. 2008).

5.2 Hydropower Projects in American Eel Range

Out of the 2,247 hydro projects in the US, approximately 873 are in the native range of the American eel (Figure 5-1) and 263 sites will be up for relicensing by 2035 (Figure 5-2). A dataset containing information on flow, head, generating capacity, and current downstream fish passage facilities was developed to determine which sites may need to address silver eel



passage and, consequently, may benefit from the new eel bypass designs. The majority of these sites (64.6%) are considered small hydro (>5 MW) (Table 5-1).

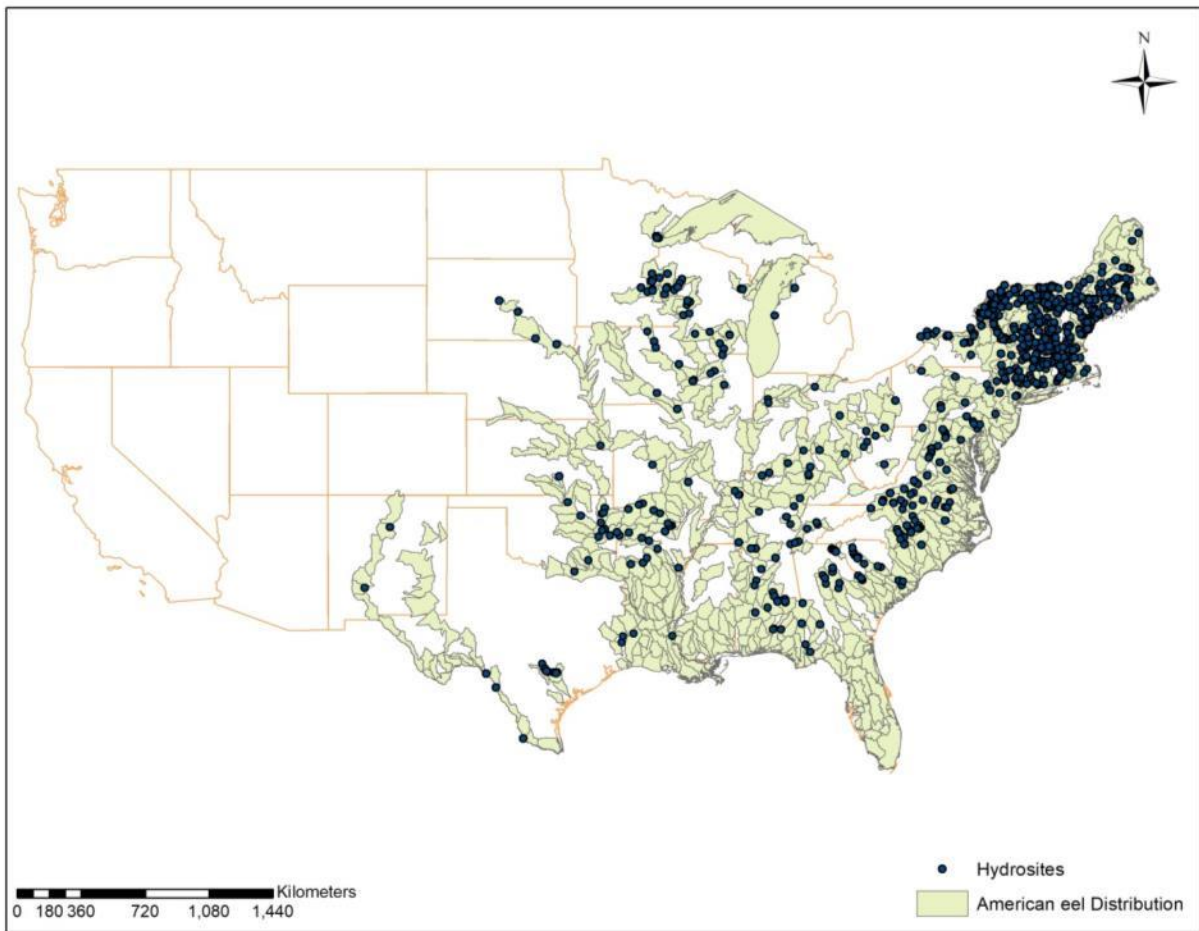


Figure 5-1. Hydropower sites that fall in the native range of American Eels.

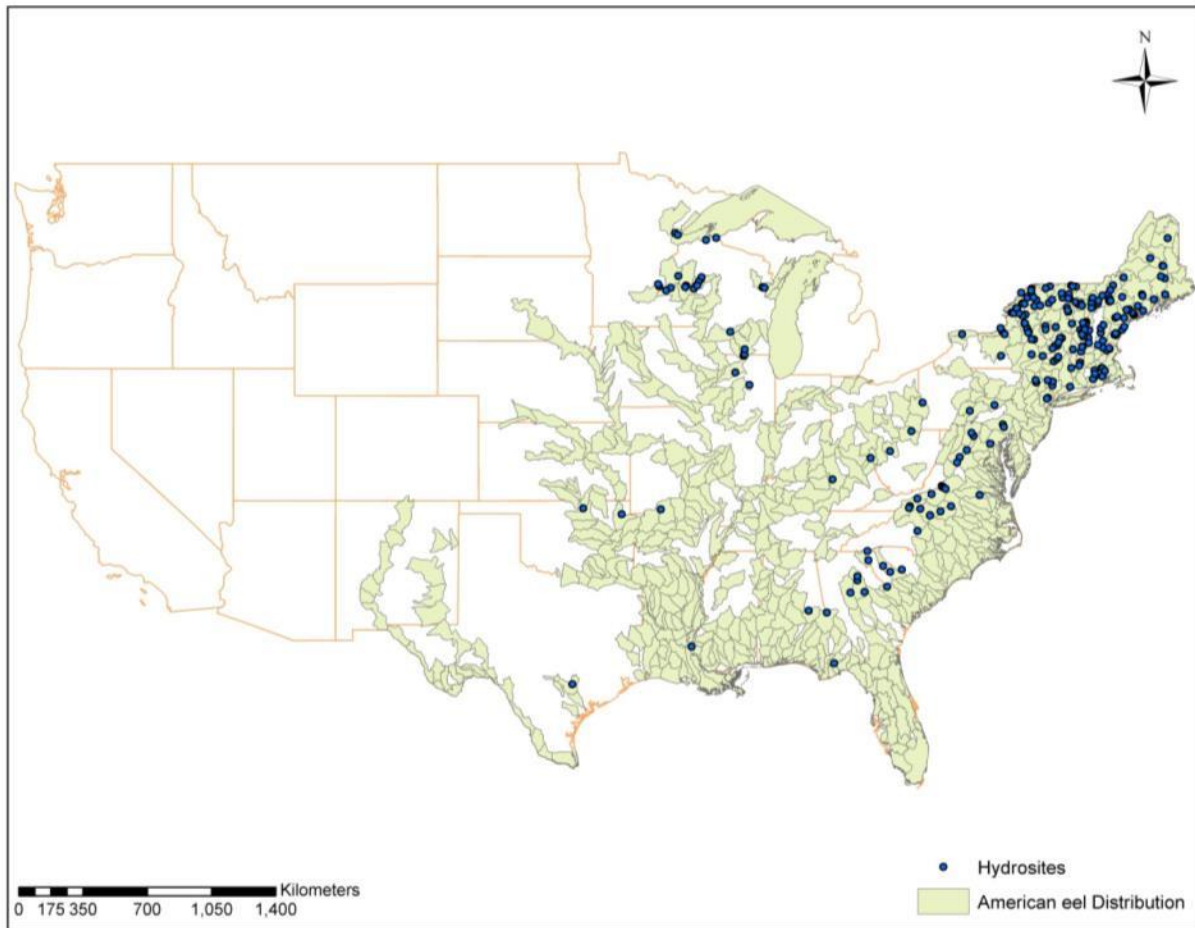


Figure 5-2. Hydropower sites that fall in the native range of American Eel with license expirations from 2019-2035.

Table 5-1. Size of projects in the native range of American eel

Size	# of	Percent of
Small (<5 MW)	170	64.6
Medium (5-20)	53	20.2
Large (>20 MW)	40	15.2

5.3 Case Studies

Case study evaluations of downstream eel passage were conducted for four projects of varying sizes (with respect to generating and turbine flow capacities) and configurations. For each selected project, conceptual designs and order-of-magnitude cost estimates were developed for application of the new eel bypass systems (vertical and horizontal zig-zag) and existing technologies and operational measures that are currently accepted by the USFWS for reducing turbine entrainment and passing eels downstream at hydro projects. Additionally, total project



survival was calculated for each downstream passage alternative considered for application at each project to compare biological benefits.

Downstream passage alternatives assessed for each site included the following:

- Existing project design and operational conditions
- Nightly turbine shutdowns
- 0.75-inch clear bar spacing on existing intake structure
- Angled bar rack with 0.75-inch clear bar spacing
- Vertical and horizontal eel bypass systems with 1-inch clear bar spacing

Order-of-magnitude costs were developed for structural downstream passage options using standard cost estimating techniques for conceptual engineering designs. Estimation of biological performance (i.e., bypass efficiency and total downstream passage survival) is described in the following section (5.3.1).

The goal of the case studies was to determine operational, cost, and biological benefits that may be realized with the new eel bypass systems when considered for a set of typical hydropower projects located within the population range of American Eel. However, based on the results of the field evaluation conducted at Mine Falls (Section 4), bypass efficiency and total project survival rates for the new bypass designs are unlikely to be as high as they would be for approaches currently accepted by the USFWS (i.e., 0.75-inch clear spacing on bar racks and 1.5 ft/s or less intake approach velocities, or nightly turbine shutdowns during the entire annual eel migration period), unless intake bar spacing is reduced to 0.75 inches and flow velocities are sufficiently low. Although USFWS sites requires a maximum approach velocity of 1.5 ft/s for silver eels, there is evidence from lab and field studies that velocities up to 2.0 ft/s can provide adequate protection from impingement. It is possible that the new bypass systems could meet USFWS requirements for downstream eel passage if future design improvements lead to higher bypass efficiencies or if the existing designs are installed in conjunction with bar rack clear spacings of 1 inch or less and with approach velocities less than 2.0 ft/s (i.e., to physically exclude eels from entrainment and eliminate impingement). The new bypass designs provide an economic advantage over conventional surface or submerged bypasses because they will require significantly less flow (by one or more orders of magnitude) for operation and eel passage.

5.3.1 Total Project Survival Estimation Methods

Total project survival was estimated by determining the proportion of eels using each available downstream passage route (turbines, gates, and spillway) and applying route-specific survival estimates. The proportions of eels approaching the powerhouse and spillway were assumed to be the same as the proportion of river flow passing through each route. That is, if 50% of the river discharge was passing over the spillway, then 50% of eels were assumed to also be passing downstream via this route. Eels approaching turbine intakes were assigned bypass or turbine passage based on effectiveness rates expected for each technology or operational measure as determined by existing literature (i.e., lab and field studies) or known performance (e.g., nightly



shutdowns are expected to be about 95 to 100% effective for bypassing eels, depending on the level of mortality experienced during spillway or gate passage). Bypass efficiency of the new eel bypass designs was assumed to be 40% based on the results of field testing at Mine Falls and assuming approach velocities would be sufficiently low to prevent impingement and reduce entrainment. Installation of 0.75-inch spaced bar racks on the existing intake or part of a new structured angled to the flow were assumed to have bypass efficiencies of 90 to 95% and 92 to 98% depending on estimated approach velocities at a given site. Estimates of total project survival were generated for the specified migration periods established by resource agencies for geographic regions based on known downstream movements of silver eels.

For the calculation of total project survival, silver eels passing downstream over spillways were assumed to have survival rates of 98% and survival of eels passing downstream through bypass systems was assumed to be 100%. Theoretical blade strike probability and mortality models are often used to estimate survival of fish passing through turbines at low head hydro projects. However, laboratory (Cook et al. 2003; Amaral et al. 2003) and field studies (Normandeau Associates 2011; ONEMA 2012) that have evaluated turbine passage survival of American and European eels have demonstrated that they have higher survival rates than typically would be estimated with the theoretical blade strike models. Consequently, the theoretical models, which have been shown to be reliable for predicting turbine mortality of many teleost fish species, are not considered applicable to eels. As an alternative, Alden used a multiple linear regression (MLR) model with a Gaussian error distribution developed from field studies eel turbine survival to estimate survival of silver eels passing through the turbines. The field data were initially compiled and analyzed by Gomes and Larinier (2008). Most of the field studies were conducted at projects in Europe with European eel, but some of the data are also from studies conducted with American Eel at projects in the U.S. and Canada.

5.3.2 Mine Falls Hydroelectric Project

Mine Falls hydroelectric Project is located on the Nashua River in Nashua, New Hampshire, and was the site of the field evaluation of the two new eel bypass designs described in Section 4. Mine Falls is owned by the city of Nashua and is operated by Essex Hydro. The project is operated as a run-of-river facility and consists of a 132-ft long spillway, three spillway sluices (one with a gate and two with stoplogs), a headgate structure, a power canal (forebay), a turbine intake structure, and a powerhouse with two Kaplan turbines (Figure 5-3). The forebay channel is about 167 ft long with a width of 22 ft over the first 62 ft of its length downstream of the head gate structure, after which it gradually widens to maximum width of 36 ft at the trash racks. The depth of the channel also gradually increases from upstream to downstream due to the floor sloping downward as it approaches the intake. Depending on flow, depth at the upstream end of the channel is about 18 to 20 ft and at the intake it is about 20 to 22 ft. The project has two vertical Kaplan turbines, each with a generation capacity of 1.5 MW (3 MW total) and a hydraulic capacity of about 990 cfs. Minimum flow for the bypass reach is 20 cfs. River flow exceedance probabilities and allocations at the project are provided in Table 5-2.



Figure 5-3. Mine Falls site configuration.

5.3.2.1 Modified Bar Rack with 0.75-inch clear Spacing

For this alternative, the bar rack clear spacing would be reduced to 0.75 inches in order to physically exclude entrainment of silver eels through the Mine Falls turbines. The existing bars would be removed and replaced with 0.25 inch thick by 3.00 inch wide rectangular cross section bars with 0.75 inch clear spacing. The new bar rack will be anchored to the existing supports and structures used for the current bar rack and the rack orientation to the flow would also remain perpendicular. The new bar rack would occupy the same dimensions as the existing structure (36 ft wide and have an effective height of 21.5 ft). Consequently, the narrower spacing would not alter intake approach velocities. This narrower spacing was chosen to meet the USFWS design criterion for silver eels. Some steel supports may need to be installed as the new bars will be placed on the existing rack structure. Eels entering the intake channel and excluded from turbine entrained would pass downstream into the bypass reach through the existing surface bypass, or they could return upstream to the impoundment and pass over the spillway (this behavior was observed during the field evaluation of the two new bypass designs). To provide an approach velocity less than 2 ft/sec, the turbines would have to be operated at a reduced load. The total cost estimate for installation of this alternative is about \$547,000 (Table 5-3). This estimate does not include the cost of lost generation due to reduced turbine load to achieve the desired approach velocities.



Table 5-2. Flow exceedance probabilities and allocations for the Mine Falls Project during the silver eel migration period.

River Flow (cfs)	Flow Exceedance Probability (%)	Unit 1		Unit 2		Spillway		Mill Pond Gatehouse		Fish Bypass	
		Allocated Flow (cfs)	Percent of Total Flow	Allocated Flow (cfs)	Percent of Total Flow	Allocated Flow (cfs)	Percent of Total Flow	Allocated Flow (cfs)	Percent of Total Flow	Allocated Flow (cfs)	Percent of Total Flow
30	99.5	0	0.0	0	0.0	20	66.7	10	33.3	0	0.0
55	97.5	0	0.0	0	0.0	20	36.4	10	18.2	25	45.5
100	90.2	0	0.0	0	0.0	65	65.0	10	10.0	25	25.0
205	71.8	150	73.2	0	0.0	20	19.8	10	4.9	25	12.2
300	57.3	245	81.7	0	0.0	20	6.7	10	3.3	25	8.3
400	45.5	345	86.3	0	0.0	20	5.0	10	2.5	25	6.3
500	35.2	445	89.0	0	0.0	20	4.0	10	2.0	25	5.0
600	28.6	545	90.8	0	0.0	20	3.3	10	1.7	25	4.2
700	24.0	645	92.1	0	0.0	20	2.9	10	1.4	25	3.6
755	21.5	550	72.8	150	19.9	20	2.6	10	1.3	25	3.3
800	19.8	550	68.8	195	24.4	20	2.5	10	1.3	25	3.1
900	17.0	550	61.1	295	32.8	20	2.2	10	1.1	25	2.8
1,000	14.8	550	55.0	395	39.5	20	2.0	10	1.0	25	2.5
1,155	11.5	550	47.6	550	47.6	20	1.7	10	0.9	25	2.2
1,500	6.8	550	36.7	550	36.7	365	24.3	10	0.7	25	1.7
2,000	3.2	550	27.5	550	27.5	865	43.3	10	0.5	25	1.3
2,500	1.3	550	22.0	550	22.0	1,365	54.6	10	0.4	25	1.0
3,000	0.0	550	18.3	550	18.3	1,865	62.2	10	0.3	25	0.8



Table 5-3. Estimated Construction Costs to Modify the Existing Bar Rack at Mine Falls

Item	Cost
Trash Rack and supports	\$312,930
New Trash Rake	\$233,680
Total Estimated Project Costs	\$546,610

5.3.2.2 Angled Bar Rack

For this alternative, a new angled bar rack structure would be constructed in the intake channel upstream of the powerhouse and existing rack (Figure 5-4, Figure 5-5). The angled rack will be positioned at a 45 degree angle to the flow and consist of bars that have 0.25 inch thick by 3.00 inch deep rectangular cross sections and a clear spacing of 0.75 inches. With a length of 42 ft and height of 21.5 ft, the angled rack will have a maximum approach velocity of 1.3 ft/sec. The approach velocity was calculated allowing for up to 10% of the rack area to be used for supports and bypasses. The narrow bar spacing and low approach velocity meet USFWS for preventing entrainment and impingement of silver eels. The top of the bar rack would be mounted to a new 7 ft wide work deck. The rack will extend down from the work deck vertically to the forebay floor. A steel structure and concrete mat would be constructed in the forebay to support the rack and walkway structures. The existing trash rack would no longer be needed and could be removed from the intake.

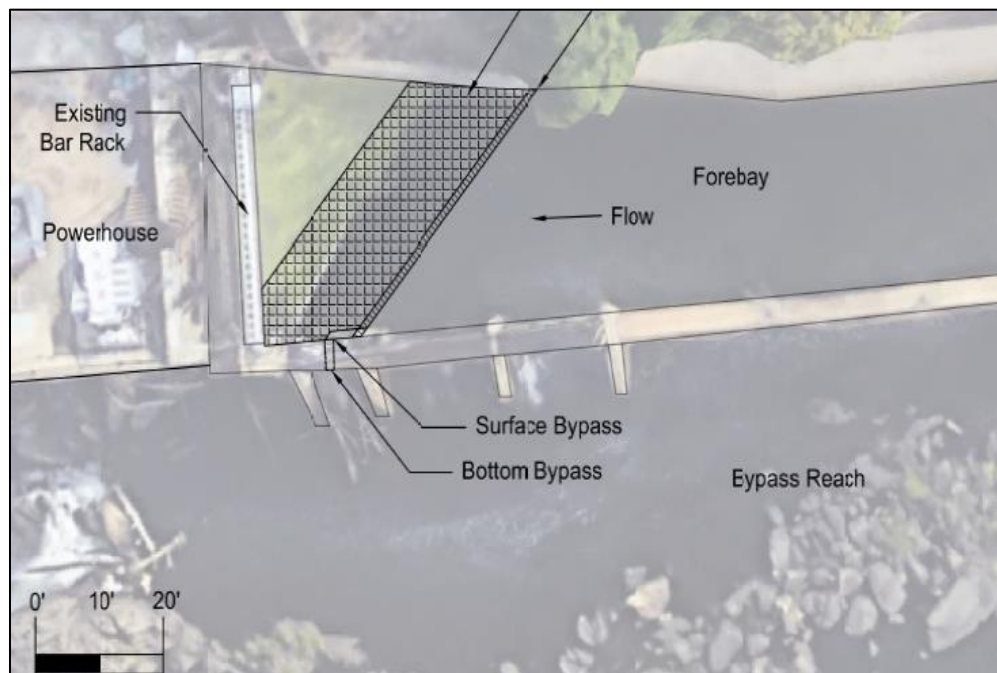


Figure 5-4. Conceptual design of an angled bar rack installed at Mine Falls (plan view).

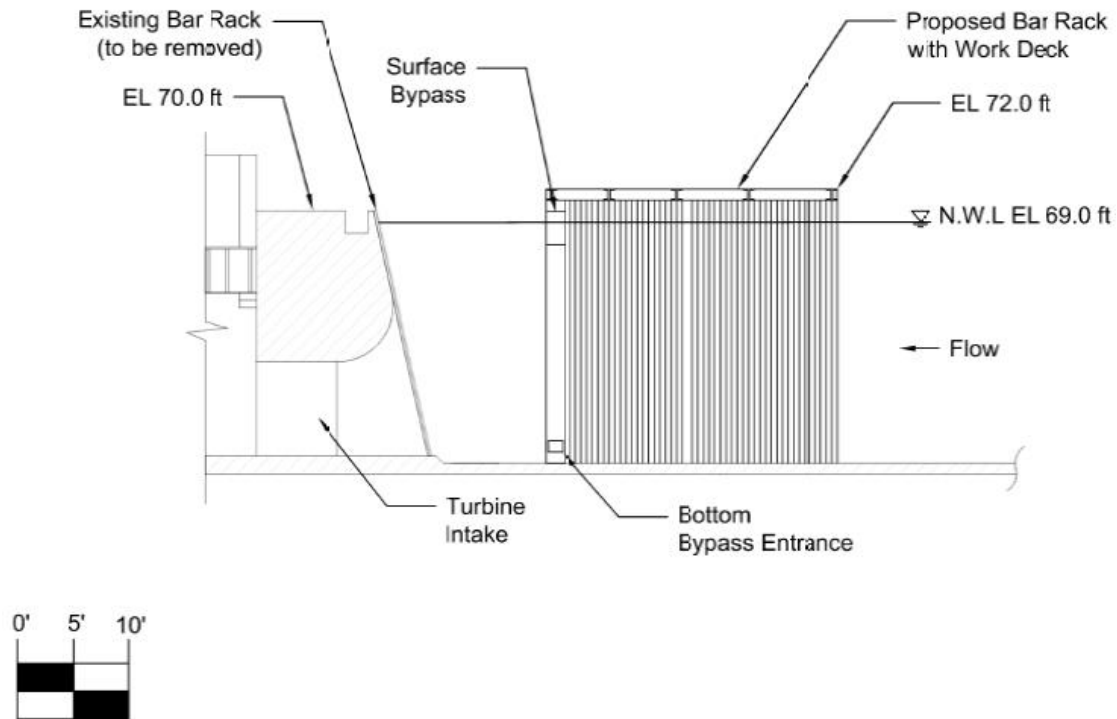


Figure 5-5. Conceptual Design of an angled bar rack installed at Mine Falls (section view).

The angled bar rack alternative provides physical exclusion of eels from entrainment through the turbines and guidance to a bypass. Two downstream bypasses would be installed on the rack, one at the surface and one at the bottom. The bottom bypass will be piped through the drain hole located in the forebay wall and discharge into the bypass reach. The surface bypass will be plumbed via a siphon that will pass the downstream migrants over the forebay wall discharging them into the bypass reach. The total cost estimate for installation of an angled bar rack in the Mine Falls intake channel is about \$950,000 (Table 5-4).

5.3.2.3 Modified Operations: Nightly Turbine Shutdowns

Modified turbine operations designed to reduce eel entrainment at Mine Falls would involve nightly shutdowns for the entire eel migration season or for targeted multi-day periods based on rain events. Targeted turbine shutdowns would be implemented following significant rain events (i.e., high flow periods) that are expected to trigger downstream movements of silver eels. During these events, the turbines would not be operated for a specified number of days and eels would pass via spill over the dam or through the existing surface bypass adjacent to the intake.



Table 5-4. Estimated costs for installation of an angled bar rack at Mine Falls.

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$45,399
New Rack and Supports	\$424,589
Work deck and Cleaning Rake	\$29,400
Distributable Costs (20% labor and Materials)	\$99,878
Direct Costs Subtotal	\$599,265
Indirect Costs	\$59,927
Direct and Indirect Costs Subtotal	\$659,192
Allowance for Indeterminates (25%)	\$164,798
Allowance for Contingencies (15%)	\$123,598
Total Estimated Project Cost	\$947,588

Under current project conditions, the turbines at Mine Falls are operated when there is enough flow in the river to meet the bypass reach minimum flow requirement and operation of at least one unit at the minimum flow required for startup. Currently, the USFWS accepts nightly turbine shutdowns as a permanent downstream passage approach for silver eels when units are turned off every night of the migration season. Targeted shutdowns that rely on specified rain fall amounts to trigger turbine shutdowns for a predefined period of time (e.g., two days following a rain event) have only been accepted as an interim measure until alternative downstream passage facilities are installed and are operational. Nightly shutdowns would require frequent start and stop operations of the turbines. This can cause significant wear to the units as well as cause significant reductions and surges in flows downstream of the project. Due to these impacts to the equipment and downstream flows, as well as potential significant generation losses, modified (targeted) nightly shutdowns triggered by rain were evaluated as the only feasible alternative for modified project operations at Mine Falls. However, without validation of the proportion of the silver eel protected by targeted shutdowns, the state and federal resource agencies may not accept this approach as a permanent measure for downstream eel passage.

Criteria for the amount of rainfall needed to trigger a shutdown would need to be established, as well as how many subsequent nights the shutdown would be implemented for following the rain event. For this scenario, it was assumed that 28 nights of shutdowns for rain triggered events would occur each year, on average, compared to 113 night for shutdowns every night of the eel migration season. For comparison purposes between the two approaches to nightly shutdowns, generation losses were calculated for the entire four month migration season, and for 28 nights of targeted shutdowns. These losses were calculated based on annual power generation data from 2000 to 2017. It was estimated that nightly shutdowns during the entire eel migration season would result in a 46% reduction in generation, whereas rain triggered



shutdowns would only lead to a 12% reduction. The estimated generation and revenue losses are provided in Table 5-5.

5.3.2.4 Vertical and Horizontal Zig-Zag Eel Bypass Systems

The vertical and horizontal zig-zag bypass systems were assessed as a downstream passage alternative for Mine Falls without any modifications to the existing bar racks. The horizontal zig-zag bypass would include a series of 8-inch diameter pipes connected together at 30 degree angles in a zig-zag pattern (Figure 5-6, Figure 5-7). At each interior angle, there is a bypass port (entrance opening). The pipes are set horizontally across the base of the trash rack and are plumbed via a siphon to exit over the dam and into the bypass reach. A row of brushes would be installed just upstream of the zig-zag piping to provide a resting area (velocity refuge) for the eels and to reduce debris accumulation on the bypass pipes. The total flow through the horizontal portion of the system installed at Mine Falls would be about 0.8 cfs.

The vertical bypass conduits would include four 12-inch diameter vertical pipes. The pipes would be located at each end of the trash rack and one on the center line of each unit. Each vertical bypass would have a central pipe with tangential plates oriented at right angles along the lengths of the pipe with a series of entrance ports located sequentially over the pipe length. Large horizontal plates between entrance locations would provide additional guidance for eels towards the inlet ports. Brushes would be installed along the leading edges of the plates to provide a velocity refuge for the eels as well as provide the entrance ports with some protection from becoming clogged with debris. Each bypass would be designed for a flow of about 0.56 cfs, resulting in a total flow of 2.24 cfs for the whole vertical system. The bypasses would flow into a header pipe which would be controlled by a siphon and discharge into the bypass reach at the same location as the horizontal bypass system.

The estimated total cost for installation of the two eel bypass systems at Mines Falls is about \$80,000 (Table 5-6).

Table 5-5. Estimated lost generation and revenue for nightly turbine shutdown alternatives at Mine Falls.

Option	Reduction in Generation (%)	Reduction in Generation (MWh)	Lost Revenue (\$)
Nightly shutdowns (113 Days)	46%	1,627	\$47,938
Targeted Nightly Shutdowns (28 Days)	12%	424	\$12,506

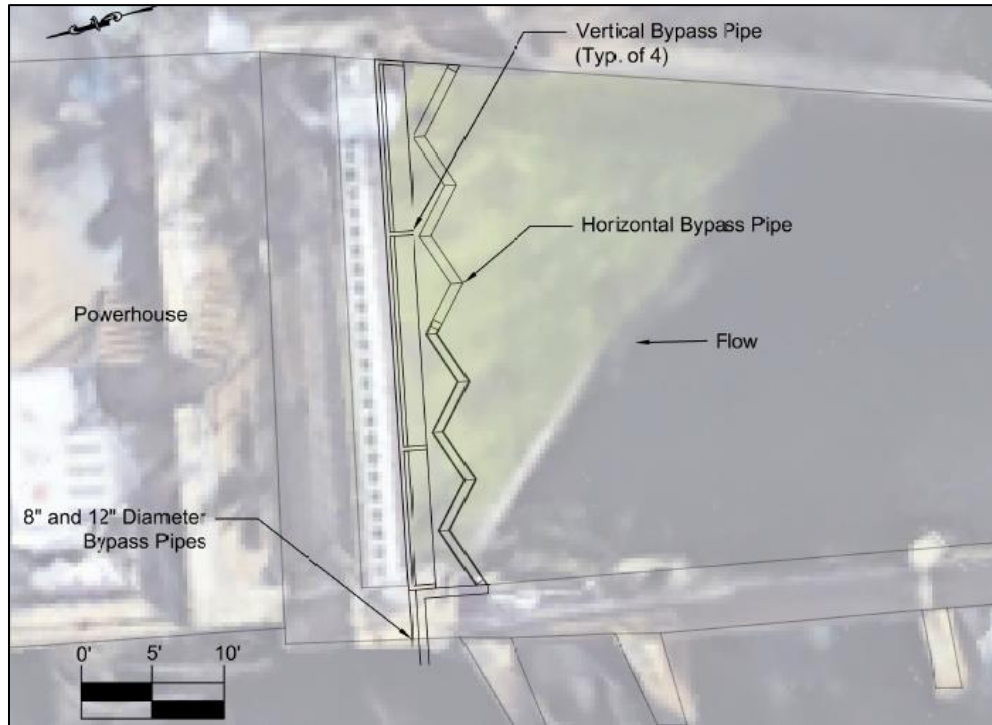


Figure 5-6. Vertical and horizontal eel bypass conceptual designs for Mine Falls (plan View).

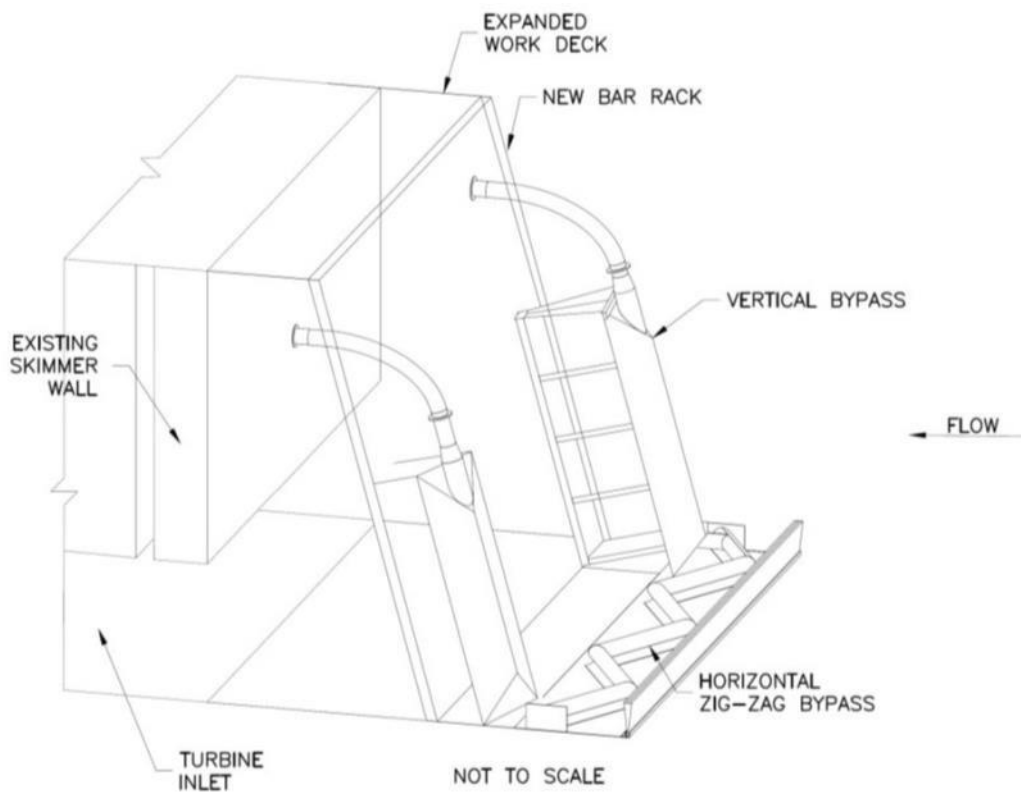


Figure 5-7. Vertical and horizontal eel bypass conceptual designs for Mine Falls (isometric View).



Table 5-6. Estimated for vertical and horizontal zig-zag bypass system installed at Mine Falls.

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$16,244
Horizontal Zig-Zag with Bypass Piping	\$52,071
Vertical Bypass with Piping	\$110,367
Distributable Costs	\$35,736
Direct Costs Subtotal	\$214,418
Indirect Costs	\$21,442
Direct and Indirect Costs Subtotal	\$271,596
Allowance for Indeterminates	\$67,899
Allowance for Contingencies	\$40,739
Total Estimated Project Costs	\$380,235

5.3.2.5 Mine Falls Turbine and Total Project Survival

The independent variables included in the multiple linear regression model developed to estimate eel turbine survival accounted for 88% of the variability in survival estimates among the study sites where field studies were conducted (Table 5-7). Turbine survival estimates for eels entrained through the Mine Falls units ranged from 29.0 to 31.3 (Table 5-8). Total project survival for the existing design and operational conditions at Mine Falls ranged from 52 to 98%, with an overall survival rate across the entire migration period of 61.5% (Table 5-9). For the two downstream passage alternatives with 0.75-inch clear bar spacing, total project survival ranged from about 93 to 98%, with an overall survival rate of 96% (Table 5-9). Total project survival ranged from 58 to 98% for new eel bypass designs, with an overall survival rate of 73.6% (Table 5-9).



Table 5-7. Multiple linear regression model results used to estimate turbine survival of silver eels at Mine Falls.

Regression Statistics				
Residual SE	0.088			
DF	50			
Multiple R^2	0.885			
Adjusted R^2	0.878			
F-statistic	128.4			

Coefficients	Estimate	SE	T-value	P-value
(Intercept)	1.2583	0.0679	18.519	0.0000
Test Flow	0.0007	0.0002	4.202	0.0001
Eel Length	-0.6156	0.1096	-5.618	0.0000
RPM	0.0017	0.0001	-12.612	0.0000

Table 5-8. Turbine survival estimates for silver eels passing through the Mine Falls units.

Gate Opening (%)	Turbine Survival (%)	95% CI
27	31.3	24.3-38.3
35	31.0	24.8-37.3
45	30.7	25.4-36.1
54	30.4	25.3-33.1
63	30.2	25.9-34.3
72	29.9	26.0-33.8
81	29.6	25.7-33.5
99	29.1	24.3-33.8
100	29.0	24.2-33.8



Table 5-9. Total project survival estimates by river flow for silver eels passing downstream at Mine Falls for the existing conditions and each passage design alternative considered.

River Flow (cfs)	Flow Proportion	Total Project Survival (%)			
		Existing Conditions	Bar Rack with 0.75-inch Spacing	Angled Bar Rack with 0.75-inch Spacing	Vertical/Horizontal Eel Bypass Systems with 1-inch Spacing
30-54	3.0	98.0	98.0	98.0	98.0
55-99	7.0	98.0	98.0	98.0	98.0
100-204	18.0	98.0	98.0	98.0	98.0
205-300	15.0	54.1	95.6	95.6	68.7
300-399	11.0	48.5	95.3	95.3	65.0
400-499	11.0	45.4	95.1	95.1	62.9
500-599	7.0	43.2	95.0	95.0	61.5
600-699	4.0	41.7	91.7	93.0	60.5
700-754	2.0	40.8	91.6	92.9	59.9
755-799	2.0	40.8	91.6	92.9	59.9
800-899	3.0	40.6	91.6	92.9	59.7
900-999	3.0	40.1	91.6	92.9	59.4
1000-1154	3.0	39.6	91.5	92.8	59.1
1155-1499	4.0	38.9	91.4	92.7	58.6
1500-1999	4.0	52.5	92.9	94.0	67.6
2000-2499	2.0	63.8	94.2	95.0	75.2
>2500	1.0	70.7	95.0	95.6	79.8
Totals	100.0	61.5	96.0	96.0	73.6

5.3.2.6 Mine Falls Case Study Conclusions

The use of 0.75-inch bar spacing on the existing intake structure or with a new angled bar rack would produce high downstream passage survival rates (96%) for silver eels at Mine Falls (Table 5-10). However, these two options were also estimated to be the most costly alternatives for protecting eels (Table 5-10). Targeted nightly shutdowns would provide the highest survival rate (98%) for eels passing downstream at Mine Falls. The target shutdowns would produce an estimated annual generation loss of about \$12,000 (shutting down every night during the eel migration season would be two to three times more). However, the cost of lost generation would be about \$500,000 over the course of a 40 year FERC license term. Installation of vertical and horizontal eel bypass systems at Mine Falls would cost about \$380,000, but the downstream passage survival estimate (73.6%) was considerably lower for this alternative. With both units operating and maintained at generation levels that limited intake approach velocities to less than 2.0 ft/s, the new eel bypass designs could potentially provide higher survival rates comparable to the other options while diverting significantly less flow for bypass use than the two narrow-spaced bar rack alternatives (i.e., about 3 to 6 cfs compared to 400 to 500 cfs). Based on observations from the field evaluation at Mine Falls, use of narrow bar spacings (1 inch or less) would be problematic due to high intake approach velocities and extensive debris loading, both of which could contribute to unacceptable levels of eel impingement.



Table 5-10. Summary of bypass efficiency, total project survival, and approximate cost for silver eel downstream passage alternatives considered for Mine Falls.

Downstream Passage Alternative	Assumed Bypass Efficiency (%)	Total Project Survival (%)	Approximate Cost (\$)
Existing conditions	10	61.5	--
Bar rack with 0.75-inch spacing	90-95	96.0	550,000
Angled bar rack with 0.75-in spacing	92-95	96.0	950,000
Targeted nightly turbine shutdowns	100	98.0 ¹	12,500/500,000 ²
Vertical/horizontal eel bypasses with 1-in spacing	40	73.6	380,000

¹ Total project survival over the course of the entire eel migration season likely would be lower than 98% given some proportion of eels will pass downstream during daylight hours and nights when the turbines are operating.

² Annual cost of lost generation due to nightly shutdowns and total cost over 40 year license term.

5.3.3 Pepperell

The Pepperell Hydroelectric Project (PHP) is located on the Nashua River in Pepperell, MA and is owned and operated by Pepperell Hydro Company, LLC (PHC). The project is a run-of-river facility with a 244-ft long and 26.5 ft high concrete gravity ogee spillway with 30 ft of head (Figure 5-8). The 565-ft long penstock leads to the forebay where the intake has a trash rack with 1.75 inch clear bar spacing and approach velocities ranging from 0.1 to 1.2 ft/s depending on turbine flow (Table 5-11). The minimum flow requirement for the bypass reach is 46 cfs, which is released through a gate at the dam when there is no spill. The powerhouse consists of three Francis turbines with a combined generating capacity of 1.9 MW and a total hydraulic capacity of 2,310 cfs. River flow exceedance probabilities and allocations at the project are provided in Table 5-11.

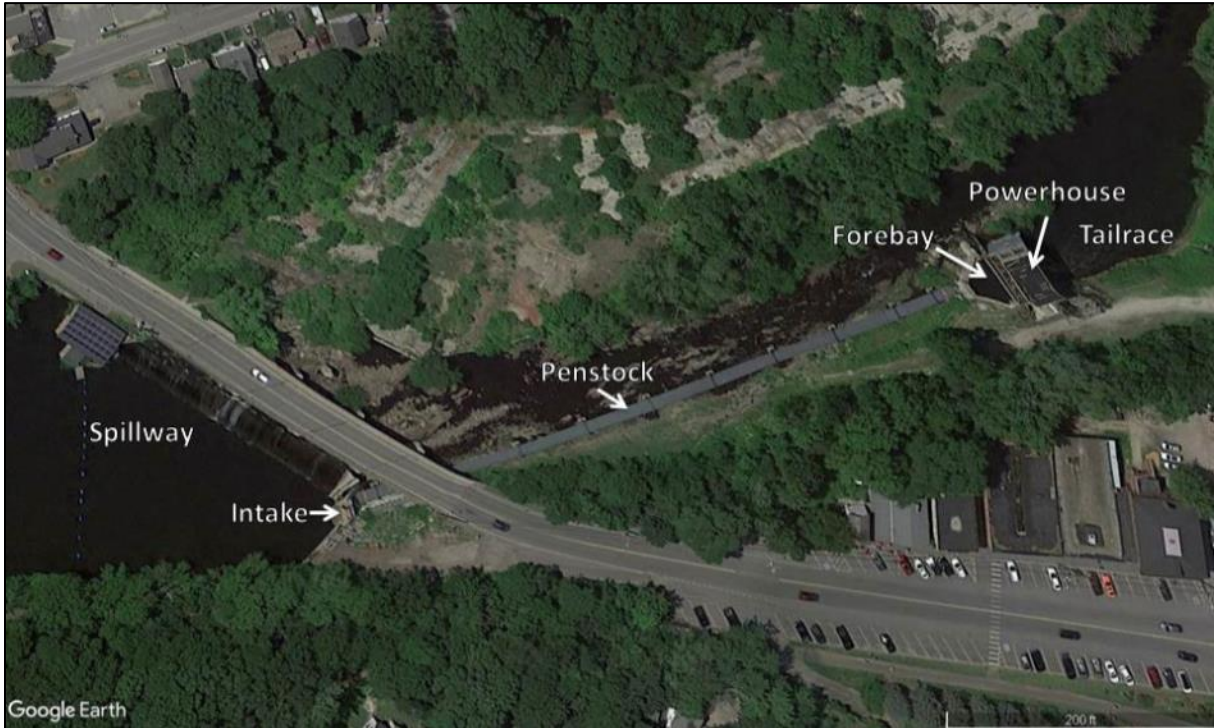


Figure 5-8. Configuration of the Pepperell Hydroelectric Project.

5.3.3.1 Modified Bar Rack with 0.75-inch Clear Spacing

For this alternative, the bar rack clear spacing would be reduced to 0.75 inches in order to physically exclude silver eels from passing through the Pepperell turbines. The current area of the bar racks would remain at 58.0 ft wide and 17.3 ft high. New bar slats would be 0.25 inches thick by 3.00 inches deep with rectangular cross section. The new bar rack will be anchored to the existing supports and structures used for the current rack and the orientation to the flow would also remain perpendicular. The spacing and bar size would not alter intake approach velocities, which are estimated to be about 1.2 ft/s at maximum generation flow (all three units combined). Because this option provides physical exclusion from turbine entrainment, a dedicated downstream bypass would need to be installed to provide eels with a safe downstream passage route from the forebay to the tailwater. Based on USFWS design criteria, the bypass would require a flow rate of 70 to 115 cfs (i.e., 3 to 5% of station discharge). Debris loading and head loss would increase due to the narrower bar spacing, requiring more effort to maintain a clean rack. The total estimated cost for this alternative is \$640,000 (Table 5-12).



Table 5-11. Flow exceedance and allocation at the Pepperell Project during the silver eel downstream migration period.

River Flow (cfs)	Flow Exceedance Probability (%)	Trash Rack Approach Velocity (ft/s)	Spillway		Unit 1		Unit 2		Unit 3	
			Allocated Flow (cfs)	Percent of Total Flow (%)	Allocated Flow (cfs)	Percent of Total Flow (%)	Allocated Flow (cfs)	Percent of Total Flow (%)	Allocated Flow (cfs)	Percent of Total Flow (%)
50	97.8	0.0	50	100.0	0	0.0	0	0.0	0	0.0
196	73.2	0.1	46	23.5	150	76.5	0	0.0	0	0.0
250	64.6	0.2	46	18.4	204	81.6	0	0.0	0	0.0
350	50.6	0.3	46	13.1	304	86.9	0	0.0	0	0.0
475	37.9	0.4	71	15.0	429	90.3	0	0.0	0	0.0
600	28.3	0.4	171	28.5	429	71.5	0	0.0	0	0.0
750	21.8	0.7	46	6.1	429	57.2	0	0.0	275	36.7
863	18.0	0.8	83	9.6	429	49.7	0	0.0	345	40.0
1,000	14.3	0.8	183	18.3	429	42.9	180	18.0	345	34.5
1,208	10.4	1.2	88	7.3	429	35.5	388	32.1	345	28.6
1,350	8.3	1.2	188	13.9	429	31.8	388	28.7	345	25.6
1,500	6.7	1.2	338	22.5	429	28.6	388	25.9	345	23.0
1,750	4.7	1.2	588	33.6	429	24.5	388	22.2	345	19.7
2,000	3.4	1.2	838	41.9	429	24.5	388	19.4	345	17.3
2,500	1.3	1.2	1,338	53.5	429	17.2	388	15.5	345	13.8
3,000	0.8	1.2	1,838	61.3	429	14.3	388	12.9	345	11.5



Table 5-12. Estimated costs for reducing the bar spacing at the existing intake to 0.75 inches (clear) at Pepperell.

Component	Cost Estimate
Trash Rack and Supports	\$406,323
New trash rake	\$233,680
Total Estimated Project Costs	\$640,004

5.3.3.2 Angled Bar Rack

For this alternative, a new bar rack structure would be constructed upstream of the existing penstock intake in the impoundment (Figure 5-9, Figure 5-10). The new rack would have 0.75-inch clear bar spacing. The bar rack would be 46 ft long with an effective height of 29 ft. This size was selected to maintain maximum average approach velocities below the 1.5 ft/sec USFWS design criterion for silver eels, while allowing for up to 10% of the trash rack area to be used for supports or bypasses. The maximum approach velocity calculated over the range of turbine flows for this rack design is 1.1 ft/sec. The new rack would consist of 0.25 inch thick by 3.00 inch deep rectangular cross section bars. The top of the bar rack would be mounted to a new 7-ft wide work deck constructed over the intake. The new bar rack would extend down vertically from the work deck to the river bed. A steel superstructure and concrete mat would support the work deck and bar rack. The existing trash rack would no longer be needed and could be removed.

Eels excluded and diverted by a new intake rack would utilize either a surface or bottom bypass installed at the downstream end of the rack and both of which would discharge over the spillway and into the bypass reach. The bottom bypass would consist of a siphon tube extending from the entrance to a location on the downstream side of the spillway. The bypasses would be designed to pass 3 to 5% (about 70 to 115 cfs) of the powerhouse flow capacity to meet USFWS design criteria. This intake design is expected to meet USFWS biological performance requirements due to the narrow bar spacing, low approach velocities, and the use of bottom and surface bypasses. The cost estimate for this alternative is provided in Table 5-13.

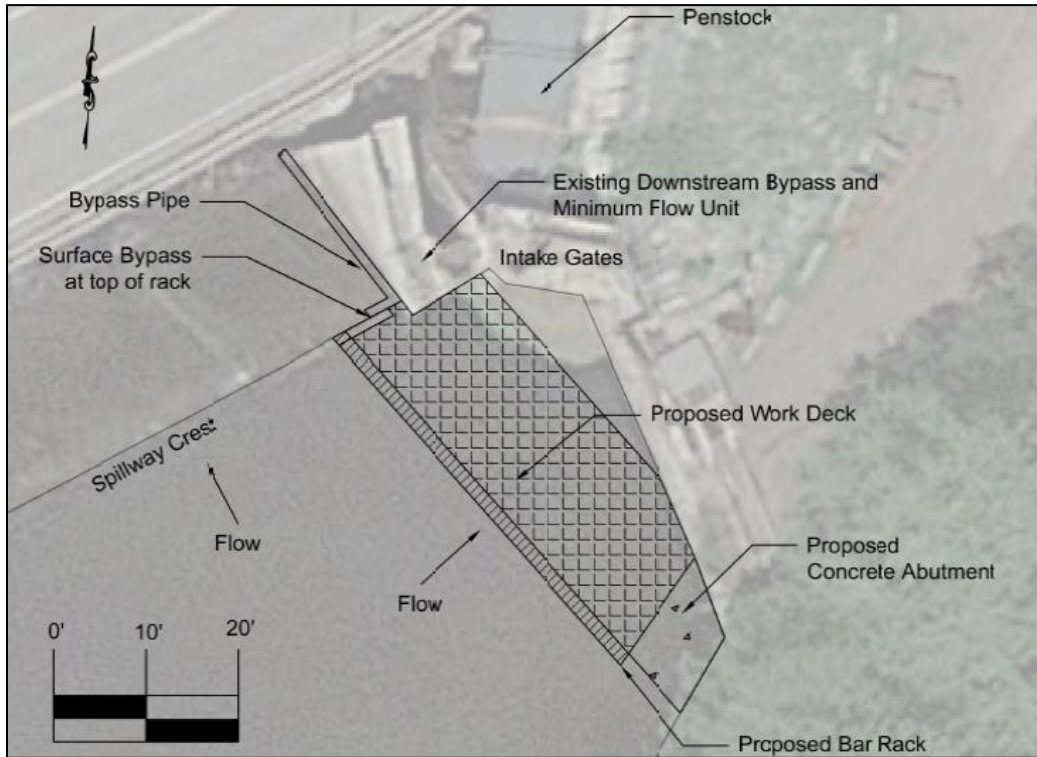


Figure 5-9. Angled bar rack designed for the Pepperell penstock intake (plan view).

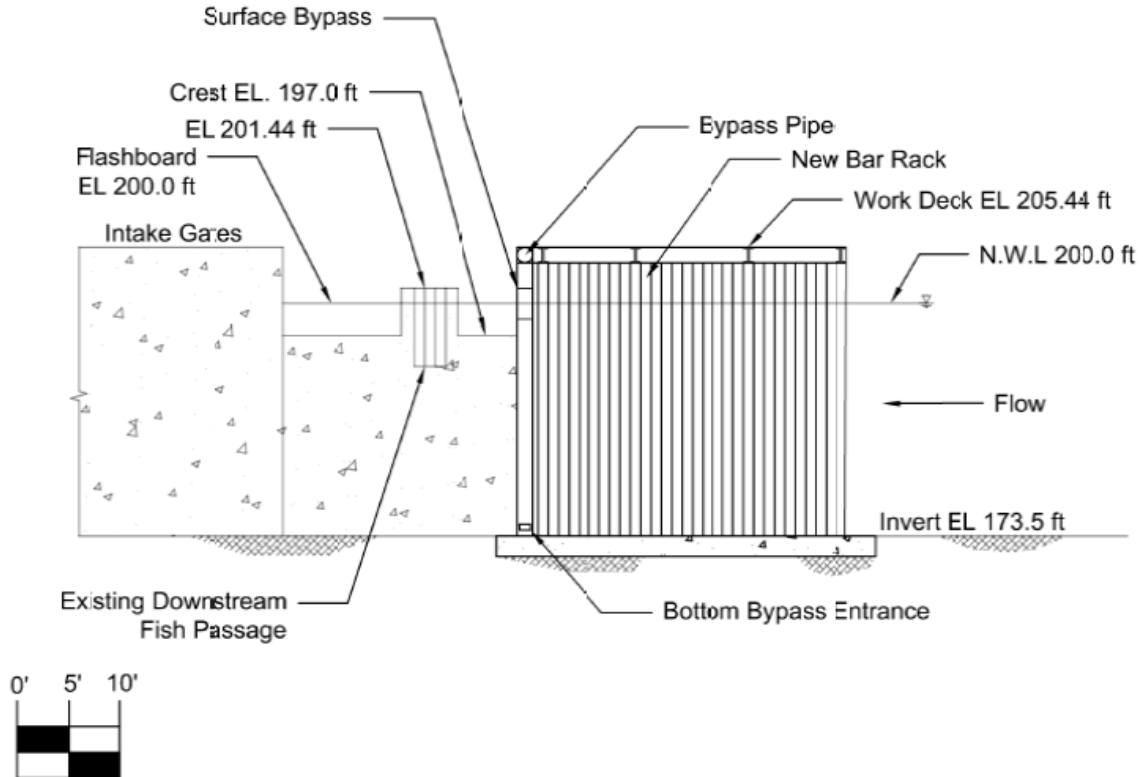


Figure 5-10. Angled bar rack designed for the Pepperell penstock intake - section view.



Table 5-13. Estimated costs for an angled bar rack installed at the penstock intake at Pepperell.

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$73,815
Dredging and Earthwork	\$15,810
New Rack and Supports	\$539,430
Side Walls	\$145,851
Work deck and Cleaning Rake	\$37,352
Distributable Costs (20% labor and Materials)	\$162,452
Direct Costs Subtotal	\$974,709
Indirect Costs	\$97,471
Direct and Indirect Costs Subtotal	\$1,072,180
Allowance for Indeterminates (25%)	\$268,045
Allowance for Contingencies (15%)	\$201,034
Total Estimated Project Costs	\$1,541,259

5.3.3.3 Modified Operations: Nightly Turbine Shutdowns

Modified turbine operations designed to reduce eel entrainment at Pepperell would involve nightly shutdowns for the entire eel migration season or for targeted multi-day periods based on rain events. Targeted turbine shutdowns would be implemented following significant rain events (i.e., high flow periods) that are expected to trigger downstream movements of silver eels. During these events, the turbines would not be operated for a specified number of days and eels would pass via spill over the dam or through an existing gate adjacent to the intake.

Under current project operations, the turbines at Pepperell are brought online when there is enough flow in the river to meet the bypass reach minimum flow requirement and allow for unit operation. Currently, the USFWS accepts nightly turbine shutdowns as a permanent downstream passage approach for silver eels when units are turned off every night of the migration season. Targeted shutdowns that rely on specified rain fall amounts to trigger turbine shutdowns for a predefined period of time (e.g., two days following a rain event) have only been accepted as an interim measure until alternative downstream passage facilities are installed and are operational. Conducting nightly shutdowns over the entire migration season would require frequent start and stop operations of the turbines. This can cause significant wear to the units, as well as cause large reductions and surges in flow downstream of the project. Due to these impacts to the equipment and bypass reach flows, as well as significant generation losses, modified (targeted) nightly shutdowns triggered by rain were evaluated as the only feasible alternative for modified project operations at Pepperell. However, without validation of the proportion of the silver eel protected by targeted shutdowns, the state and



federal resource agencies may not accept this approach as a permanent measure for downstream eel passage.

PHC provided a model that estimated that 529 MWh would be lost due to rain-event triggered nightly shutdowns during the eel passage season of August 15 to December 15. This would result in approximately \$15,590 in lost in revenue per migration season. The model developed by PHC assumed that a shutdown is triggered by any rain even greater than 0.5 inches. Historical rainfall data was used from 1996 to 2015 from river basin gages in Fitchburg, Groton, and Ashburnham (all locations in Massachusetts) to predict the number of rainfall events that will likely occur in a single passage season. All available data from the Fitchburg gage were used as it is located centrally in the watershed, and any missing data were then filled in using the Groton and Ashburnham gages, which are located on the eastern and western edges of the watershed. Targeted shutdowns would begin the day after a rain event and last for two days before generation would resume.

5.3.4 Vertical and Horizontal Zig-Zag Eel Bypass Systems

The eel bypass systems assessed for Pepperell included the horizontal zig-zag and vertical designs. The application of each bypass system at Pepperell was based on the use of the existing bar rack to provide some level of exclusion from turbine entrainment and the effectiveness of the new bypass systems as determined from the Mine Falls field evaluation. A horizontal zig-zag bypass installed at Pepperell would include a series of 8 inch diameter pipes connected together at a 30 degree angle in a zig-zag pattern (Figure 5-11, Figure 5-12). At each interior angle, there is a bypass port (entrance opening). The pipes are set horizontally across the base of the trash rack and are plumbed via a siphon to exit over the dam and into the tailrace. A row of brushes would be installed just upstream of the rack to provide refuge for eels just upstream of the bypass and intake, as well as reduce debris build-up on the bypass pipes. The total flow through the horizontal portion of the system would be about 1.3 cfs. Because the penstock discharges water into the forebay lower than the turbine intake inlet, unique hydraulics may affect the functionality of the zig-zag bypass system.

The vertical zig-zag bypass would include five vertical pipes each with a 12 inch diameter. The pipes would be located at each end of the trash rack and one in line with the center line of each unit. Each vertical bypass would have a vertical central pipe with a tangential plates oriented at right angles along the lengths of pipe with a series of entrance ports located sequentially along the pipes. Large horizontal sections between entrance locations would further guide eels to the inlet ports. Brushes would be installed along the leading edges of the plates to provide refuge for the eels as well as protect the entrance ports from becoming clogged with debris. Each bypass would be designed for a flow of 0.35 cfs, resulting in a total flow of 1.75 cfs for the whole vertical system. The bypasses would flow into a header pipe, which is controlled by a siphon, and would discharge into the bypass reach. The total estimated cost for the installation and operation of this alternative at Pepperell about \$405,000 (Table 5-14).

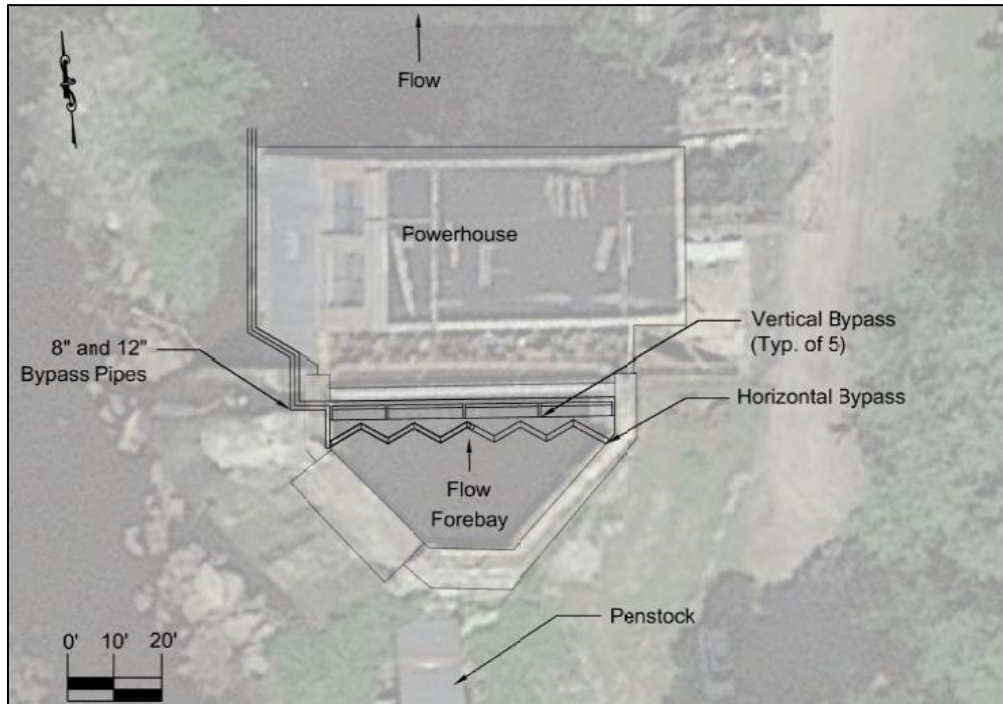


Figure 5-11. Conceptual design of vertical and horizontal bypasses installed at Pepperell (plan view).

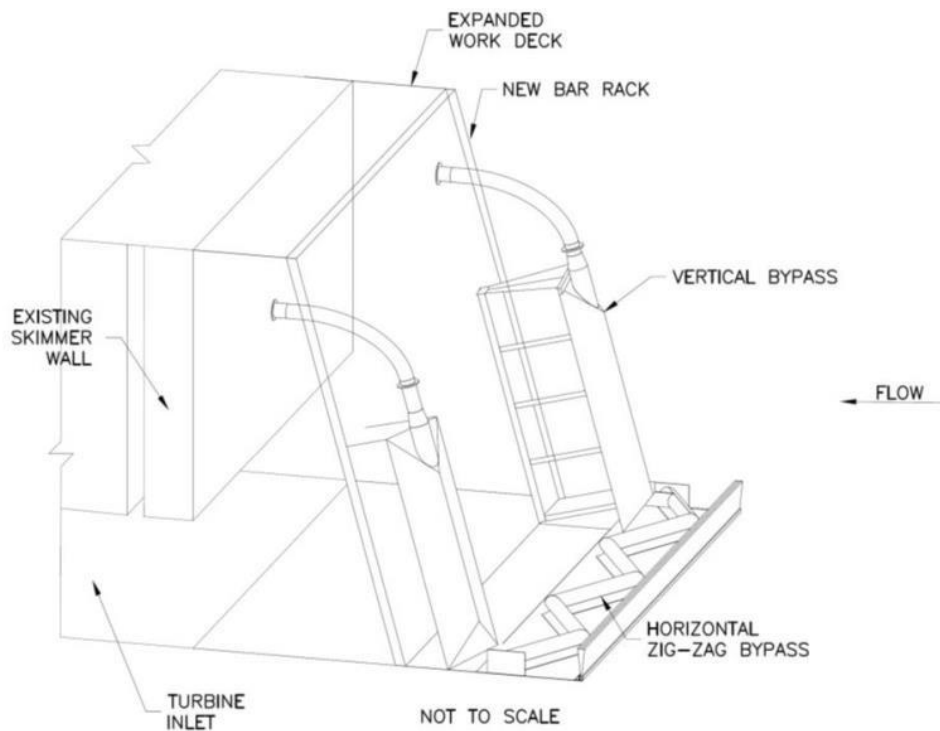


Figure 5-12. Conceptual design of vertical and horizontal bypasses installed at Pepperell (isometric view).



Table 5-14. Estimated construction costs for vertical and a horizontal zig-zag eel bypass system installed at Pepperell.

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$17,285
Horizontal Zig-Zag with Bypass Piping	\$83,893
Vertical Bypass with Piping	\$88,961
Distributable Costs	\$38,028
Direct Costs Subtotal	\$228,167
Indirect Costs	\$22,817
Direct and Indirect Costs Subtotal	\$289,011
Allowance for Indeterminates	\$72,253
Allowance for Contingencies	\$43,352
Total Estimated Project Costs	\$404,616

5.3.4.1 Turbine and Total Project Survival Estimates

The independent variables included in the multiple linear regression model developed to estimate eel turbine survival accounted for 88% of the variability in survival estimates among the study sites where field studies were conducted (Table 5-15). Turbine survival of eels passing downstream at Pepperell ranged from about 29 to 51% depending on the unit and turbine flow (Table 5-16). Total project survival for the existing (baseline) conditions ranged from about 51 to 98%, with an overall estimate 74.5% for the entire migration season (Table 5-17). The vertical and zig-zag bypass systems produced a total survival estimate of 77.6%. Installation of 0.75-inch clear bar spacing on the existing intake structure and the installation of an angled bar rack with 0.75-inch spacing produced total project survival rates of about 94% (Table 5-17).



Table 5-15. Multiple linear regression model results used to estimate turbine survival of silver eels at Pepperell.

Regression Statistics				
Residual Standard Error	0.0875			
DF	50			
Multiple R^2	0.8851			
Adjusted R^2	0.8782			
F-statistic	128.4			

Coefficients	Estimate	Std Error	T-value	P-value
(Intercept)	1.2583	0.0679	18.519	<2E-16
Unit Flow	0.0007	0.0002	4.202	0.0001
Eel Length	-0.6156	0.1096	-5.618	8.50E-07
RPM	0.0017	0.0001	-12.612	<2E-16

Table 5-16. Survival estimates for silver eels passing through the turbines at Pepperell.

Turbine	Flow (cfs)	Gate Opening (%)	Turbine Survival (%)	95% CI
Unit 1	150	35.0	51.1	45.2-57.1
	204	47.6	50.7	46.0-55.6
	304	70.9	50.0	46.4-53.7
	429	100.0	49.2	44.4-53.9
Unit 2	180	46.4	30.0	25.1-35.6
	388	100.0	28.7	23.8-33.5
Unit 3	275	79.7	50.0	45.8-53.3
	345	100.0	49.0	44.2-53.7



Table 5-17. Total project survival estimates by river flow for silver eels passing downstream at Pepperell for the existing conditions and each passage design alternative considered.

River Flow (cfs)	Flow Proportion	Total Project Survival (%)			
		Existing Conditions	Bar Rack with 0.75-inch Spacing	Angled Bar Rack with 0.75-inch Spacing	Vertical/Horizontal Eel Bypass Systems with 1-inch Bar Spacing
50-195	26.8	98.0	98.0	98.0	98.0
196-249	8.6	72.9	96.2	96.2	76.5
250-349	14	71.0	96.1	96.1	74.8
350-474	12.7	68.8	95.9	95.9	73.0
475-599	9.6	67.1	95.8	95.8	71.6
600-749	6.5	73.6	96.3	96.3	77.1
750-862	3.8	66.1	95.7	95.7	70.7
863-999	3.7	67.3	95.8	95.8	71.7
1000-1207	3.9	51.1	94.7	94.7	57.8
1208-1349	2.1	60.5	95.3	95.3	65.9
1350-1499	1.6	64.4	95.6	95.6	69.2
1500-1749	2	67.8	95.8	95.8	72.1
1750-1999	1.3	72.1	96.2	96.2	75.8
2000-2499	2.1	75.3	96.4	96.4	78.6
2500-2999	0.5	79.9	96.7	96.7	82.5
>3000	0.8	82.9	96.9	96.9	85.1
Totals	100.0	76.7	96.5	96.5	79.7

5.3.4.2 Pepperell Case Study Conclusions

The use of 0.75-inch bar spacing on the existing intake structure or with a new angled bar rack would produce high downstream passage survival rates (96.5%) for silver eels at Pepperell (Table 5-18). However, these two options were also estimated to be the most costly alternatives for protecting eels (Table 5-18). Targeted nightly shutdowns would provide the highest survival rate (98%) for eels passing downstream at Pepperell and have an estimated annual generation loss of about \$15,600 (shutting down every night during the eel migration season would be two to three times more). Using this approach, the cost of lost generation would be about \$624,000 over the course of a 40 year FERC license term. Installation of vertical and horizontal eel bypass systems at Mine Falls would cost about \$405,000, but the downstream passage survival estimate (79.7%) was considerably lower for this alternative compared to the two options with 0.75-inch clear bar spacing. If bar spacing is reduced to 0.75 inches for the new eel bypass designs, total downstream passage survival would likely exceed 95% because little or no turbine entrainment would occur. This would also provide a significant cost savings over the other narrow bar spacing alternatives which will require about 115 to 230 cfs bypass flow compared to 3 to 6 cfs for the vertical and horizontal eel bypass systems.

**Table 5-18. Summary of bypass efficiency, total project survival, and approximate cost for silver eel downstream passage alternatives considered for Pepperell.**

Downstream Passage Alternative	Assumed Bypass Efficiency (%)	Total Project Survival (%)	Approximate Cost (\$)
Existing conditions	30	76.7	--
Bar rack with 0.75-inch spacing	95	96.5	640,000
Angled bar rack with 0.75-in spacing	95	96.5	1,540,000
Targeted nightly turbine shutdowns	100	98.0 ¹	15,600/624,000 ²
Vertical/horizontal eel bypasses with 1-in spacing	40	79.7	405,000

¹ Total project survival over the course of the entire eel migration season likely would be lower than 98% given some proportion of eels will pass downstream during daylight hours and nights when the turbines are operating.

² Annual cost of lost generation due to nightly shutdowns and total cost over 40 year license term.

5.3.5 Worumbo

The Worumbo hydroelectric project, which is owned by Brown Bear II Hydro, Inc., is located in Lisbon Fall, Maine on the Androscoggin River. The project has a 520-ft concrete ogee spillway creating 30.5-ft of operating head (Figure 5-13). Worumbo is operated as a run-of-river facility with two Kaplan turbines that have a combined maximum hydraulic capacity of 9,600 cfs and a total install capacity of 19.4 MW. Current downstream fish passage consists of three bypasses near the trash racks that transition into a 36-inch diameter plastic pipe that discharges into a plunge pool on the downstream side of the dam. The minimum flow to the bypass reach is 200 cfs from September 1 through October 31 (Table 5-19). River flow exceedance probabilities and allocations at the project are provided in Table 5-19.

5.3.5.1 Modified Bar Rack with 0.75-inch Clear Spacing

This alternative includes the installation of a 0.75-inch clear bar spacing on the existing intake structure and modified turbine operation to reduce approach velocities to meet the USFWS criterion of 1.5 ft/sec or less. The lower approach velocities will also minimize increases in head loss associated with a narrower bar spacing. The new bar rack spacing would be installed on the existing rack structure. The two existing racks, each about 40 ft high by 33 ft wide, will be replaced with the 0.75-inch clear spacing using the same rack area. The new bars would consist of 0.25 inch by 3.00 inch rectangular cross section bars set perpendicular to the intake flow. Because the new rack will have the same dimensions as the existing structure, the effective area will not change and the maximum approach velocities at full generation will be 3.4 ft/sec. To reduce the approach velocity to 1.5 ft/sec, the turbines will need to be operated at significantly lower hydraulic rates. This operational change will result in considerable generation losses. Also, the estimated cost of retrofitting the existing intake structure with the 0.75-inch clear bar spacing and a new trash rack is approximately \$1.3 million (Table 5-20).

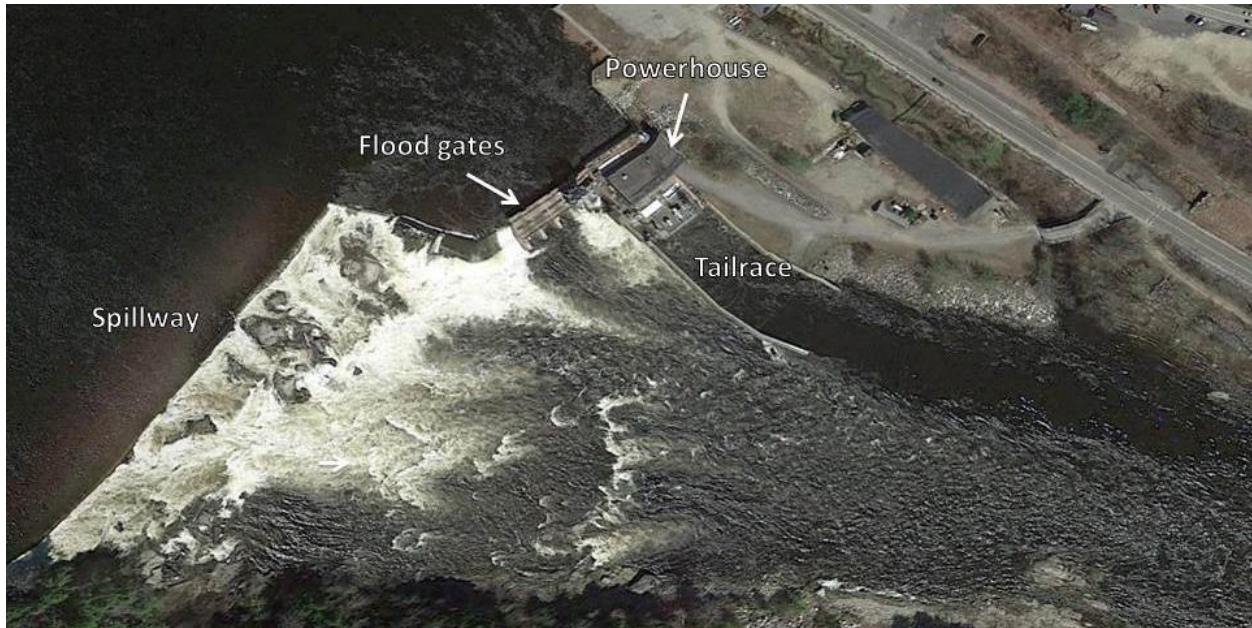


Figure 5-13. Worumbo site configuration.

5.3.5.2 Angled Bar Rack

Installation of a new angled bar rack structure upstream of the existing intake was considered as an alternative for passing silver eels downstream at Worumbo. The angled rack would have 0.75 inch clear spacing to meet USFWS criteria for preventing turbine entrainment of silver eels. This design would also address the need for approach velocities of 1.5 ft/sec or less to meet the USFWS velocity criterion and to minimize increases in head loss associated with the narrower bar spacing. For this alternative, a new bar rack structure would be installed in front of the current powerhouse intake (Figure 5-14 and Figure 5-15). The angled rack would be 122 ft long, oriented 45 degrees to the intake flow, and span between two concrete abutments installed at either end (Figure 5-14 and Figure 5-15). Using the effective area and dimensions of the new rack, the maximum approach velocity was estimated to be 1.8 ft/sec. The new rack would have 0.25 inch by 3.00 inch rectangular cross sectional bars set perpendicular to the rack structure. The top of the rack would be mounted to a new 7 ft wide work deck constructed at the face of the intake. The rack would extend vertically down from the work deck to a concrete mat on the river bed. The existing trash racks would no longer be needed and could be removed from the intake.

The angled bar rack alternative will physically exclude silver eels from turbine entrainment and guide them towards the downstream end of the rack where they can pass downstream through a floodgate. This alternative is expected to improve hydraulics (i.e., lower approach velocities) and reduce clean rack head loss compared to the existing bar rack. However, the estimated costs for installation and operation of this alternative are high, exceeding \$6 million (Table 5-21).



Table 5-19. Flow exceedance and distribution at Worumbo by river discharge during the silver eel migration period.

River Flow (cfs)	Flow Exceedance Probability (%)	Trash Rack Approach Velocity (ft/s)	Spillway		Unit 1		Unit 2		Floodgates		Fishway and Downstream Bypasses	
			Allocated Flow (cfs)	Percent of Total Flow	Allocated Flow (cfs)	Percent of Total Flow	Allocated Flow (cfs)	Percent of Total Flow	Allocated Flow (cfs)	Percent of Total Flow	Allocated Flow (cfs)	Percent of Total Flow
200	100.0	0.0	200	100.0	0	0.0	0	0.0	0	0.0	0	0.0
396	100.0	0.0	200	50.5	0	0.0	0	0.0	0	0.0	196	49.5
500	100.0	0.0	304	60.8	0	0.0	0	0.0	0	0.0	196	39.2
1,000	100.0	0.0	804	80.4	0	0.0	0	0.0	0	0.0	196	19.6
1,596	99.0	0.5	200	12.5	1,200	75.2	0	0.0	0	0.0	196	12.3
1,750	95.0	0.5	200	11.4	1,354	77.4	0	0.0	0	0.0	196	11.2
2,000	89.5	0.6	200	10.0	1,604	80.2	0	0.0	0	0.0	196	9.8
2,500	74.0	0.8	200	8.0	2,104	84.2	0	0.0	0	0.0	196	7.8
3,500	55.5	1.2	200	4.7	3,104	88.7	0	0.0	0	0.0	196	5.6
4,916	35.5	1.7	200	40.1	4,520	91.9	0	0.0	0	0.0	196	4.0
5,550	30.5	1.7	834	15.0	4,520	81.4	0	0.0	0	0.0	196	3.5
6,116	27.0	2.2	200	3.3	4,520	73.9	1,200	19.6	0	0.0	196	3.2
6,500	23.5	2.3	200	3.1	4,520	69.5	1,584	24.4	0	0.0	196	3.0
7,500	18.0	2.7	200	2.7	4,520	60.3	2,584	34.5	0	0.0	196	2.6
8,550	14.5	3.1	200	2.3	4,520	52.9	3,634	42.5	0	0.0	196	2.3
9,436	12.5	3.4	200	2.1	4,520	47.9	4,520	47.9	0	0.0	196	2.1
10,000	11.0	3.4	764	7.6	4,520	45.2	4,520	45.2	0	0.0	196	2.0
15,000	5.0	3.4	3,021	20.1	4,520	30.1	4,520	30.1	2,743	18.3	196	1.3
20,000	2.5	3.4	3,021	15.1	4,520	22.6	4,520	22.6	7,743	38.7	196	1.0
22,000	2.0	3.4	3,021	13.7	4,520	20.6	4,520	20.6	9,743	44.3	196	0.9
30,000	1.0	3.4	3,021	10.1	4,520	15.1	4,520	15.1	17,743	59.1	196	0.7
34,257	1.0	3.4	3,021	8.8	4,520	13.2	4,520	13.2	22,000	64.2	196	0.6



Table 5-20. Estimated costs for retrofitting the existing turbine intake at Worumbo with 0.75-inch clear bar spacing.

Items	Cost
Trash Rack and Supports	\$1,070,207
New Trash Rake	\$233,680
Total Estimated Project Costs	\$1,303,887

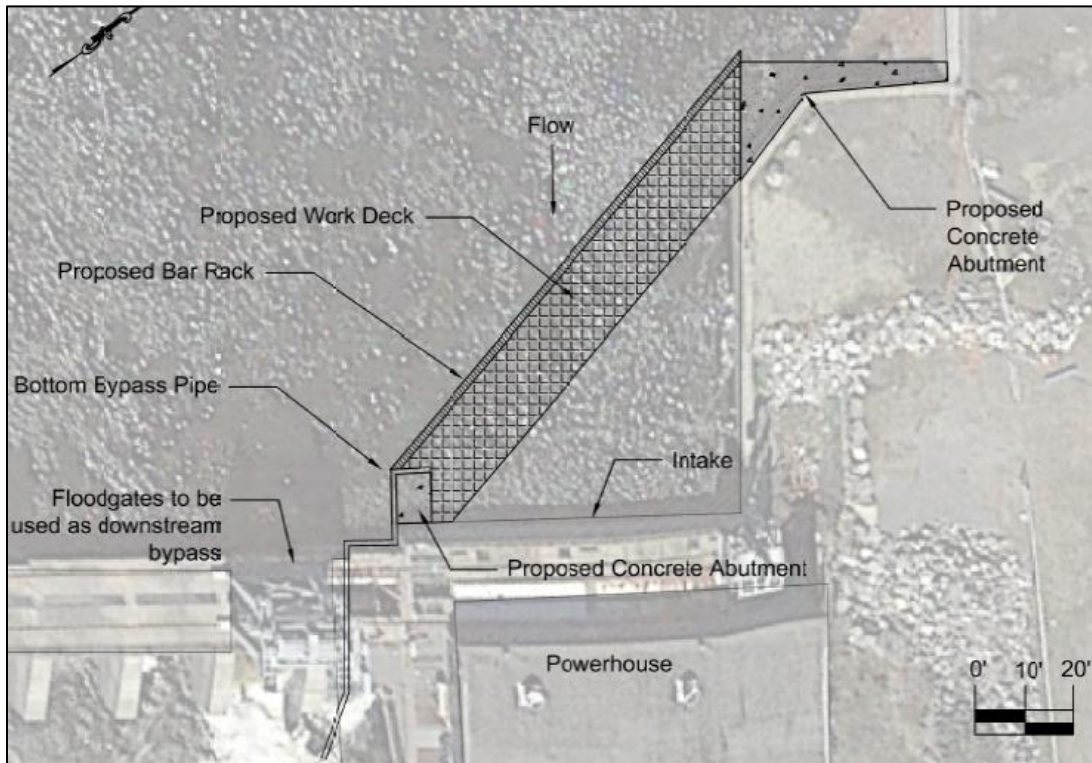


Figure 5-14. Conceptual design of an angled bar rack installed at Worumbo (plan view).

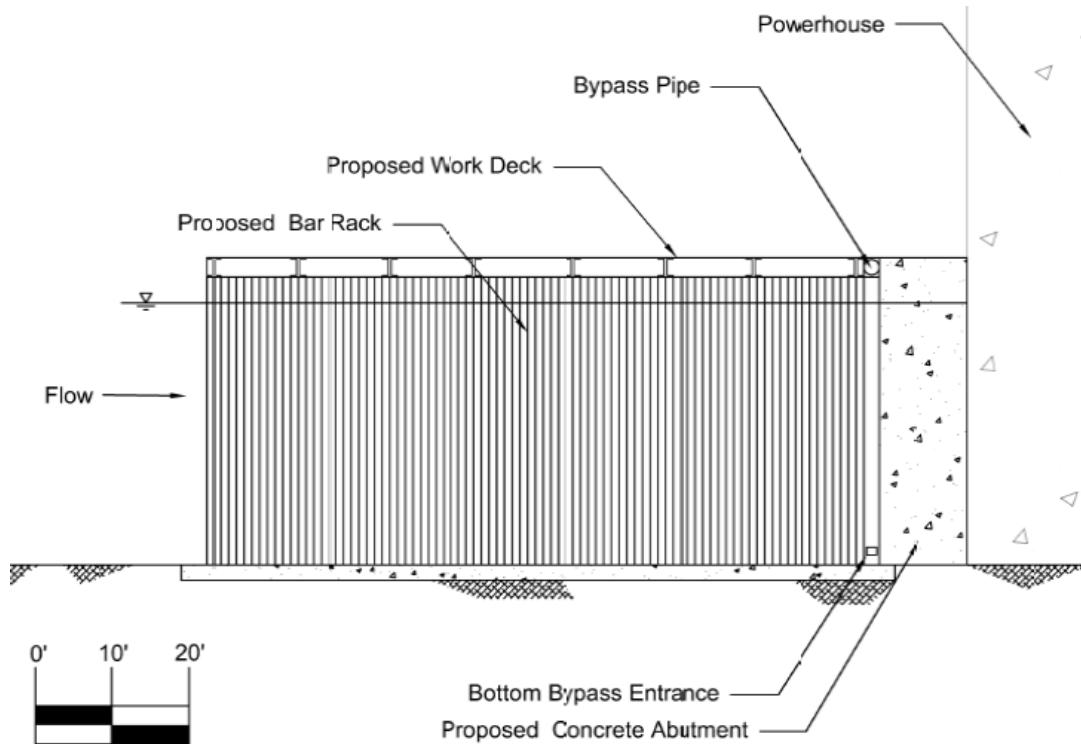


Figure 5-15. Conceptual design of an angled bar rack installed at Worumbo (section view).

Table 5-21. Estimated costs for an angled bar rack installed upstream of the Worumbo turbine intakes.

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$303,902
Dredging and Earthwork	\$65,067
New Rack and Supports	\$2,219,993
Side Walls	\$600,240
Work deck and Cleaning Rake	\$153,720
Distributable Costs (20% labor/Materials)	\$668,584
Direct Costs Subtotal	\$4,011,506
Indirect Costs	\$401,151
Direct and Indirect Costs Subtotal	\$4,412,657
Allowance for Indeterminates (25%)	\$1,103,164
Allowance for Contingencies (15%)	\$827,373
Total Estimated Project Costs	\$6,343,194



5.3.5.3 Modified Operations: Nightly Turbine Shutdowns

Two modified turbine operation scenarios were examined for reducing eel entrainment at Worumbo: nightly shutdowns for the entire eel migration season and targeted nightly shutdowns following significant rain events (i.e., high flow events). Under current project conditions, the turbines at Worumbo are operated when there is enough flow in the river to successfully meet both the fishway and turbine flow requirements. Nightly shutdowns would require the starting and stopping of units daily, which would increase flow fluctuations in the bypass reach. Also, frequent starts and stops of the units can increase wear and tear, resulting in increased potential for mechanical issues and repairs. In addition to having the turbines offline on a nightly basis for eel passage, greater maintenance requirements could also lead to lost generation time and revenue.

Implementation of targeted nightly shutdowns based on precipitation events would result in much fewer turbine starts and stops compared to shutdowns on a nightly basis for the entire eel migration season. Criteria for the amount of rainfall needed to trigger a shutdown would need to be established, as well as how many subsequent nights the shutdown would be implemented following a rain event. For the targeted shutdowns, it was assumed there will be 28 nights of shutdowns for rain triggered events compared to 113 night for shutdowns occurring every night of the eel migration season.

Estimates of lost generation and lost revenue were calculated for Worumbo using a yearly average of 92,000 MWh of generation. It was assumed that 33% of this total annual output is produced during the eel passage season, which would be approximately 30,360 MWh. Nightly shutdowns for the entire eel migration season will result in a 46% reduction in generation, whereas rain event triggered shutdowns would only reduce generation by 12% (Table 5-22). Estimated lost revenues for these reductions in generation are \$411,566 for shutdowns on every night of the migration season and \$107,365 for targeted shutdowns based on specified precipitation amounts (Table 5-22).

Table 5-22. Estimated lost generation and revenue for nightly turbine shutdown alternatives at Worumbo.

Option	Reduction in Generation (%)	Reduction in Generation (MWh)	Lost Revenue
Nightly shutdowns (113 Days)	46%	13,966	\$411,566
Targeted Nightly Shutdowns (28 Days)	12%	3,643	\$107,365



5.3.5.4 Vertical and Horizontal Zig-Zag Eel Bypass Systems

The vertical and horizontal zig-zag bypass systems were assessed as a downstream passage alternative for Worumbo without any modifications to the existing bar racks. The horizontal zig-zag bypass would include a series of 10 inch diameter pipes connected together at 30 degree angles in a zig-zag pattern (Figure 5-16, Figure 5-17). At each interior angle, there is a bypass port (entrance opening). The pipes are set horizontally across the base of the bar rack and discharge via a siphon on the downstream side of the dam in the bypass reach adjacent to the powerhouse (Figure 5-16, Figure 5-17). A row of brushes would be installed just upstream of the zig-zag piping to provide a resting area (velocity refuge) for eels and to reduce the potential for debris accumulation on the bypass pipes. The total flow through the horizontal portion of the system installed at Worumbo would be about 1.3 cfs.

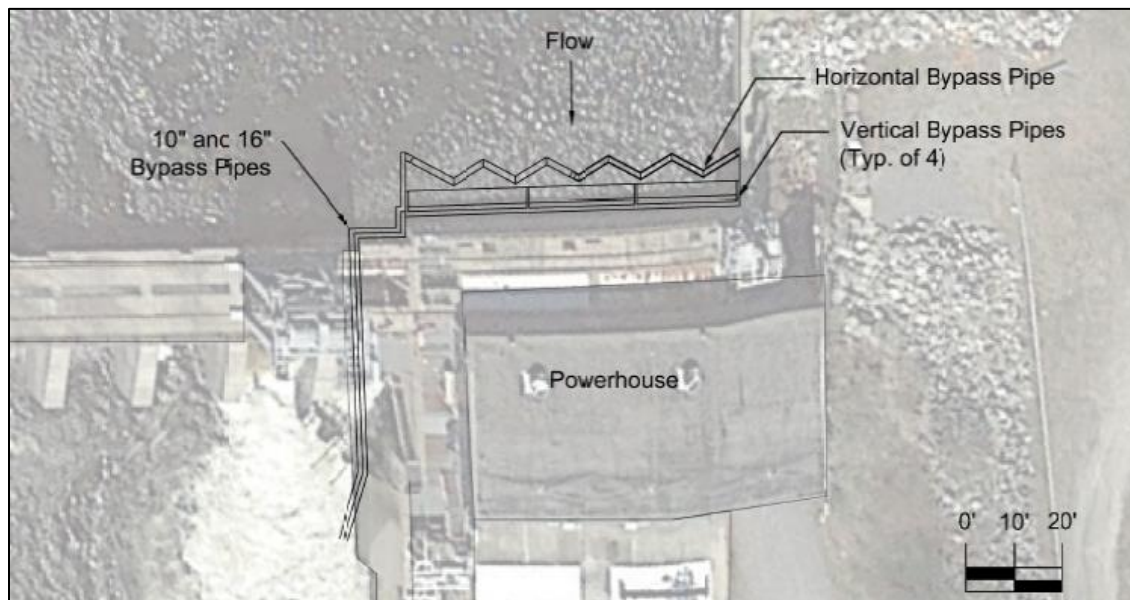


Figure 5-16. Conceptual design of vertical and horizontal zig-zag eel bypasses installed at Worumbo (plan view).

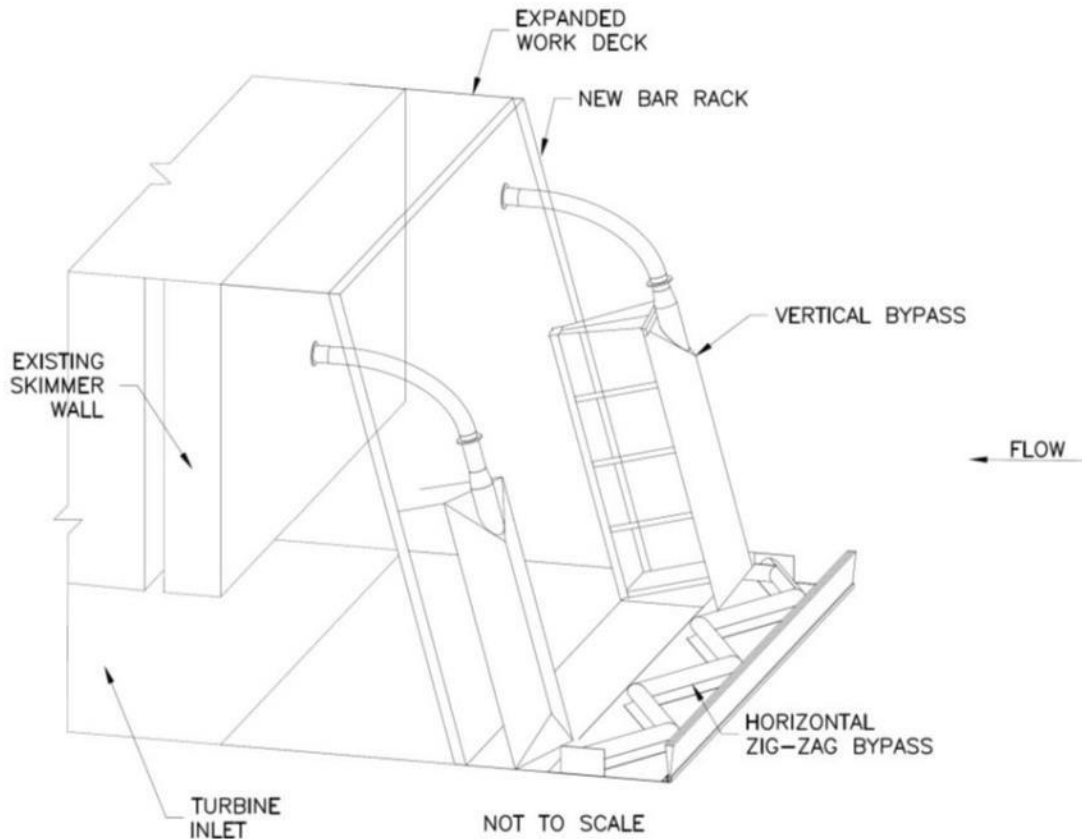


Figure 5-17. Conceptual design of vertical and horizontal zig-zag bypasses installed at Worumbo (isometric view).

The vertical bypass conduits would include four vertical 16-inch diameter pipes. The pipes would be located at each end of the intake rack and one in line with the center line of each unit (Figure 5-16, Figure 5-17). Each vertical bypass would have a central pipe with tangential plates oriented at right angles along the lengths of the pipe with a series of entrance ports located sequentially over the pipe length. Large horizontal plates between entrance locations would provide additional guidance for eels towards the inlet ports. Brushes would be installed along the leading edges of the plates to provide a velocity refuge for the eels as well as provide the entrance ports with some protection from becoming clogged with debris. Each vertical bypass pipe would be designed for a flow of about 0.85 cfs, resulting in a total flow of approximately 3.4 cfs for the whole entire vertical bypass system. The bypasses would flow into a header pipe which would be controlled by a siphon and discharge into the bypass reach at the same locations as the zig-zag system (Figure 5-16). The estimated cost for the installation and operation of the two bypass systems at Worumbo would be about \$590,000 (Table 5-23).



Table 5-23. Estimated costs for vertical and horizontal zig-zag eel bypass systems installed at Worumbo.

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$25,208
Horizontal Zig-Zag with Bypass Piping	\$44,434
Vertical Bypass with Piping	\$207,643
Distributable Costs	\$55,457
Direct Costs Subtotal	\$332,742
Indirect Costs	\$33,274
Direct and Indirect Costs Subtotal	\$421,474
Allowance for Indeterminates	\$105,368
Allowance for Contingencies	\$63,221
Total Estimated Project Costs	\$590,063

5.3.5.5 Turbine and Total Project Survival Estimates

The independent variables included in the multiple linear regression model developed to estimate eel turbine survival at Worumbo accounted for 88% of the variability in survival estimates among the study sites where field studies were conducted (Table 5-24). Turbine survival for eels entrained through the units at Worumbo ranged from 68 to 71% (Table 5-25). Total project survival for the existing (baseline) conditions ranged from about 79 to 98%, with an overall estimate of 82% for the entire migration season (Table 5-26). The vertical and horizontal zig-zag bypasses had the same total project survival as the baseline condition (82%). The two bar rack design alternatives with 0.75-inch clear spacing produced total overall passage survival estimates of about 98% (Table 5-26).



Table 5-24. Multiple linear regression model results of the effects of turbine design and operational parameters on eel survival at Worumbo.

Regression Statistics				
Residual Std Error	0.0881			
DF	49			
Multiple R ²	0.8857			
Adjusted R ²	0.8764			
F-statistic	94.95			

Coefficients	Estimate	Std Error	T-value	P-value
(Intercept)	1.2752	0.0762	16.7310	< 2e-16
Test Flow	0.0008	0.0002	4.1280	0.0001
Eel Length	-0.6087	0.1112	-5.4720	0.0000
RPM	-0.0017	0.0001	-12.4880	< 2e-16
TGOpening	-0.0003	0.0006	-0.5040	0.6163

Table 5-25. Turbine survival for silver eels passing through the units at Worumbo.

Flow (cfs)	Gate Opening (%)	Turbine Survival (%)	95% CI
1,200	26.5	70.6	62.9-78.3
1,354	30.0	70.5	63.2-77.8
1,584	35.0	70.4	63.6-77.1
1,604	35.5	70.4	63.6-77.1
2,104	46.5	70.0	64.4-75.6
2,584	57.2	69.7	65.0-74.3
3,104	68.7	69.3	65.6-73.1
3,634	80.4	69.0	65.7-72.3
4,520	100.0	68.4	64.7-72.0



Table 5-26. Total project survival estimates by river flow for silver eels passing downstream at Worumbo for existing conditions and each passage design alternative considered.

River Flow (cfs)	Flow Proportion	Total Project Survival (%)			
		Existing Conditions	Bar Rack with 0.75-inch Spacing	Angled Bar Rack with 0.75-inch Spacing	New Eel Bypass Systems with 1-inch Bar Spacing
1000-1595	1.0	98.3	98.4	98.4	98.4
1596-1749	4.0	84.3	98.6	98.6	84.3
1750-1999	5.5	83.8	98.6	98.6	83.8
2000-2499	15.5	83.2	98.6	98.6	83.2
2500-3499	18.5	82.2	98.6	98.6	82.2
3500-4915	20.0	80.8	98.5	98.5	80.8
4916-5549	5.0	79.6	97.0	97.6	79.6
5550-6115	3.5	81.7	97.1	97.6	81.7
6116-6499	3.5	79.5	97.0	97.6	79.5
6500-7499	5.5	79.5	97.0	97.6	79.5
7500-8549	3.5	79.3	97.0	97.6	79.3
8550-9435	2.0	79.0	97.0	97.6	79.0
9436-9999	1.5	78.8	96.9	97.5	78.8
10000-14999	6.0	79.9	97.0	97.6	79.9
15000-19999	2.5	86.0	97.3	97.7	85.9
20000-21999	0.5	88.9	97.5	97.8	88.9
22000-29999	1.0	89.8	97.5	97.8	89.8
30000-34256	0.0	92.0	97.7	97.9	92.0
>34257	1.0	92.7	97.7	97.9	92.7
Total	100.0	82.0	98.0	98.2	84.5

5.3.5.6 Worumbo Case Study Conclusions

The use of 0.75-inch bar spacing on the existing intake structure or with a new angled bar rack would produce the highest estimated downstream passage survival rates (about 98%) for silver eels at Worumbo (Table 5-27). However, these two options were also estimated to be the most costly alternatives for protecting eels (Table 5-27). Targeted nightly shutdowns would also provide a similar survival rate (98%) and have an estimated annual generation loss of about \$107,400 (shutting down every night during the eel migration season would be two to three times more). The cost of lost generation would be about \$4.3 million over the course of a 40 year FERC license term. Installation of vertical and horizontal eel bypass systems at Worumbo would cost about \$590,000, but the downstream passage survival estimate (84.5%) was lower for this alternative compared to the two options with 0.75-inch clear bar spacing and only slightly higher than the current baseline. If bar spacing is reduced to 0.75 inches for the new eel bypass designs, total downstream passage survival would likely exceed 95% because little or no turbine entrainment would occur. This would also provide a significant cost savings over the other narrow bar spacing alternatives which will require about 480 to 960 cfs bypass flow compared to 3 to 6 cfs for the vertical and horizontal eel bypass systems.



Table 5-27. Summary of bypass efficiency, total project survival, and approximate cost for silver eel downstream passage alternatives considered for Worumbo.

Downstream Passage Alternative	Assumed Bypass Efficiency (%)	Total Project Survival (%)	Approximate Cost (\$)
Existing conditions	10	82.0	--
Bar rack with 0.75-inch spacing	90-95	98.0	1,070,000
Angled bar rack with 0.75-in spacing	92-95	98.2	6,350,000
Targeted nightly turbine shutdowns	100	98.0 ¹	107,400/4,296,000 ²
Vertical/horizontal eel bypasses with 1-in spacing	40	84.5	590,000

¹ Total project survival over the course of the entire eel migration season likely would be lower than 98% given some proportion of eels will pass downstream during daylight hours and nights when the turbines are operating.

² Annual cost of lost generation due to nightly shutdowns and total cost over 40 year license term.

5.3.6 Roanoke Rapids

The Roanoke Rapids Hydroelectric Project is owned and operated by Dominion Energy and located on the Roanoke River on the Virginia and North Carolina border. The project has a concrete gravity dam with an ogee-type spillway measuring 3,050 ft long and 72 ft high (Figure 5-18). The powerhouse has one Kaplan and three fixed-blade propeller turbines, each with a hydraulic capacity of 5,000 cfs with a total generating capacity of 95 MW. The intake bar racks currently have 6 inch clear spacing and an average approach flow velocity of 4 ft/s. River flow exceedance probabilities and allocations at the project are provided in Table 5-28.



Figure 5-18. Roanoke Rapids site configuration.



Table 5-28. Flow exceedance probabilities and distributions at Roanoke Rapids during the silver eel migration period.

River Flow (cfs)	Flow Exceedance Probability	Average Intake Approach Velocity (ft/s)				Flow Distribution (cfs)				
		Unit 1	Unit 2	Unit 3	Unit 4	Spillway and Skimmer Gates	Unit 1	Unit 2	Unit 3	Unit 4
1,500	0.980	1.0	0.0	0.0	0.0	325	1,175	0	0	0
2,000	0.896	1.5	0.0	0.0	0.0	325	1,675	0	0	0
2,500	0.700	1.9	0.0	0.0	0.0	325	2,174	0	0	0
3,000	0.632	2.3	0.0	0.0	0.0	325	2,675	0	0	0
4,000	0.556	3.2	0.0	0.0	0.0	325	3,675	0	0	0
5,000	0.507	4.1	0.0	0.0	0.0	325	4,675	0	0	0
5,325	0.490	4.4	0.0	0.0	0.0	325	5,000	0	0	0
6,000	0.460	4.4	0.6	0.0	0.0	325	5,000	675	0	0
7,000	0.430	4.4	1.5	0.0	0.0	325	5,000	1,675	0	0
7,500	0.430	4.4	1.9	0.0	0.0	325	5,000	2,174	0	0
8,000	0.380	4.4	2.3	0.0	0.0	325	5,000	2,675	0	0
9,000	0.290	4.4	3.2	0.0	0.0	325	5,000	3,675	0	0
10,325	0.240	4.4	4.4	0.6	0.0	325	5,000	5,000	0	0
12,000	0.210	4.4	4.4	1.5	0.0	325	5,000	5,000	1,675	0
12,500	0.200	4.4	4.4	1.9	0.0	325	5,000	5,000	2,175	0
13,000	0.190	4.4	4.4	2.3	0.0	325	5,000	5,000	2,675	0
14,000	0.174	4.4	4.4	3.2	0.0	325	5,000	5,000	3,675	0
15,325	0.140	4.4	4.4	4.4	0.0	325	5,000	5,000	5,000	0
16,000	0.129	4.4	4.4	4.4	0.0	325	5,000	5,000	5,000	675
17,000	0.120	4.4	4.4	4.4	0.0	325	5,000	5,000	5,000	1,670
17,500	0.120	4.4	4.4	4.4	0.0	325	5,000	5,000	5,000	2,167
18,000	0.116	4.4	4.4	4.4	2.3	325	5,000	5,000	5,000	2,675
19,000	0.099	4.4	4.4	4.4	3.2	325	5,000	5,000	5,000	3,675
20,325	0.050	4.4	4.4	4.4	4.4	325	5,000	5,000	5,000	5,000
35,000	<0.01	4.4	4.4	4.4	4.4	15,000	5,000	5,000	5,000	5,000



5.3.6.1 New Intake Bar Rack with 0.75-inch Clear Spacing

This alternative involves reconfiguration of the Roanoke Rapids intake for installation of a bar rack with 0.75 inch clear spacing upstream of the existing intake structure. This design is intended to reduce approach velocities to meet the USFWS velocity criteria for downstream eel passage (1.5 ft/sec or less), as well as to minimize increases in head loss associated with the narrower bar spacing. For this alternative, a new bar rack structure would be located just upstream of the existing intake (Figure 5-19, Figure 5-20). The new bar rack would be 224 ft long with an effective height of 60 ft. This size was selected to maintain maximum average approach velocities below the 1.5 ft/sec criteria while allowing for up to 10% of the trash rack area to be used for supports and/or bypasses. The new rack would consist of 0.25 inch thick by 3.00 inch wide rectangular cross section bars set perpendicular to the intake flow. The top of the bar rack would be mounted to a new 7-ft wide work deck constructed at the face of the intake. The new bar rack would extend from the work deck down at a 25 degree angle from vertical to the bottom of the forebay (Figure 5-20). A steel superstructure and concrete mat would support the work deck and bar rack. The existing trash rack would no longer be needed and could be removed. Because this option provides physical exclusion from turbine entrainment and not guidance away from the intake, a downstream bypass system with eight entrances (four bottom and four surface) was incorporated into the design.

This alternative will improve hydraulic conditions and decrease clean rack head loss as compared to the existing bar rack. However, this alternative would require significant construction and engineering costs in excess of \$15 million (Table 5-29).

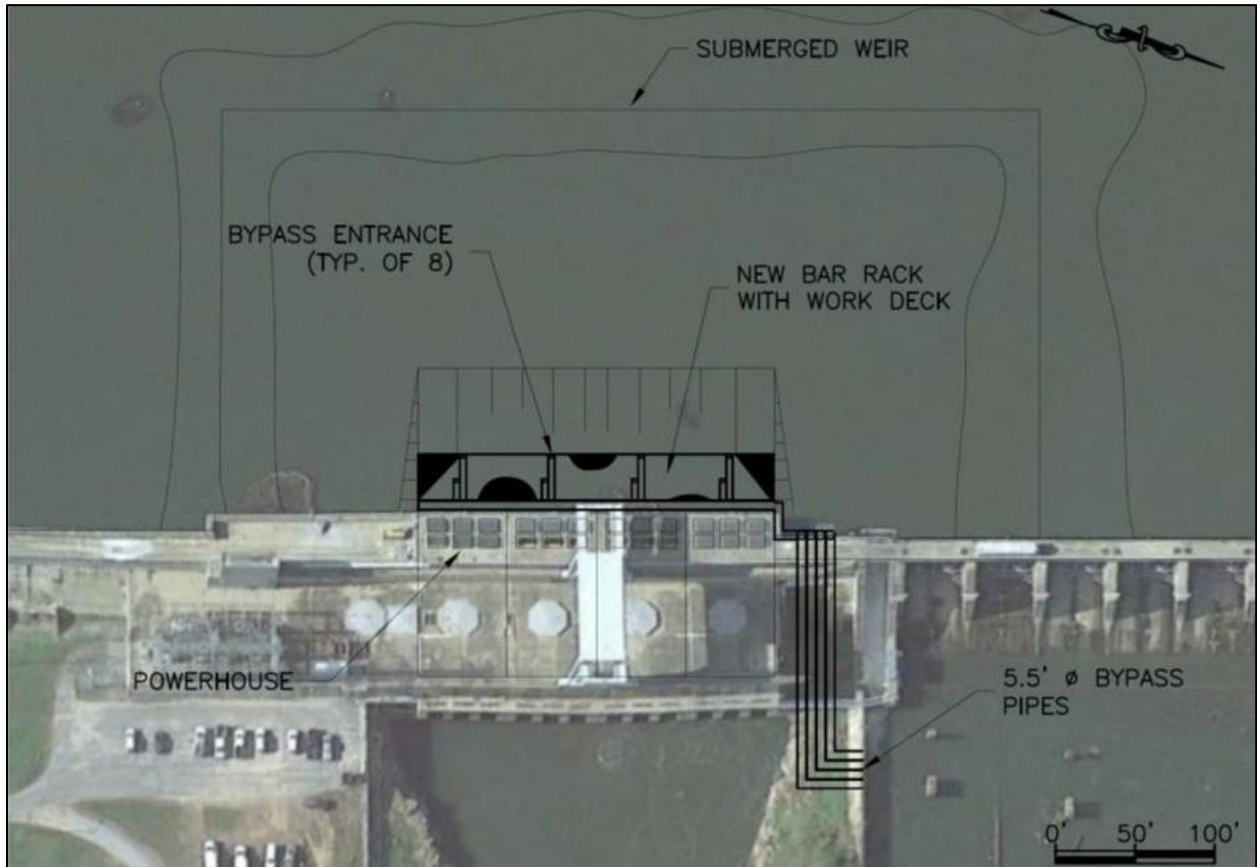


Figure 5-19. Conceptual design of new intake bar rack alternative at Roanoke Rapids (plan view).

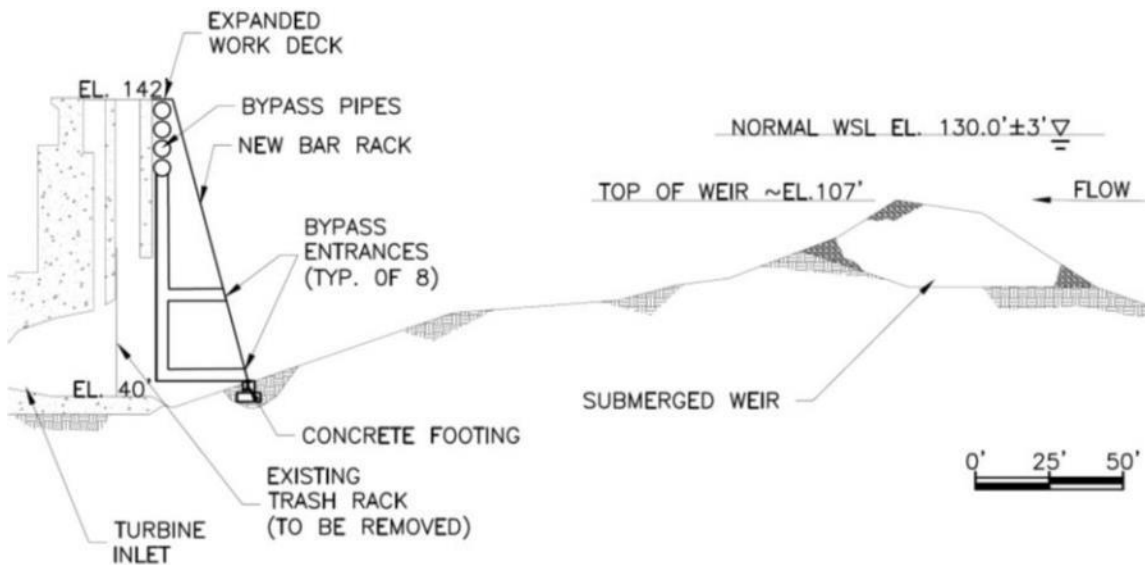


Figure 5-20. Conceptual design of new bar rack alternative installed at the Roanoke Rapids intake (section view).

**Table 5-29. Estimated costs for new turbine intake bar rack installed at Roanoke Rapids.**

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$747,000
Dredging and Earthwork	\$160,000
New Rack and Supports	\$5,459,000
Side Walls	\$1,476,000
Work deck and Cleaning Rake	\$378,000
Distributable Costs	\$1,495,000
Direct Costs Subtotal	\$9,715,000
Indirect Costs	\$972,000
Direct and Indirect Costs Subtotal	\$10,687,000
Allowance for Indeterminates (25%)	\$2,672,000
Allowance for Contingencies (15%)	\$1,603,000
Total Estimated Project Costs	\$15,363,000

5.3.6.2 Angled Bar Rack

For this alternative, a new bar rack structure would be angled to the intake flow in a V-configuration. Angling the bar rack is expected to improve guidance to a bypass and reduce migration delays. A rack angle of 45 degrees to the approach flow is recommended by USFWS and was used for this design (Figure 5-21, Figure 5-22). The angled bar rack would consist of two 320 ft long sections with an average wetted height of 75 ft. This size results in average approach velocity of approximately 0.8 ft/sec. The actual approach velocities are expected to be lower than this near the vertex and increase closer to the existing intake structure. The angled rack would consist of 0.25 inch thick by 3.00 inch deep rectangular cross section bars with 0.75 inch clear openings. The top of the bar rack would be mounted to a new 10-ft wide work deck constructed at the face of the intake. The new bar rack would extend vertically down from the work deck to a concrete mat on the bottom of the forebay (Figure 5-22). A steel superstructure and concrete mat would support the work deck and bar rack. The existing trash rack would no longer be needed and could be removed.

The angled bar rack alternative provides a physical barrier to prevent eel entrainment and is angled to guide downstream migrants to a bypass. A piped bypass with four entrances (two near the bottom and two higher in the water column) was assumed for the angled bar rack design. This alternative was estimated to improve hydraulic conditions and decrease clean rack head loss as compared to the existing bar rack. The angled rack is expected to meet biological performance requirements due to the narrow bar spacing, low approach velocities, and angle to the flow. However, this alternative would require significant construction and engineering costs (Table 5-30).

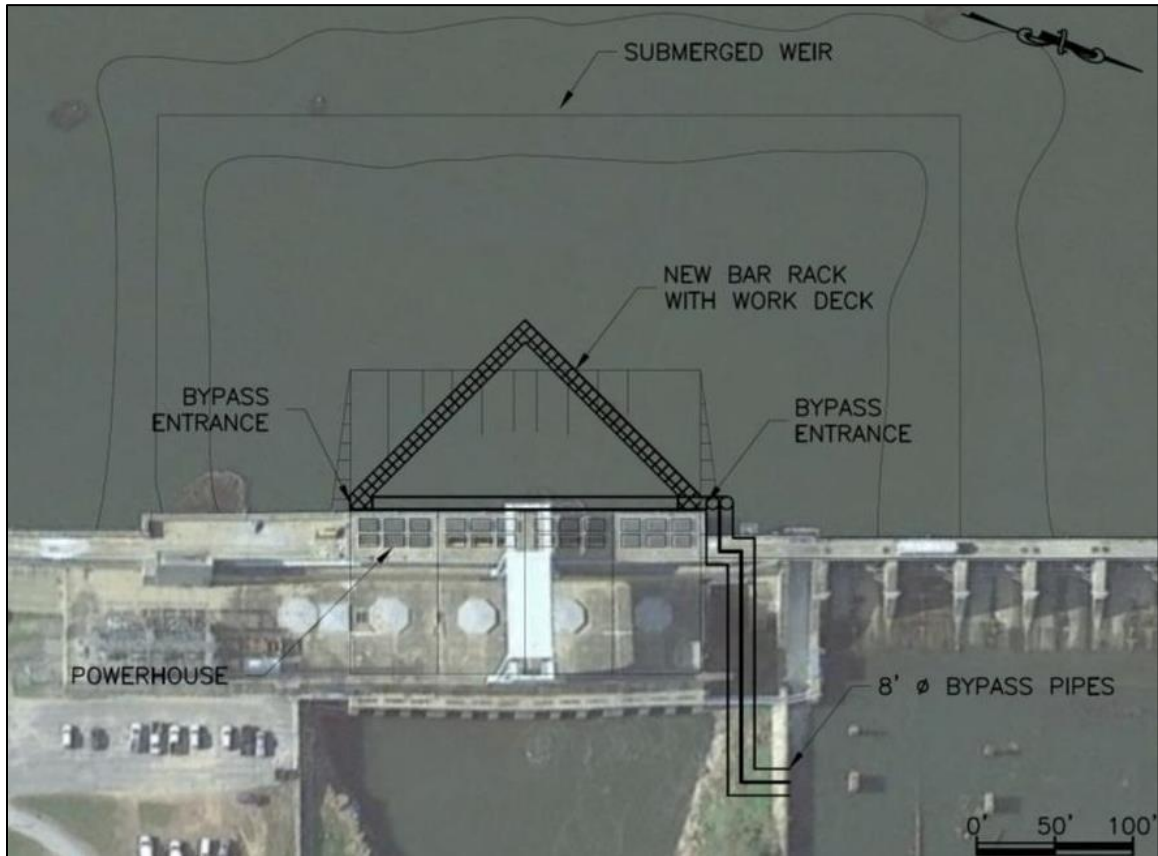


Figure 5-21. Conceptual design of an angled bar rack installed at Roanoke Rapids (plan view).

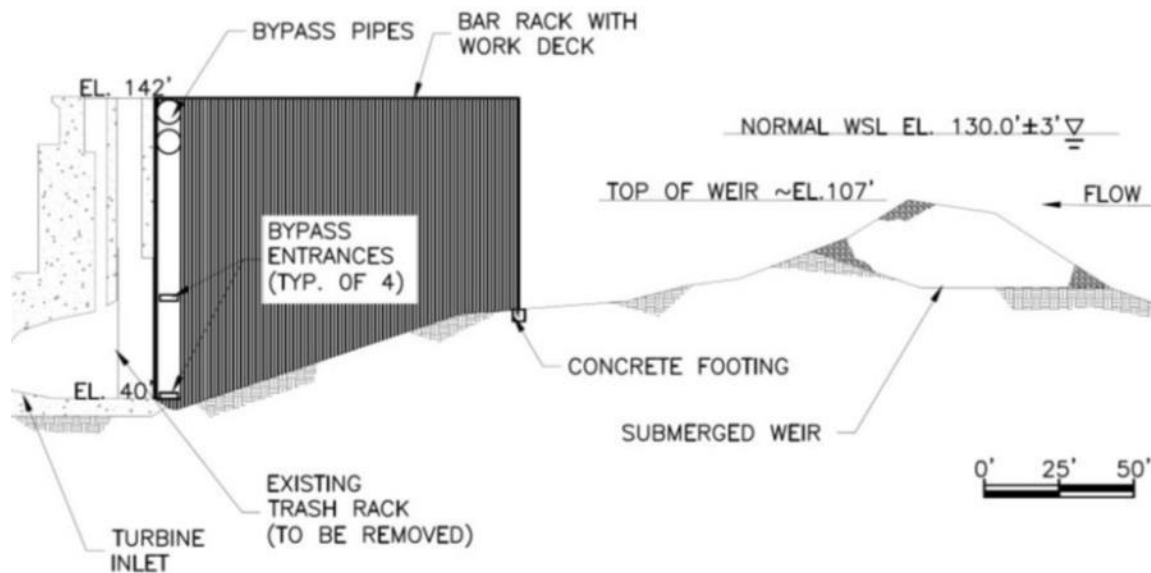


Figure 5-22. Conceptual design of an angled bar rack installed at Roanoke Rapids (section view).

**Table 5-30. Estimated Construction Costs for an Bar Rack Angled to the Intake Flow at Roanoke Rapids**

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$2,656,000
Dredging and Earthwork	\$568,888
New Rack and Supports	\$19,409,777
Side Walls	\$5,248,000
Work deck and Cleaning Rake	\$1,344,000
Distributable Costs (20% labor and Materials)	\$5,845,333
Direct Costs Subtotal	\$35,072,000.00
Indirect Costs	\$3,507,200
Direct and Indirect Costs Subtotal	\$44,424,533.33
Allowance for Indeterminates (25%)	\$11,106,133
Allowance for Contingencies (15%)	\$6,663,680
Total Estimated Project Costs	\$62,194,346

5.3.6.3 Modified Operations: Turbine Shutdowns

Two modified turbine operation scenarios were examined for reducing eel entrainment at Roanoke Rapids: nightly shutdowns for the entire migration season and targeted nightly shutdowns following significant rain events (i.e., high flow events). Under current project operations, the turbines are operated when there is enough flow in the river to meet bypass reach flow requirements and to start one or more units. Stopping and starting turbines on a nightly basis would increase flow fluctuations within the bypass reach. The flow through the turbines and into the bypass reach would need to be ramped down in accordance with Article 408 of the FERC License for Roanoke Rapids to prevent significant transient surges or dips.

Implementing nightly shutdowns based on precipitation events and discharge from the Gaston Project (next dam upstream) would result in much fewer turbine stops and starts compared to shutdowns on every night of the eel passage season. Criteria for the amount of rain fall or discharge from Gaston that would trigger a turbine shutdown period would need to be established, as well as how many subsequent nights the shutdown would be implemented following the end of a rain event. This scenario was assumed to require flow reductions for 28 nights compared 113 nights for shutdowns occurring every night of the eel migration period.

Generation losses were estimated to be about 18% for targeted nightly shutdowns based on rain and flow criteria, and 73% for shutdowns on every night of the migration season (October through January) (Table 5-31). These losses account for ramping down the flows in the bypass reach. It should be noted that at total project flows over 1,325 cfs, Roanoke Rapids will not be able to reach pre-shutdown generation levels during daylight hours.

**Table 5-31. Estimated lost generation and revenue for nightly turbine shutdown alternatives at Roanoke Rapids.**

Option	Reduction in Generation (%)	Reduction in Generation (MWh)	Lost Revenue
Nightly Shutdowns (113) ¹	73	55,589	\$1,638,200
Targeted Nightly Shutdowns (28) ^{1,2}	18	13,897	\$409,600

¹ Included losses associated with ramp down requirements for the bypassed reach.

² Assumes a 75% reduction in nightly shutdowns.

5.3.7 Vertical and Horizontal Zig-Zag Bypass Systems

The design of the vertical and horizontal zig-zag eel bypass systems considered for Roanoke Rapids were based on the installation of a new intake bar rack to reduce turbine entrainment. The primary benefit of the new bypass designs is the significant reduction in bypass flow that would be required for operation and passing eels downstream. The horizontal zig-zag system consists of a series of 18-inch diameter stainless steel pipes connected together at 30 degree angles in zig-zag pattern (Figure 5-23, Figure 5-24). At each interior angle there is a bypass port (entrance opening). The pipe array is set horizontally across the base of the trash rack and is plumbed via siphon to exit over the dam and into the bypass reach. A row of bristles installed just upstream of the rack provides a resting area (velocity refuge) for eels upstream of the bypass pipe and intake. The total flow through the horizontal portion of the two bypass designs was estimated to be approximately 4.6 cfs.

Six vertical bypasses would be used at Roanoke Rapids, one at each end of the trash rack and one in line with the centerline of each unit. Each bypass would consist of a 10 inch diameter vertical central pipe with tangential plates oriented at right angles along the length of the pipe with a series of entrance ports located sequentially along the pipe. Large horizontal pipe sections between the ports would further guide eels to the inlet ports. Like the horizontal system, brushes are installed along the leading edge of the plates to create a refuge for eels. Each bypass would be designed for a flow of 1.3 cfs, resulting in a total vertical bypass flow of 7.8 cfs. The six bypass pipes would flow into a 2-ft diameter header pipe that would discharge in the bypass reach downstream of the dam. A siphon would be used to create the flow.

The estimated total cost for the installation of the vertical and horizontal eel bypass systems is \$1,298,000 (Table 5-32). This is in addition to the cost of a new bar rack as described previously.

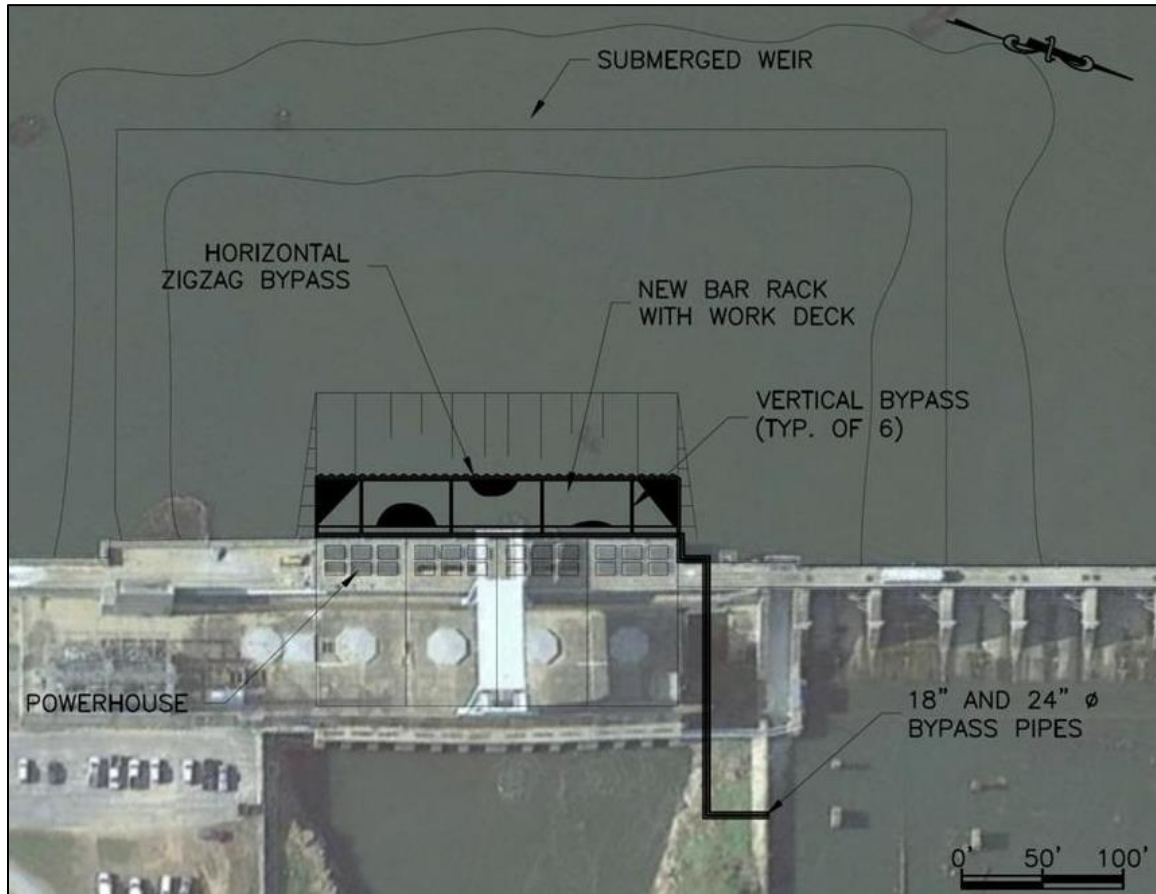


Figure 5-23. Vertical and Horizontal Zig-zag Bypass System- Plan View

5.3.7.1 Turbine and Total Project Survival

The independent variables included in the multiple linear regression model developed to estimate eel turbine survival accounted for 88% of the variability in survival estimates among the study sites where field studies were conducted (Table 5-33). Results from this model produced turbine survival estimates of about 52 to 88% for silver eels ranging in size from 400 to 1000 mm (Table 5-34). Total project survival ranged from 67.7 to 84.6% for the existing conditions at the range of expected river flows, with an overall survival of 68.5% for the entire eel migration period (Table 5-35). Project survival increased with all three alternatives. The zig-zag bypass increased survival to 75.5%, followed by the $\frac{3}{4}$ in perpendicular rack (95.2%), and the 0.75-in angled rack had the highest project survival of 95.6% (Table 5-35). As expected, total survival was lowest when the majority of flow was passing through one or more turbines.

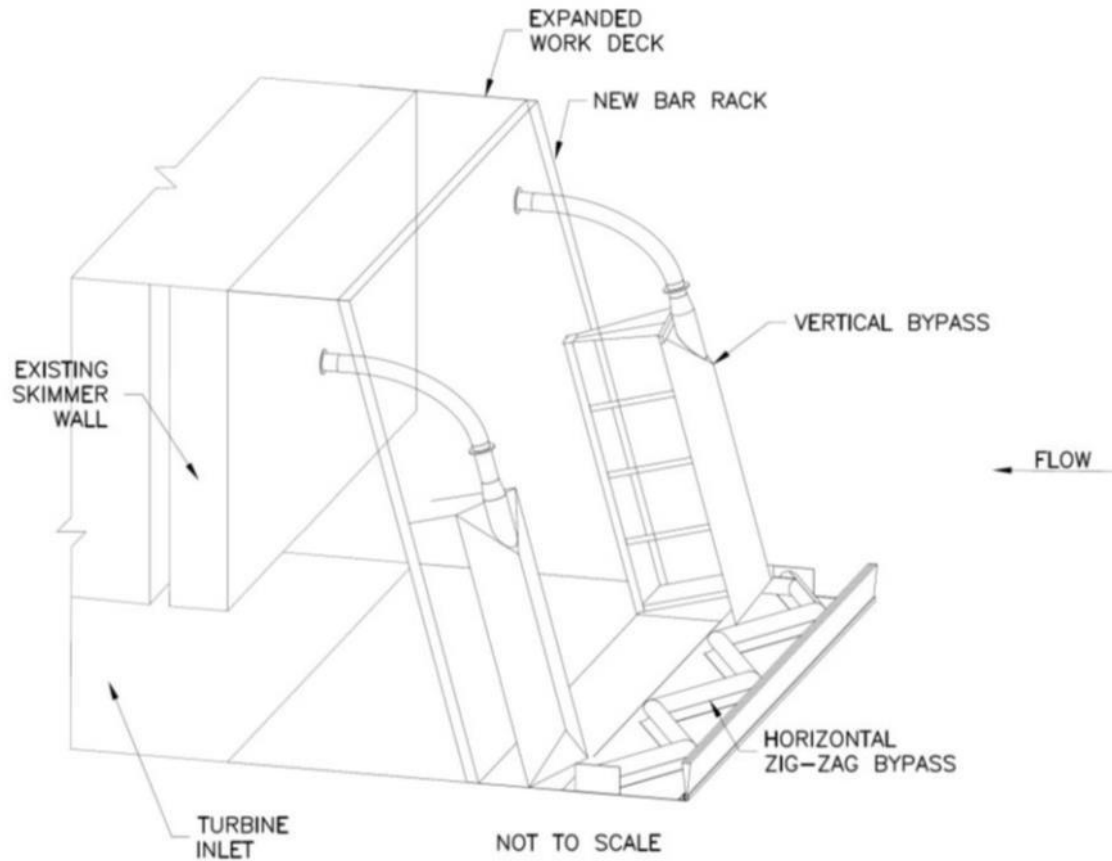


Figure 5-24. Vertical and Horizontal Zig-zag Bypass System – Isometric View

Table 5-32. Cost Estimate for Vertical and Horizontal Zig-zag Bypass System

Item	Estimated Cost
Direct Costs	
Mobilization and Demobilization	\$63,000
Horizontal Zig-Zag with Bypass Piping	\$324,000
Vertical Bypass with Piping	\$308,000
Distributable Costs	\$126,000
Direct Costs Subtotal	\$821,000
Indirect Costs	\$82,000
Direct and Indirect Cost Subtotal	\$903,000
Allowance for Indeterminates	\$226,000
Allowance for Contingencies	\$169,000
Total Estimated Project Costs¹	\$1,298,000

¹ Would be paired with the new bar rack option (~\$15.4M)



Table 5-33. Multiple linear regression model results of the effects of turbine design and operational parameters on eel survival at Roanoke Rapids.

Regression Statistics	
Residual Std Error	0.0877
DF	49
Multiple R ²	0.8868
Adjusted R ²	0.8775
F-statistic	95.92

Coefficients	Estimate	Std Error	T-value	P-value
(Intercept)	1.1819	0.1140	10.367	0.0000
Test Flow	0.0007	0.0002	3.125	0.0030
Eel Length	-0.5903	0.1140	-5.180	0.0000
Blade spacing	-0.0016	0.0002	-7.857	0.0000
RPM	0.0170	0.0203	0.836	0.4072

Table 5-34. Turbine survival (\pm 95% CL) estimates for silver eel passing through the Roanoke Rapids units by length at 100% gate opening.

Eel Length (mm)	Turbine Survival (%)
400	88.2 \pm 8.4
600	76.4 \pm 4.9
800	64.6 \pm 4.1
1000	52.8 \pm 7.1



Table 5-35. Total project survival by river flow for silver American Eel (800 mm) at Roanoke Rapids for each passage design alternative considered.

River Flow (cfs)	Flow Proportion	Total Project Survival (%)			
		Existing Conditions	Bar Rack with 0.75-inch Spacing	Angled Bar Rack with 0.75-inch Spacing	New Eel Bypass Systems with 1-inch Bar Spacing
500-1499	0.1	84.6	97.3	97.3	89.1
1500-1999	10.3	68.8	96.4	96.4	78.5
2000-2499	19.6	68.1	96.3	96.3	78.1
2500-2999	6.8	67.7	94.6	95.3	77.8
3000-3999	7.5	67.7	94.6	95.3	77.8
4000-4999	4.9	68.3	94.7	95.4	78.2
5000-5324	1.7	69.4	94.8	95.5	75.7
5325-5999	3.0	69.7	94.9	95.5	76.0
6000-6999	3.0	68.7	94.4	95.2	74.6
7000-7499	0.0	68.0	94.0	94.9	73.3
7500-7999	5.0	67.8	94.6	95.3	74.5
8000-8999	9.0	67.8	94.6	95.3	74.5
9000-10324	5.0	68.1	94.7	95.3	74.7
10325-11999	3.0	68.9	94.8	95.4	75.3
12000-12499	1.0	68.0	94.3	95.1	73.8
12500-12999	1.0	67.9	94.7	95.3	74.6
13000-13999	1.6	67.9	94.7	95.3	74.6
14000-15324	3.4	68.0	94.7	95.3	74.7
15325-15999	1.1	68.6	94.7	95.4	75.1
16000-16999	0.9	68.2	94.5	95.2	73.2
17000-17499	0.0	67.9	94.1	94.8	74.6
17500-17999	0.4	67.9	93.9	94.7	74.5
18000-18999	1.7	67.9	94.7	95.3	74.6
19000-20324	4.9	68.0	94.7	95.3	74.7
20325-24999	5.0	68.4	94.7	95.4	75.0
25000-34999	<0.1	73.9	95.3	95.9	79.3
>35000	<0.1	80.8	96.1	96.5	84.6
Total	100.0	68.5	95.2	95.6	76.6

5.3.7.2 Roanoke Rapids Case Study Conclusions

The use of 0.75-inch bar spacing on the existing intake structure or with a new angled bar rack would likely produce high downstream passage survival rates (about 95%) for silver eels at Roanoke Rapids (Table 5-36). However, the angled rack was estimated to be the most costly alternative for protecting eels (Table 5-36), whereas the cost of the 0.75-inch bar spacing installed at the existing intake would be similar to the cost of the two eel bypass designs, which would also require major intake modifications for a narrower bar spacing (Table 5-36). Targeted



nightly shutdowns would provide the greatest protection for silver eels (98% total survival) and have an estimated annual generation loss of about \$410,000 (shutting down every night during the eel migration season would be two to three times more). The cost of lost generation would be about \$16.4 million over the course of a 40 year FERC license term. The downstream passage survival estimate for the two new eel bypass designs was 74.5%, which is higher than the current conditions but considerably lower than the two options with 0.75-inch clear bar spacing. If bar spacing is reduced to 0.75 inches for the new eel bypass designs, total downstream passage survival would likely be about 95% because little or no turbine entrainment would occur. This would also provide a significant cost savings over the other narrow bar spacing alternatives which will require about 1,000 to 2,000 cfs bypass flow compared to 6 to 12 cfs for the vertical and horizontal eel bypass systems.

Table 5-36. Summary of bypass efficiency, total project survival, and approximate cost for silver eel downstream passage alternatives considered for Roanoke Rapids.

Downstream Passage Alternative	Assumed Bypass Efficiency (%)	Total Project Survival (%)	Approximate Cost (\$)
Existing conditions	10	68.5	--
Bar rack with 0.75-inch spacing	90-95	95.2	15,365,000
Angled bar rack with 0.75-in spacing	92-95	95.6	62,195,000
Targeted nightly turbine shutdowns	100	98.0 ¹	410,000/16,400,000 ²
Vertical/horizontal eel bypasses with 1-in spacing	40	75.5	16,665,000

¹ Total project survival over the course of the entire eel migration season likely would be lower than 98% given some proportion of eels will pass downstream during daylight hours and nights when the turbines are operating.

² Annual cost of lost generation due to nightly shutdowns and total cost over 40 year license term.



6.0 Study Conclusions and Discussion

6.1 Primary Study Conclusions

The following are the primary conclusions from the results of the evaluation of the two eel bypass designs:

Laboratory Evaluation

- The laboratory evaluation of the two bypass designs, which was conducted in a large recirculating flume with a simulated turbine intake, demonstrated bypass efficiencies of 68 % for the vertical system tested alone and 91% for both systems evaluated together when the intake bar spacing was 1-inch clear and small-mesh perf-plate was placed over the lower 16 inches of the bar rack.
- The horizontal bypass system also produced a bypass efficiency of 75% when tested alone with a 2-inch bar spacing on the intake rack and with the perf-plate overlay on the lower portion of rack.
- The estimated bypass efficiencies from the laboratory tests indicated both bypass systems had potential to provide acceptable levels of protection for silver eels when installed at an actual turbine intake.
- The CFD modeling demonstrated accelerations in flow around the bypass systems and into the bar racks with eddies and back flows on the downstream side of each bypass design.
- Despite the flow acceleration directly upstream of the bar racks, the channel velocity of 2.0 ft/s and the increase to velocities up to about 2.5 to 3.0 ft/s did not lead to impingement of eels and produced acceptable levels of bypass efficiency for some of the test conditions.
- With the narrower bar spacing (1-inch) and the perf-plate installed, test fish appeared to have more opportunity to search, locate, and enter the bypass openings. This was particularly evident for the vertical bypasses which were ineffective with the 2-inch bar spacing, but had a bypass efficiency of 68% with the 1-inch spacing.

Field Evaluation

- The field evaluation of the two eel bypass designs, which was conducted at a turbine intake at a small hydropower project in New Hampshire, did not demonstrate effective downstream passage for test fish released upstream of the intake in the project's power canal.
- CFD modeling indicated the turbine operating conditions that were evaluated produced flow velocities approaching the powerhouse intake that were too high (up to 4 ft/s) for



eels to effectively avoid entrainment and impingement before locating a bypass opening for safe downstream passage.

- The CFD modeling also indicated a blockage over some portion of the lower bar rack (i.e., similar to what was tested in the flume with perf-plate) could not be used at the field site because it would have created even higher approach velocities and produced flow conditions downstream of the bar rack that could negatively impact turbine operation.
- Bypass efficiencies were estimated to be 0 to 33% for the range of turbine generation levels and the two bar spacings (1.13 and 3.00 inches) evaluated, with most bypassed eels using the horizontal zig-zag system.
- A large proportion of test fish (13 to 60%) moved upstream out of the power canal and did not interact with the turbine intake or bypass systems. These fish either remained upstream or passed downstream over the spillway. The loss of these fish to the evaluation of the bypass system reduced the robustness of the efficiency estimates due to smaller than anticipated sample sizes.

Technology Application Assessment

- There are about 265 hydropower projects in the range of American Eel that will be undergoing FERC relicensing in the next 15 years, many of which could benefit from an affordable and effective eel diversion system that can reduce turbine entrainment and minimize impacts to project operation.
- The four case studies demonstrated that the two existing eel protection technology alternatives that comply with USFWS prescription requirements (i.e., 0.75-inch bar spacing on existing intake structure or installation of an angled rack with the same spacing, and both with approach flow velocities of 1.5 ft/s or less) are likely to be the most costly approaches.
- Targeted nightly shutdowns that are triggered by precipitation events could provide very high levels of protection for silver eels (potentially as high as 98% total project survival), as would shutdowns on every night of the migration season. However, although annual costs for this alternative would be low for each of the case study sites, it could be very costly over a 30 to 40 year FERC license term at each project.
- The two eel bypass designs were typically the least expensive technology option, but also had the lowest estimated total project survival rates at each case study site. However, the eel bypass systems could potentially provide levels of bypass efficiency similar to the two narrow-spaced bar rack alternatives while using orders of magnitude less flow, if they are combined with the 0.75-inch clear bar spacing.
- When considered with the laboratory and field testing results, the case study assessments suggest that the two eel bypass designs could potentially be effective at



sites with relatively low approach velocities and narrow intake bar spacings (e.g., 0.75 inch clear openings), while using significantly less flow than more conventional bypass systems. The cost savings of the lower bypass flow could be substantial over the course of FERC license term (30 to 50 years).

Recommendations for Future Research

- Although neither of the two eel bypass systems evaluated as part of this research effort performed to a standard (i.e., bypass efficiencies exceeding at least 75%) that would allow them to be considered for immediate application at hydropower projects in the U.S., the results of laboratory and field testing indicate further development and testing of these technologies could lead to more effective designs.
- Potential modifications that could improve performance include larger openings, an increase in bypass flow, and improvement in hydraulic conditions around the bypass pipes (this may be more important to the vertical system than the horizontal design). Techniques that reduce entrainment and allow fish more time to search for the bypass openings, such as the use of solid or small-mesh panel on the bottom of a turbine intake's bar racks, should also be examined in more detail to develop approaches that positively influence eel behavior without impacting turbine operation.
- CFD modeling and laboratory testing should both be used to develop and evaluate design enhancements and optimize each bypass system before any additional testing is conducted in the field.

6.2 Discussion

The evaluation of the two new bypass designs (vertical and horizontal zig-zag conduits with small entrance openings) developed for downstream passage of silver eel at hydropower dams incorporated three study components (biological testing in the lab and field and CFD modeling of both test locations) to determine the efficacy of these technologies and the potential need for further development. The laboratory results indicated that the two systems, operated alone or in combination, had potential to effectively bypass silver eels at turbine intakes under certain design and operational conditions. These conditions included intake bar rack clear spacing of 1 inch (or less), approach velocities of 2 ft/s (or less), and the use of a solid panel over a portion of the lower bar rack (a 16 inch height was tested in the lab). The horizontal bypass also was shown to provide effective passage (75% bypass efficiency) with a 2-inch clear bar spacing.

Based on the positive laboratory results, a field evaluation was conducted using similar design and operational conditions that were considered effective in the lab. However, CFD modeling of the hydraulic conditions at the field site indicated the use of a solid panel bottom overlay would affect flow entering the turbine intake in a manner that could negatively impact turbine operation and the ability of silver eels to avoid entrainment and impingement. Therefore, a bottom panel was not installed on the bar rack at the field site. Several turbine operating conditions were evaluated, primarily with a 1-inch clear spaced bar rack overlay. One release of tagged eels was also conducted without this overlay to evaluate the bypass systems with the



existing clear bar spacing at the project (3 inches). Bypass efficiencies for all four test releases of tagged silver eels were low (0 to 33%). The ineffective application of the bypass systems at the field site was attributed primarily to high velocities at the turbine intake (up to about 4 ft/s based on CFD modeling) that made it difficult for eels to locate a bypass opening before becoming entrained or impinged. Additionally, for three of the four test releases about 40 to 60% of test fish were last detected in the impoundment, indicating they moved upstream out of the power canal and likely passed downstream over the spillway. This significantly reduced the effective number of tagged fish encountering the turbine intake and bypass systems and, consequently, limits the robustness of the results to some degree.

In addition to the biological testing and CFD modeling of the bypass systems, a technology application assessment was conducted to determine the number of hydropower projects within the range of American Eel that might benefit from new bypass systems that are biologically effective and are less costly to install and operate (from the perspective of installation costs and lost revenues due to reduced generation). There are hundreds of projects that will likely need to address downstream passage of silver American Eels during FERC relicensings underway now and that will be initiated in the next 10 to 15 years. The current standards and requirements for downstream eel passage prescribed by state and federal resource agencies, including 0.75-inch spaced bar racks to reduce entrainment and intake approach velocities less than 1.5 ft/s to prevent impingement, can be onerous and difficult to implement from operational and cost standpoints. The results of four case studies completed as part of the technology application assessment indicate that the new bypass systems may not achieve acceptable levels of bypass efficiency and total downstream passage survival for silver eels, but the two systems would be less costly to implement mainly due to bypass flow requirements that can be one to two orders of magnitude less than conventional submerged and surface bypasses. Also, the field test site used for this study was not conducive to the use of the new bypass designs primarily due to the high velocities at the turbine intake. Bypass efficiencies would likely be higher at projects with turbine intake approach velocities of lower than 2 ft/s. However, some projects may need to install new or modified bar racks with narrow clear spacings (one inch or less).

The results of this study indicate there is potential for effective application of the two new eel bypass designs if specific intake rack bar spacings and approach velocity conditions are met. Also, CFD modeling of the hydraulic conditions at the bypass openings and in the conduits suggest that design modifications may be needed to optimize the designs to improve the detection of entrances by silver eels and increase the likelihood of entry and passage. With design modifications and field testing at sites that are more conducive to the application of these bypass systems, it may be determined that many hydropower projects could benefit from these technologies, primarily with respect to the reduced flow required for their operation.



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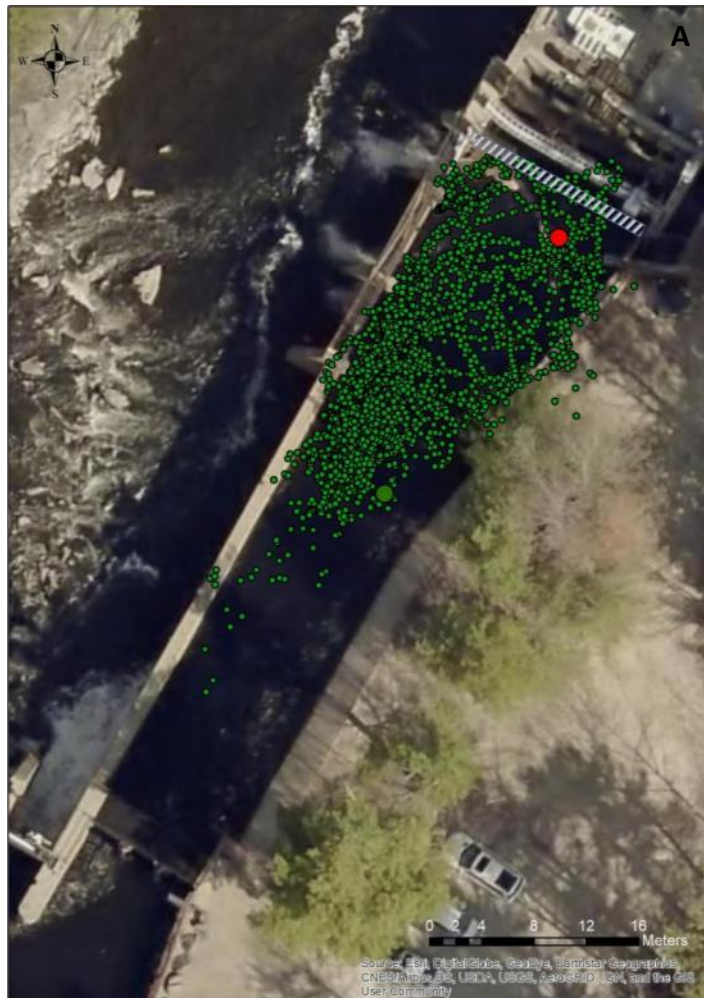
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Appendix A – Acoustic Telemetry Eel Track Examples



A-1. Bypass eel (tag 2045_12) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



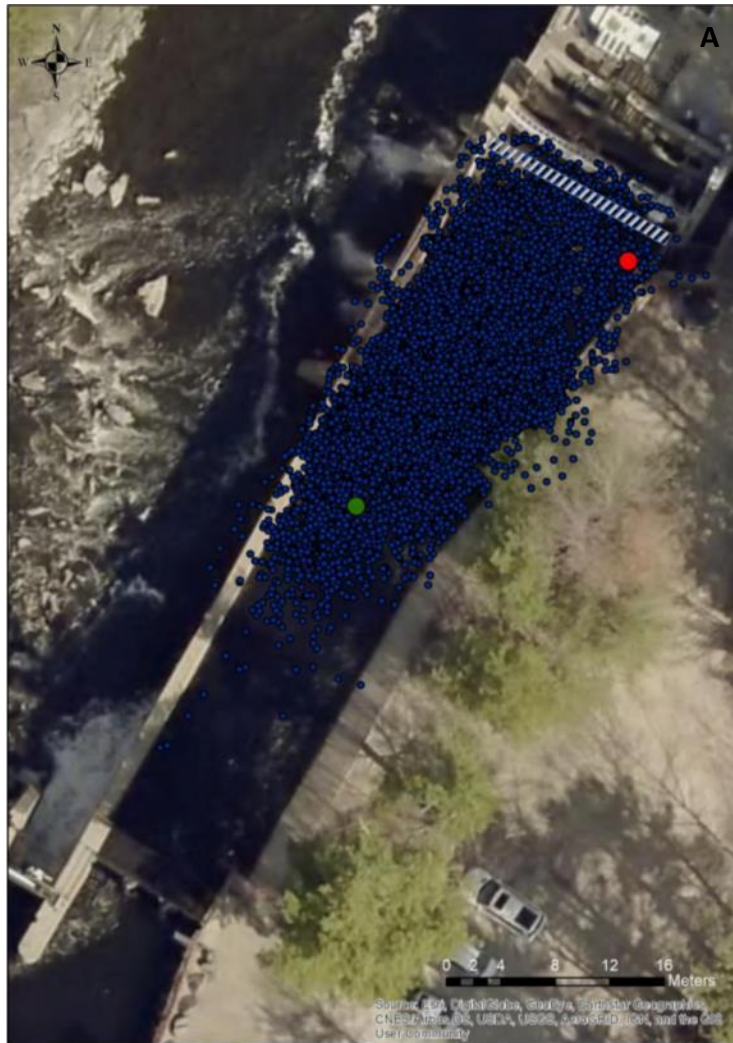
A-2. Bypass eel (tag 2171_29) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



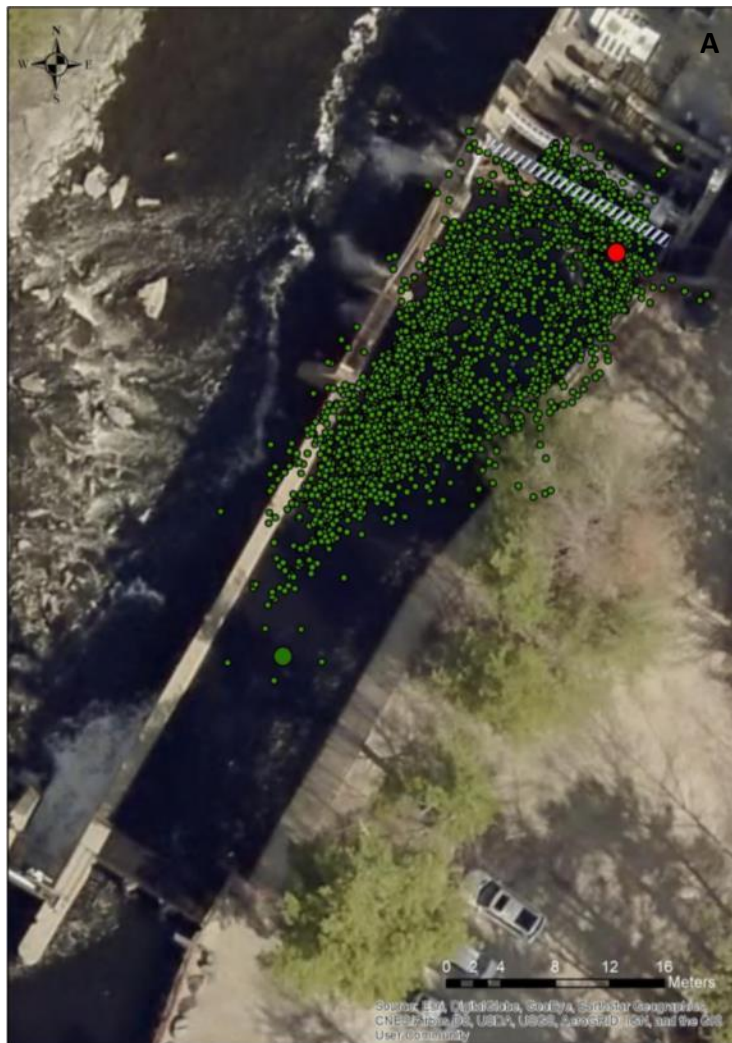
A-3. Bypass eel (tag 2185_02) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



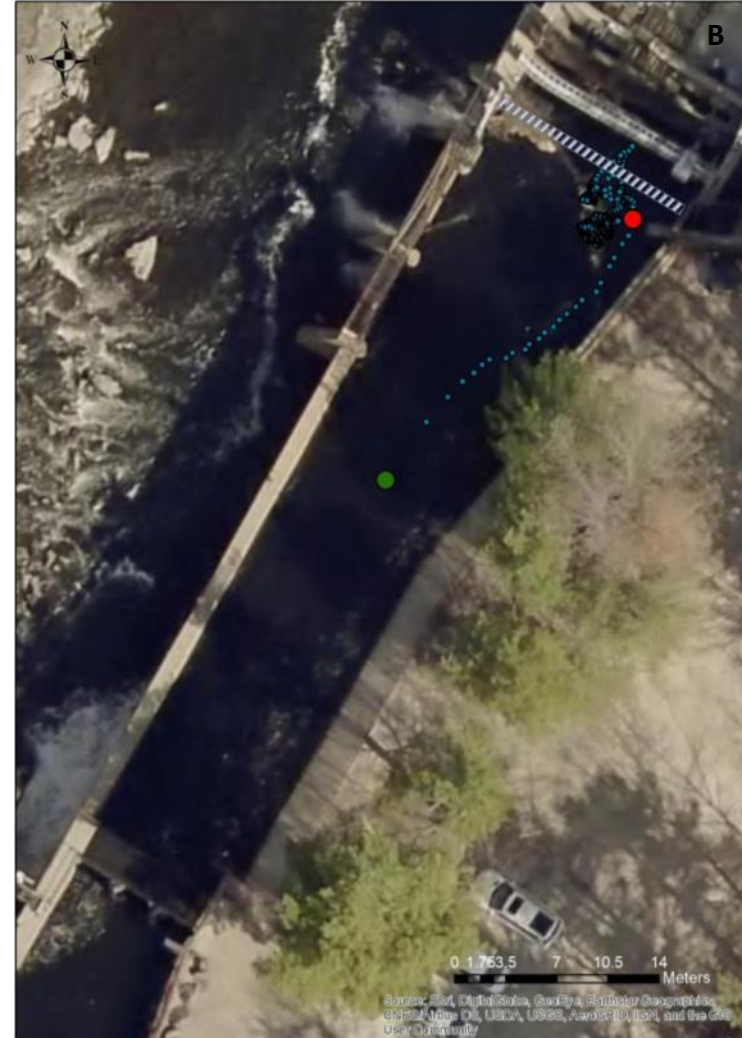
A-4. Bypass eel (tag 2186_24) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



A-5. Bypass eel (tag 2297_02) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



A-6. Bypass eel (tag 2382_13) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



A-7. Bypass eel (tag 2507_06) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



A-8. Bypass eel (tag 2535_27) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



A-9. Bypass eel (tag 2801_22) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



A-10. Bypass eel (tag 2899_21) individual track where (A) is the track for 3 days after release and (B) is the last hour before passage.



A-11. Entrained eel (tag 2410_20) individual track for the 3 days after release.



A-12. Entrained eel (tag 2493_03) individual track for the 3 days after release.



A-13. Entrained eel (tag 2536_12) individual track for the 3 days after release.



A-14. Upstream eel (tag 2409_19) individual track for the 3 days after release.



A-15. Upstream eel (tag 2437_24) individual track for the 3 days after release.



A-16. Upstream eel (tag 2480_01) individual track for the 3 days after release.