Study Report
for the
Desktop Entrainment, Impingement, and Turbine Passage Survival Assessment

Lawrence Project (FERC No. 2800)

Prepared For
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Table of Contents

List of Tables

List of Figures

1 Introduction

Essex Company, LLC (Essex), a subsidiary of Patriot Hydro, LLC, is the Licensee, owner, and operator of the Lawrence Hydroelectric Project, which is Federal Energy Regulatory Commission (FERC or Commission) Project No. 2800 (Project or Lawrence Project). The Project was licensed by the FERC on December 4, 1978 (with an effective date of December 1, 1978), and the license expires on November 30, 2028. The Lawrence Project is located at river mile (RM) 29 of the Merrimack River in the City of Lawrence in Essex County, Massachusetts.

In accordance with 18 C.F.R. § 5.15, Essex provided studies and information gathering activities in the study plan in support of its intent to relicense the project. On April 10, 2024, Essex filed a Revised Study Plan (RSP) after evaluating all the study requests submitted by the stakeholders, which was approved by the Commission in their May 10, 2024 Study Plan Determination (SPD).

Among the studies requested was a desktop-based evaluation and summary of the potential for entrainment, impingement, and turbine passage survival at the Project. This study report includes the findings of this effort developed from the FERC-approved study plan.

2 Goal and Objectives

The goal of the Desktop Entrainment, Impingement, and Turbine Passage Survival Assessment was to evaluate the potential risk of impingement and entrainment and to provide estimates of passage survival for outmigrating diadromous fish species.

Specific objectives of the study include:

- Describe the physical and operational characteristics of the Project, including the location, dimensions, specifications, and hydraulics of the intake, trashrack, powerhouse, turbines, bypass, and spillway.
- Calculate approach velocities at the intake over a probabilistic range of inflow values representative of the expected out-migration window of target fish species and life stages for comparison to swim speeds.
- Compile and summarize available passage survival data from entrainment and mortality field studies performed for target fish species and life stages at other hydroelectric projects and compare those facility characteristics to Lawrence.
- Generate estimates of project survival by simulating downstream passage for a theoretical number of target fish species and life stages through the Project under a series of inflow values representative of a high, median, and low flow downstream passage condition.

3 Methods

This study addresses the risk potential for fish impingement, entrainment, and the probability of downstream passage survival at the Project using a review of relevant biological criteria and physical Project characteristics for four diadromous fish species: river herring [i.e., Blueback Herring and Alewife], American Shad, and American Eel. While only the adult life stage is relevant for American Eel, the juvenile life stage will also be evaluated for American Shad, Blueback Herring, and Alewife (collectively referred to as "juvenile alosines"). Factors that can influence the potential for impingement or entrainment at a hydropower project include structural characteristics such as the size and depth of the intake structure, the velocity of water as it enters the intake structure, the location of the intake structure relative to fish habitat, and the biological and behavioral characteristics (e.g., size, movement or migration patterns, and habitat preferences) of the specific life stages of fish species of interest. Turbine survival rates are primarily affected by engineering factors such as the amount of head differential of a turbine, its number of blades, rotational speed, hydraulic capacity, and the length of an entrained fish. Estimating whole station survival for each species and life stage is influenced by degree of river inflow, flow proportion through egress routes and likelihood of flow occurrence to occur during the migration period.

3.1 Description of Project Structures and Operations

The first step in the evaluation of the potential for fish impingement and entrainment was to describe the physical features of the impoundment, intake structure, and turbine units that will affect entrainment, impingement and turbine passage survival. Project dimensions were obtained from available engineering drawings of the Project.

3.2 Life History and Habitat Requirements of Target Fish Species

A description of the life history, habitat requirements, and behavior of fish species was compiled to determine the likelihood of presence near the Project intakes and to evaluate entrainment potential. The "Traits Based Assessment" of Čada and Schweizer (2012) was used to qualitatively assess the potential entrainment risk for considered fish species, and includes each species' primary location within the Project, preferred habitat, local movements and reproductive strategy. Species-specific behavioral requirements determine if and when a given life stage interacts with intake operation. The potential for each species to be susceptible to entrainment can be determined based on their life history characteristics in relation to the location of the Project's intake structure.

Categories of entrainment potential based on the likelihood that a fish species/life stage will be located near the intake structures are described as:

- None - species/life stage (e.g., adult, spawning, or juvenile) are not known to prefer the habitat near the intake structures
- Minimal - species may only occasionally be found occupying the habitat near the intake structures

- Moderate - species routinely or seasonally found occupying the habitat near the intake structures
- High - species likely to be found occupying the habitat near the intake structures

3.3 Impingement and Entrainment Potential of Target Fish Species

The distance between bars on a trash rack (i.e., clear spacing) can affect the likelihood of an individual fish being excluded from moving through the trash rack and entering the turbine intakes. Fish species and life stages with a body width greater than the clear spacing are physically excluded from passing through a trash rack and becoming entrained. Proportional estimates of body width to total length (scaling factor) were compiled by Smith (1985) for a suite of fish species. These species-specific scaling factors were used to determine the minimum length of each species excluded from the turbines by the intake trash rack spacing. The clear spacing values were divided by the scaling factors to calculate the minimum length for each target species that would be excluded at the Project.

In addition to body size, the ability for an individual fish to avoid being impinged or entrained at a powerhouse intake often depends on its swimming performance (Castro-Santos and Haro 2005). The swimming performance is directly related to the size of an individual fish; however, the swimming capability also varies among species based on morphological differences. Although there is no standard method that defines how swimming performance is measured, three commonly used definitions or types of swim speed are described in the scientific body of literature for fish (Katopodis and Gervais 2016). The three swim speed types, cruising, prolonged, and burst, are described as the following:

- Cruising or sustained swim speeds can be maintained indefinitely (Bain and Stevenson 1999);
- Prolonged swim speeds can be maintained between 5 and 8 minutes (Bain and Stevenson 1999); and
- Burst (also called startle, darting or sprint) swim speeds can be maintained for less than 20 seconds (Beamish 1978).

Burst swim speeds were used to assess if a fish can adequately escape involuntary impingement or entrainment. If a fish has a greater burst swim speed than the turbine intake approach velocity, it is capable of moving away from the intake flow field to avoid interaction. To assess swimming capabilities for the target fish species of interest, burst swim speeds were compiled from the available scientific literature.

To ascertain whether or not a certain size fish of a particular species is likely to be impinged or entrained, the burst swim speeds were compared to the calculated approach velocity of the intake trash racks at the maximum hydraulic capacity of the Project. The approach velocity at the Project intake was calculated using the velocity equation:

$$V = Q/A$$

Where:
Q = flow rate (cfs);
V = approach velocity (feet per second (fps)); and
A = area (square feet (ft^2)).

Fish species and sizes whose burst swim speeds are less than the approach velocity at the Project intake are susceptible to impingement at the trash racks if their body widths are greater than the trash rack spacing. If the body width of a fish is less than the trash rack spacing and its burst swim speed is less than the approach velocity, it is more susceptible to entrainment.

3.4 Qualitative Assessment of Entrainment Potential

Data related to Project characteristics, habitat and life history, and swim speeds were used to compile a qualitative assessment of the potential entrainment of target fishes. The qualitative assessment used a multi-step rank of:

- High (H)
- Moderate (M)
- Low (L)

This desktop assessment assigned an overall entrainment potential rank to each of the relevant life stages of target species based on consideration of habitat and life history, swim speed relative to intake velocity, and minimum exclusion lengths relative to trash rack spacing. In general, fish with life history attributes that include obligatory downstream migration are given a rating of ‘High’, while those with juvenile life history stages placing them in the vicinity of the intakes or as adults with swim speeds not necessarily greater than the approach velocity are labeled as ‘Moderate’ risk. Species with life history attributes that generally keep them away from the intakes or fish that have a burst swim speed greater than the intake velocity are listed as a ‘Low’ risk for entrainment. In relation to swim speed, regardless of life stage, fish are considered ‘High’ risk if the maximum burst speed does not exceed the intake velocity, ‘Moderate’ risk if the intake velocity falls within the range of burst swim speed, and ‘Low’ risk if the burst swim speed completely exceeded the intake velocity.

The entrainment potential classification for trash rack spacing depended on the minimum body length exclusion results. If the minimum exclusion length for the existing trash rack spacing was longer than the standard length for a juvenile or adult (i.e., many individuals of that species and life stage are likely to be shorter than the minimum exclusion length) it received a “High” entrainment risk potential. A “Moderate” entrainment risk potential was applied when the minimum exclusion length overlapped with a portion of the individuals that would be expected to achieve that length by the life stage indicated. A “Low” entrainment risk potential was applied when the minimum exclusion length of a trash rack was less than the standard length of the life stage being considered.

3.5 Project Survival Estimates

3.5.1 Literature Review

Existing literature summarizing studies previously conducted to evaluate downstream passage route utilization, turbine entrainment rates, and estimates of route-specific mortality available for target fish species and life stages from other hydropower projects were reviewed. These studies included previously conducted HI-Z tag-recapture, mark-recapture survival studies, and telemetry evaluations. Available information included specifics related to the hydroelectric project where the study was conducted and rates of passage route survival to inform route selection probabilities under different inflow conditions to be used in estimating Project passage survival at Lawrence. In addition to summarizing passage results observed elsewhere, previously conducted studies in the vicinity of the Lawrence Project were used to define representative sample sizes and length ranges, ensuring that modeled survival and passage estimates reflect the species encountered at the Project.

3.5.2 Turbine Blade Strike Analysis (TBSA)

To estimate survival of fish that entrain and pass through Project turbines, theoretical predictions were used to estimate a survival rate using a blade-strike model developed by the Department of Energy (Franke et al. 1997) that uses various turbine, fish and operations characteristics of a hydroelectric project to calculate a turbine blade strike and survival probability. This model was further modified by the United States Fish and Wildlife Service which produced the Turbine Blade Strike Analysis (TBSA) Tool that estimates the fraction of a population of fish that are killed by blade strike passing through a hydroelectric project (Towler and Pica 2018). TBSA creates a normally distributed population of fish described by its number, mean length, and standard deviation of length that are routed through hazards at a hydroelectric project, e.g., a turbine. Monte Carlo simulations are performed to determine the percentage of individuals subjected to turbine blade strike.

TBSA is informed by turbine parameter values specific to the Project and calculated using methods outlined in Franke et al. (1997). The probability of blade strike in the model is based on several factors, including the number of runner blades, fish length, runner blade speed, turbine type, runner diameter, turbine efficiency, and total discharge. These factors are inputs into the model which predicts survival for a fish of a designated length, regardless of species. The TBSA model was used to predict turbine passage survival estimates expected for each target species in the Project area and up to the maximum lengths (rounded to whole inch) for each target fish species that could entrain through the existing trash rack spacing at the Project. The TBSA model simulations for American Shad and river herring were run using a correlation factor (λ) of 0.2 which is the recommended conservative value (Towler and Pica 2018).

The TBSA model underestimates American Eel turbine survival rates (Lake et al. 2024) and as a result, blade strike probabilities for adult eels were instead estimated using a multiple linear regression model described by Alden (2017) which provides a parameterized multiple linear regression model for axial-style turbines. Blade strike probabilities derived from the Alden model were computed using the Project-specific set of turbine parameters. The turbine survival estimates were converted to turbine mortality values and were applied to the TBSA model as a static value for turbine passage to evaluate the survival outcomes for American Eels across all passage routes under the modeled fall flow conditions.

3.5.3 Total Project Survival Estimates

Estimates of total project survival for each target species and life stage were estimated for downstream passage at Lawrence following the methodologies for survival estimate outlined in Lake et al. (2024). In short, this process included:

1. The identification of hypothetical operating regimes for the Lawrence Project under the range of inflow expected during the spring (April 1 – July 15) and fall (September 1 – November 15) outmigration periods which allocate the total inflow among potential conveyance routes for passing water downstream (i.e., bypass, turbine, spillway).
2. The identification of suitable estimates of passage route utilization and associated route-specific passage survival for each target species and life stage (see Section 3.5.1)
3. A simple model by which to generate an estimate of total passage survival for each species and life stage under each hypothetical operating regime. For the purposes of this study, the "total project" capability of the TBSA Tool was used which relied on a Monte Carlo simulation of a simulated fish population to estimate project survival based on user defined route utilization rates and user defined (i.e., spill, bypass, turbine [eel only]) or calculated (i.e., turbine [herring and shad only]) route-specific survival rates (see Section 3.5.2).
4. Incorporation of site-specific flow duration curves to quantify the proportion of a passage season during which each hypothetical operating regime is occurring such that the associated estimates of total station survival for each regime can be proportioned such that the sum provides an estimate of total project survival representative of the full passage season. Flow duration curves representing the spring (April 1 to July 15) and fall (September 1 to November 15) fish passage seasons are presented in Figures 3-1 and 3-2.

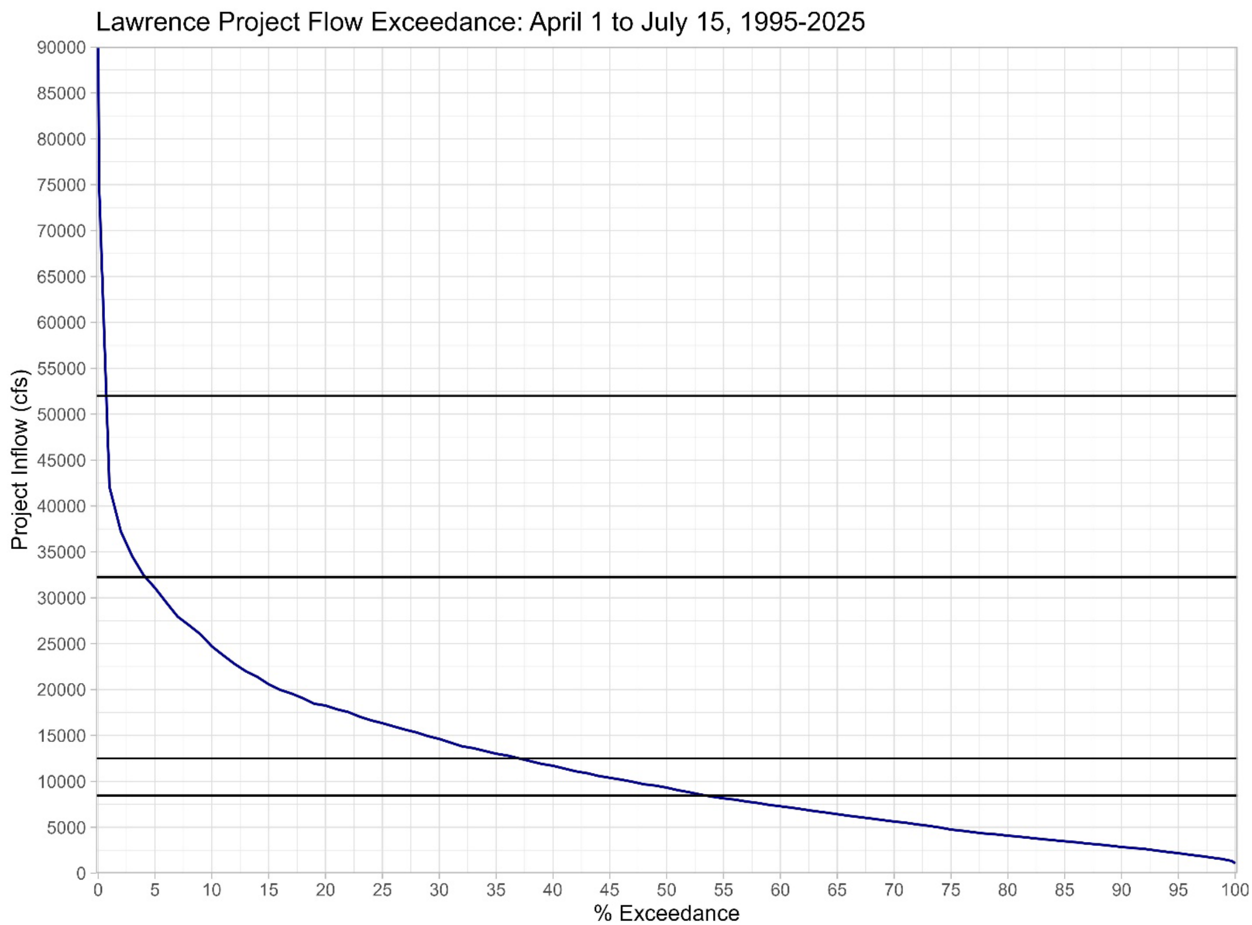

Figure 3-1. Flow duration curve for the spring diadromous fish passage season from April 1 to July 15 at Lawrence [1]

[1] Note: Horizontal reference lines in Figure 3-1 represent discharge values used to delineate the series of operational scenarios considered during the evaluation of total project survival (see Section 4.5.3)

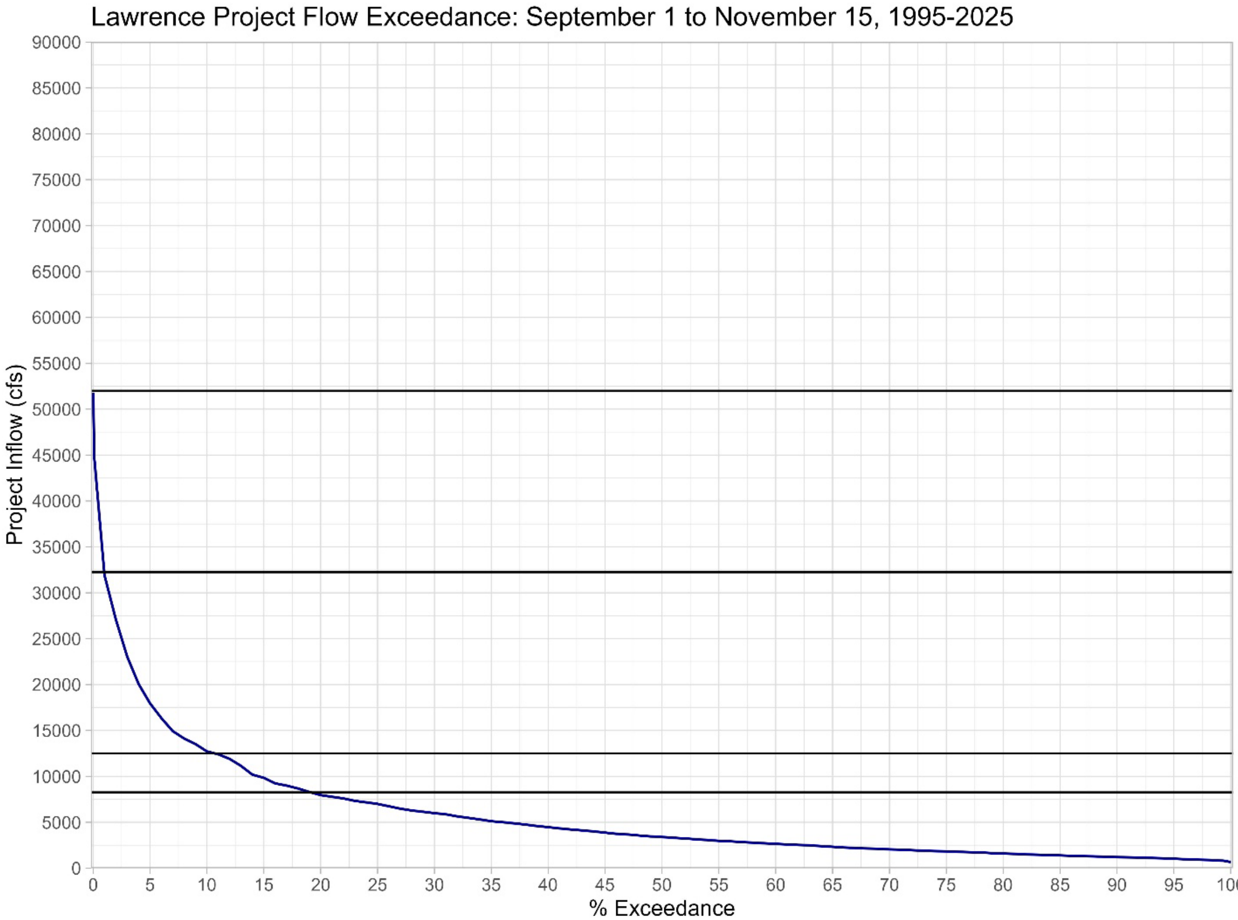

Figure 3-2. Flow duration curve for the fall diadromous fish passage season from September 1 to November 15 at Lawrence.[2]

[2] Note: Horizontal reference lines in Figure 3-2 represent discharge values used to delineate the series of operational scenarios considered during the evaluation of total project survival (see Section 4.5.3)

4 Results

4.1 Description of Project Structures and Operations

Table 4-1 presents the characteristics of the impoundment and Project hydraulic capacity, trash rack dimensions, intake velocity, and turbine discharge. A detailed description of project facilities and operations are provided in the Pre-Application Document (PAD) for Lawrence (HDR 2023). Excerpts from the PAD providing details pertinent to this evaluation are presented as Sections 4.1.1 through 4.1.6 below.

4.1.1 Project Location and Facilities

The Lawrence Project is located on the Merrimack River in the City of Lawrence in Essex County, Massachusetts. The Project is the first dam on the Merrimack River, approximately 29 river miles (RM) from the Atlantic Ocean, and is approximately 11 RM downstream of the Lowell Hydroelectric Project (FERC No.2790; Figure 4-1).

The Essex Dam, also known as the Great Stone Dam, is a 900-foot-long gravity structure constructed of stone masonry. The dam is 35 feet in height from the crest elevation to the downstream foundation bedrock. The spillway crest is topped by an Obermeyer pneumatic crest gate system with three independently controllable zones. Each 300-foot-long zone consists of fifteen 20-foot-long, hinged, steel panel sections supported by a tubular rubber air bladder. Restraining straps attached to each gate panel prevent the panels from being raised above the approved five-foot effective height above dam crest.

The North Canal originates at the Essex Dam impoundment, upstream of the northern abutment of the Essex Dam. The North Canal is approximately 95 feet wide and 15 feet deep, extending parallel to the Merrimack River for a distance of approximately 5,300 feet (FERC 1978). The North Canal flows are controlled by the North Canal Gatehouse located near the canal entrance opposite of the Essex Dam. The North Canal is capable of carrying controlled flows up to 3,000 cfs. At the terminus of the North Canal is a gated spillway known as the “Lower Locks.”

The South Canal originates at the south abutment of Essex Dam, adjacent to the entrance of the intake canal. The South Canal is approximately 35 feet wide and 10 feet deep, extending parallel to the Merrimack River for a distance of approximately 2,750 feet (FERC 1978). The South Canal flows are controlled by the South Canal Gatehouse located near the canal entrance. The South Canal discharges to the Merrimack River via an underground conduit.

The North and South Canals are not viable routes for downstream fish passage and were not considered in this exercise. At present, a limited amount of flow (estimated 100 cfs total) is conveyed through the two canals. However, these flows are associated with leakage and there are no routes through which a fish could pass.

4.1.2 Impoundment Characteristics

The Project's impoundment has a surface area of 655 acres and gross storage capacity of approximately 19,900 acre-feet at the impoundment's normal elevation of 44.17 feet NGVD29. As the Project is operated in a run-of-river (ROR) mode, there is no useable storage capacity. The 9.8-mile-long impoundment is bordered by urban development and forested shoreline.

4.1.3 Powerhouse, Intake Structure, and Trash Racks

The Project powerhouse is a 72-foot-wide by 128-foot-long building constructed of concrete and contains the Project's two generating units. The structure is approximately 90 feet high. The intake for the turbines is integral with the powerhouse and includes trashracks with 6-inch clear spacing.

River flows are directed to the powerhouse via a short intake forebay located adjacent to the south abutment of the dam. The forebay is approximately 170 feet long by 80 feet wide. The exit channel for the Project's fish lift system is located on the river left side of the forebay.

Flows from the Project's powerhouse discharge to the Merrimack River via an approximately 130 foot long, 100-foot-wide tailrace channel. The tailrace channel is bordered on the river side by bedrock and the concrete remains of a former fish ladder, and on the land side by bedrock and undeveloped lands leading to the south abutment of the Route 28 (Broadway) bridge.

4.1.4 Downstream Bypass

The downstream fish bypass facility is a concrete bypass chute that is typically operated annually from April 1 through July 15 and from September 1 through November 15, on a 24-hour basis. The bypass gate is mechanically driven and required to operate such that it supplies surface spill from the forebay and provides a minimum of 2% of turbine flow. During both downstream migration seasons, Essex typically operates the downstream bypass at a consistent 160 cfs, representing 2% of the maximum turbine capacity (i.e. 8,000 cfs).

4.1.5 Turbines

The powerhouse contains two horizontal, double-regulated Kaplan bulb turbines (Table 4-2). Each turbine is rated at 11,260 horsepower (HP), operating at a speed of 128.6 revolutions per minute (RPM) at a rated head of 26.5 feet. Each unit's bulb contains a horizontal shaft, air-cooled, synchronous generator directly connected to the turbine shaft. Each generator is rated at 8,842 kilovolt-amperes (kVA), 0.95 power factor, 4,160 volts, 3-phase, 60 hertz (Hz), 80 degrees Celsius (^{o}C) temperature rise. The generating units are each rated at 8.4 megawatts (MW) with a minimum hydraulic capacity of approximately 600 cubic feet per second (cfs) and a maximum of 4,000 cfs. The Project has a total installed, authorized capacity of 16.8 MW.

4.1.6 Project Operations

The Project operates in a run-of-river (ROR) mode. The crest gate control system works in concert with the powerhouse pond level control system to maintain the impoundment water level. Under normal operations the Project's turbines are operated in automatic pond level control mode, with the control setpoint established at the top of the crest gates (± 44.2 feet). When river flows are within the hydraulic capacity of the turbines (8,000 cfs or less), the pond level control system adjusts the turbines' output to maintain the impoundment level at the control setpoint, thereby matching inflow and maintaining ROR operation. Separately, the crest gate system also has an automatic pond level control system which regulates the elevation of each of the system's three zones to control the upstream impoundment water level. If inflow increases and the turbines are operating at their maximum available capacity, the water level at the dam will begin to rise above the normal pond level. The crest gate control system will sense the initial rise in the pond level and respond by incrementally lowering the crest gate panels to maintain at the normal pond level. If inflow then begins to decrease, the crest gate control system will sense the resulting drop in the water level and will start to raise the crest gate panels. Thus, these two control systems work together to minimize impoundment level fluctuations so that inflows into the Project's impoundment approximate outflows.

During periods when inflow exceeds the maximum hydraulic capacity of the Project's main turbines (8,000 cfs combined), the Project normally operates at maximum capacity, and any excess flows are discharged over the spillway. Under extreme flood conditions, the crest gate system is fully lowered using manual or automatic control to pass excessive river flows and is adjusted up to restore normal pond height after any high-flow or flood event has receded. Under low inflow conditions, Project operations are adjusted to ensure that fish passage flow requirements are maintained. The Project's turbines can only be operated when there is sufficient inflow to operate one of the turbines at its minimum hydraulic capacity of approximately 600 cfs.

The Project's crest gate system operational scheme, which details the prioritization or sequencing of turbines and spill at the Project is summarized in the PAD and recreated below in Table 4-3.

Table 4-1. Lawrence Project impoundment and turbine intake characteristics.

Site Characteristic	Lawrence Project	
Normal Full Pond Elevation (feet (ft))	44.17	
Operating Mode	Run-of-River	
Surface Area at Normal Full Pond (acres)	655	
Total Storage Volume (acre-feet)	19,900	
Impoundment Length (miles)	9.8	
Total Hydraulic Capacity (cfs)	8,000	
	Unit 1	**Unit 2**
Trash Rack Spacing (in)	6	6
Trash Rack Height (ft)	40.9	40.9
Trash Rack Width (ft)	28	28
Trash Rack Surface Area (sq. ft)	1,146	1,146
Maximum Turbine Discharge (cfs)	4,000	4,000
Intake Velocity (fps)	3.5	3.5

Table 4-2. Lawrence Project turbine characteristics.

Turbine Parameter	Units	
	1	2
Turbine Type	Kaplan	Kaplan
Number of Blades	4	4
Runner Diameter (ft)	13.125	13.125
Head (ft)	26.5	26.5
Rotational Speed (rpm)	128.6	128.6
Discharge at Max Capacity (cfs)	4,000	4,000
Discharge at Optimum Capacity (cfs)	2,470	2,470
Turbine Efficiency (%)	61.8	61.8

Table 4-3. Lawrence Project pneumatic crest gate system operational scheme.

Approximate River Flow (cfs)	Crest Gate Status	Target Pond Level (ft NGVD)	Unit Operation
0 – 8,000	Full elevation	44.2 (Normal pond)	Pond level control
8,001 – 52,000	Crest gate lowers as flow over the spillway increases, maintaining water level at normal pond	± 44.2 ft	Full available output
>52,000	Fully lowered	Rises above 44.2 ft as flows over spillway increase	Full available output

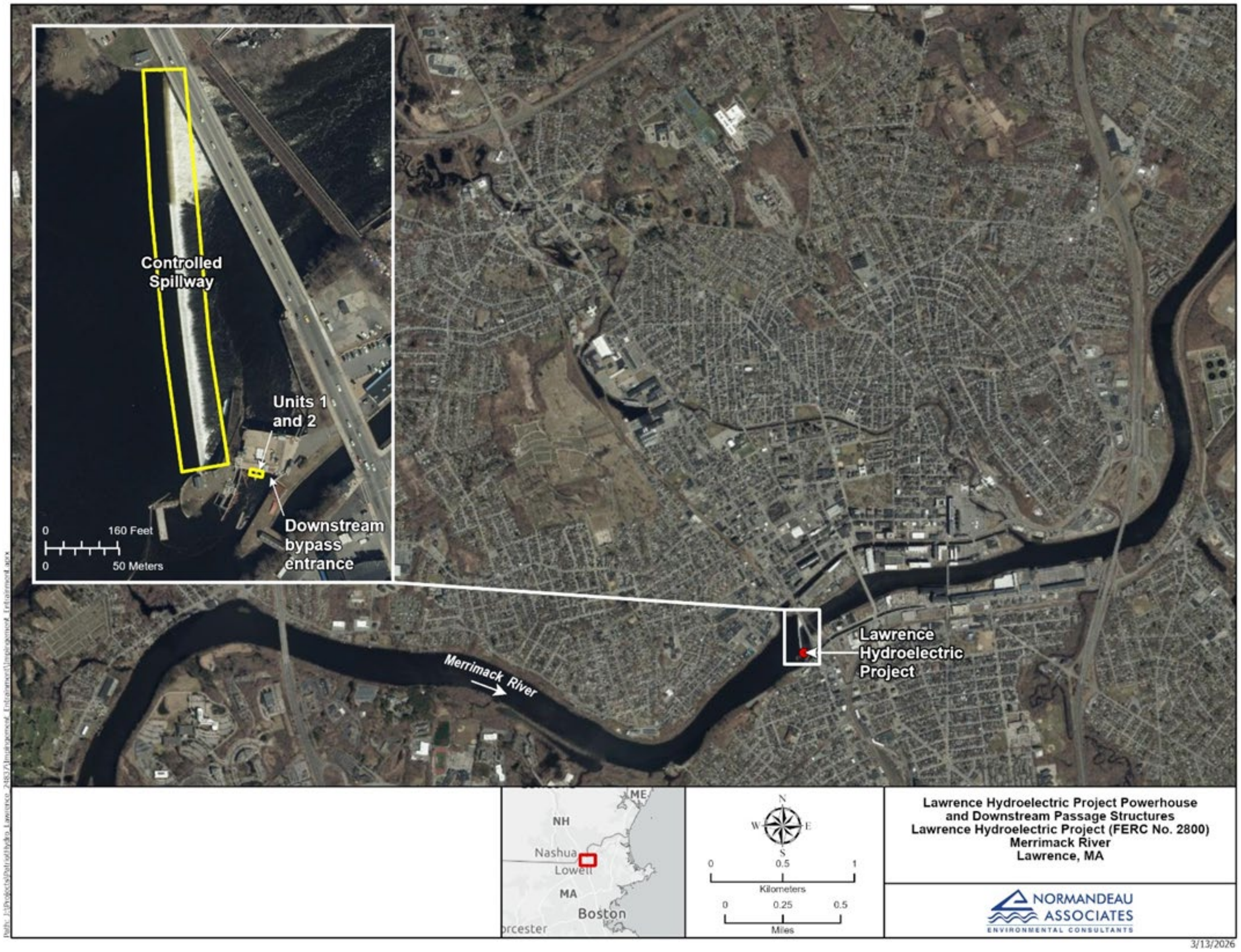

Figure 4-1. Overview of the Lawrence Hydroelectric Project (FERC No. 2800) showing potential routes of downstream passage for diadromous fish species.

4.2 Life History and Habitat Requirements of Target Fish Species

Diadromous species inherently have the highest likelihood of direct interaction with the Project as they are obligatory migrants which require passage upstream and downstream at the Project to complete their life cycles. Annual counts of diadromous fish returns for the period 2020-2025 at the Project are summarized in Table 4-4. During that period, an annual average of 37,582 American Shad, 40,617 adult river herring and 30,886 American Eel were counted during the upstream fish passage season. Due to their migratory requirements and presence in the Project area, this analysis focused on American Shad, river herring (i.e., Alewife and Blueback Herring), and American Eel, all of which are currently managed diadromous species that are found at the Lawrence Project.

4.2.1 American Shad

American Shad are an anadromous, highly migratory, coastal pelagic, schooling species that range from northern Labrador to Florida. They are the largest member of the herring family (Clupeidae), and females are larger than males at all ages. Mature male shad range from 12 to 17.5 inches (30.5 - 44.7 cm) and mature females range from 15 to 19 inches (38.3 - 48.5 cm) (Stier and Crance 1985). Males mature at age 4, while females mature at ages 5-7. The maximum age is 11 years. Spending the majority of their life in the sea, mature adults migrate upriver to natal rivers to spawn from May to July. Although shad spawn in freshwater, there is no apparent required distance upstream of brackish water (Stier and Crance 1985). American Shad return downstream to marine waters soon after spawning. American Shad are known to be prolific spawners, with females producing up to 600,000 eggs. After broadcast-spawning, fertilized eggs sink to the bottom, where they become lodged in rubble and water-harden. Hatching typically occurs after 1-2 weeks, dependent on water temperature. Larvae may remain in freshwater, or drift into brackish water and grow rapidly, transforming into juveniles approximately 4 to 5 weeks after hatching (Stier and Crance 1985). During the first fall of their life, juvenile shad leave fresh water and migrate in schools downstream to the sea. Upon reaching the ocean, they become long-range coastal migrants. While at sea, American Shad form large schools and migrate vertically to feed on zooplankton.

Period and life stages of greatest likelihood of exposure to intakes at the Lawrence Project:

- June-July: Following spawning at upstream locations, adult American Shad migrate downstream to return to marine habitat

- September-October: Following time spent in upstream rearing habitat, juveniles migrate downstream to enter marine habitat.

4.2.2 River Herring (Alewife and Blueback Herring)

Alewife and Blueback Herring are clupeid species very similar in appearance and behavior. Since it is difficult to distinguish between the two species, they are frequently considered together under the collective term “river herring”. They are anadromous, euryhaline, coastal, and pelagic fish (Bigelow and Schroeder 1953, Cooper 1961, Collette and Klein-MacPhee 2002). Alewife range from the St. Lawrence River, Canada to North Carolina (Neves 1981), mature between ages 3-6, and are typically 10 to 11 inches (250-280 centimeters (cm)) in length (Bigelow and Schroeder 1953). This species forms large schools during their spring spawning migrations from the ocean to coastal rivers. Spawning migrations occur in a south-to-north progression as water temperatures warm in the spring, typically taking place in late April to mid-May in the Gulf of Maine (Bigelow and Schroeder 1953). Blueback Herring have a greater geographical range than Alewife, ranging from Cape Breton, Nova Scotia to Florida. They spawn during early June in the Gulf of Maine, roughly four weeks later in the season than Alewife. Similar to Alewife, Blueback Herring mature between the ages of 3-6 years. Adults require little or no current for spawning, utilizing ponds, lakes, or slow-flowing riverine areas at water temperatures of 13° to 20°C (55° to 68° F) (Otto et al. 1976, Wyllie et al. 1976, Kellogg 1982). There appears to be little preference for sediment type as spawning has been observed over hard sand, gravel, stone, detritus-covered bottoms and among sticks and vegetation (O’Dell 1934, Havey 1961). Eggs are about 1 millimeter (mm) in diameter, adhesive, and require 3 to 6 days to hatch over a temperature range of 16° to 22° C (61 to 72 °F). Larvae hatch at 0.1 to 0.2 inches (3 to 5 mm) in total length and become juveniles at approximately 0.8 inches (20 mm; Cianci 1969).

Significant effort to restore habitat access for river herring in the form of fishway improvements, dam removals, and other habitat restoration in the northeast region in the last decade, with some rivers showing positive trends. However, overall, The Atlantic States Marine Fisheries Commission found no statistically significant trend signal for either species across the Atlantic coast (ASMFC 2024). River herring counts have varied while American Shad counts were more stable throughout the duration of the period of record. Over the last four years, annual river herring returns to the Merrimack River at the Lawrence Project have been under 20,000 fish (Table 4-2).

Period and life stages of greatest likelihood of exposure to intakes at the Lawrence Project:

- May-June: Following spawning at upstream locations, adult river herring migrate downstream to return to marine habitat

- September-October: Following time spent in upstream rearing habitat, juveniles migrate downstream to enter marine habitat.

4.2.3 American Eel

The American Eel is a catadromous species common in rivers, streams, lakes, tidal marshes and estuaries throughout the Northern Atlantic. It is native to Atlantic coastal waters from Newfoundland to South America. Males typically reach sizes up to 24 inches (61 cm) in length, while females reach larger sizes of 30 to 40 inches (76 to 102 cm). They are a long-lived species, able to reach up to 30 years of age. Eels spend the majority of their lives in fresh water, but upon reaching maturity, they descend to the Atlantic Ocean in the fall. They migrate to the Sargasso Sea and spawn in February to April, dying shortly after. Females are prolific egg producers, with one female producing up to 20 million eggs. After spawning, leptocephalus larvae drift at sea for up to a year and are gradually transported north by the Gulf Stream. As they approach the North American coast, the larvae metamorphose into unpigmented juveniles known as glass eels. During this metamorphosis, the body becomes cylindrical, the jaw and head are altered and the digestive tract becomes functional (Collette and Klein-MacPhee 2002).

Glass eels appear in southern New England in March at 2 to 4 inches (~ 50-100 mm) in length. They migrate upstream at night into freshwater where they feed and become pigmented; this is known as the "elver" life stage. They grow slowly until they sexually mature, which can take up to 20 years. However, eels are known to reach maturity as small as 11 inches (28 cm) for males and 18 inches (46 cm) for females. Once sexual maturity occurs in late summer to early fall, the eel begins moving downstream, the eyes and pectoral fins enlarge, and feeding stops (Collette and Klein-MacPhee 2002). Specific spawning migration routes and egg life history information are currently unknown.

American Eels are opportunistic benthic feeders that are mainly active at night. Varying by body size, eels feed on a variety of aquatic insects, macroinvertebrates and fish (Shepard 2015). Activity is restricted to the warmer months, and winter is spent buried in the mud or silt (HDR 2023). They serve as prey species for larger fish including Striped Bass, Black Bass, Common Carp and Northern Pike (Technical Committee 2021).

American Eels are documented both upstream and downstream of Essex Dam. Since 2020 an estimate of more than 315,000 American Eels have passed the Lawrence Project including 91,120 through the two existing dedicated passage structures during the most current passage year, 2025 (Table 4-2).

Period and life stages of greatest likelihood of exposure to intakes at the Lawrence Project:

- September-November: Adult "silver" eels migrate downstream to begin spawning migration to the Sargasso Sea.

Table 4-4. Counts of diadromous fish returns at the Lawrence Project for the period 2020-2025. River herring and American shad counts via camera and American Eel counts via the south eel ramp and north eel lift.

Annual diadromous fish passage counts at Lawrence Project			
Year	**River Herring**	**American Shad**	**American Eel**
2020	87,150	52,239	93,058
2021	96,429	64,162	9,296
2022	19,319	36,731	48,648
2023	10,315	28,438	22,849
2024	13,467	17,550	53,332
2025	17,021	26,374	91,120

4.3 Impingement and Entrainment Potential of Target Fish Species

4.3.1 Target Fish Species: Body Sizes

Minimum exclusion lengths of target species encountering the existing trash rack clear spacing at the Lawrence Project are presented in Table 4-5. All the calculated estimates yielded body lengths unrealistic for the target species. For example, the minimum size of an American shad predicted to be excluded by a 6.0-inch intake rack is 44.8 inches—a length not attained by this species. In all cases where the maximum size of the species did not exceed the minimum exclusion size, a designation of 'none' was applied (Table 4-5). The existing 6.0-inch clear rack spacing will not physically exclude any of the target fish species considered during this assessment from entrainment at the Essex powerhouse.

Table 4-5. Minimum length for target fish to be excluded from entrainment based on existing 6.0-inch trash rack spacing

Common Name	Scaling Factor for Body Width[5]	Typical Length (inches) for target species juveniles and adults potentially encountered at the Project		Calculated Minimum Exclusion Length (inches)*
American Shad	0.134	Juvenile	2-6[1]	none
		Adult	15-23[2]	
River Herring	0.105	Juvenile	1.25-6[1]	none
		Adult	9-13[3]	
American Eel	0.037	Adult	25-41[4]	none

1 Upper end of range based on 145 juvenile alosines handled as part of the Juvenile Alosine Downstream Passage Assessment: Lower end of range adopted from species review (Normandeau, 2021)
2 Based on 544 adult American Shad handled as part of the Upstream and Downstream Adult Alosine Passage Assessment (Normandeau, 2025a, 2025b)
3 Based on 914 adult river herring handled as part of the Upstream and Downstream Adult Alosine Passage Assessment (Normandeau, 2025a,2025b)
4 Based on 162 adult eels handled as part of the Downstream American Eel Passage Assessment (Note Soucook River origin eels ranged 27-34 inches; St. Croix River origin eels ranged 24-41 inches)(Normandeau, 2019b)
5 Smith, C. L. 1985. The Inland Fishes of New York State. Albany, NY. New York Department of Environmental Conservation.

4.3.2 Target Fish Species: Swim Performance

A summary of burst swim speeds determined for adult and juvenile American Shad and river herring and adult American Eel is presented in Table 4-6. These data were obtained using the Swim Speed & Swim Time Tool[3] (Katopodis and Gervais 2016; Di Rocco and Gervais 2020). The expected size range for each species/life stage was evaluated relative to the data available in the Swim Speed & Swim Time Tool and five representative lengths were chosen for burst speed estimation from the database. For each species/life stage, the five representative lengths included the upper and lower bounds of the anticipated size range for the Project area as well as the 25th, 50th, and 75th percentile lengths within that range. Each unique species-length combination was input into the Swim Speed & Swim Time Tool and produced a relationship for swim speed and swim time for a particular body length. For each body length selected to be assessed for each species, the following estimates were recorded:

1. Speed (ft/s) achieved by 97.5% of individuals of species X at body length Y for 3 seconds;
2. Speed (ft/s) achieved by 87.5% of individuals of species X at body length Y for 3 seconds;
3. Speed (ft/s) achieved by 50% of individuals of species X at body length Y for 3 seconds;
4. Speed (ft/s) achieved by 12.5% of individuals of species X at body length Y for 3 seconds; and
5. Speed (ft/s) achieved by 2.5% of individuals of species X at body length Y for 3 seconds.

It is understood that burst swim speeds may vary greatly among different fish species, among sizes of the same species, and within individuals of the same species and size class. Katopodis and Gervais (2016) demonstrate ascending physical capabilities as a smaller portion of the test fish are represented by each speed rating. For example, 97.5% of adult American Shad in the 15-inch size class are expected to be capable of achieving a burst swim speed of 17.3 fps for a period of 3 seconds, whereas only 2.5% of American Shad of the same size are expected to be able to achieve a burst swim speed of 26.8 fps for 3 seconds. For the purposes of this desktop evaluation values representing the 50th percentile of swim speed over a three second period were selected as representative of a fishes burst swim capability. The 50th percentile speed rating for the minimum, median, and maximum size of each of the target fish species and life stages is provided in Table 4-8.

Figure 4-2 presents the estimated burst speeds for the target species and life stages relative to the calculated intake velocity under full generation at the powerhouse intake structure (i.e., 3.5 fps). Target species whose burst swim speeds are less than the approach velocity at an intake are more

[3] Available online at: http://www.fishprotectiontools.ca/speedtime.html

likely to be involuntarily impinged or entrained depending on the size of an individual and the intake rack spacing. Burst speeds for each of target species/life stages considered in this assessment that are in excess of the calculated intake velocity at the powerhouse suggests the potential for involuntary impingement or entrainment is low. As detailed in Section 4.3.1, the existing rack spacing of 6.0 inches will not exclude any of the target species, regardless of life stage, resulting in entrainment of any individuals incapable of overcoming intake velocities for an extended duration..

Table 4-6. Burst swim speed information compiled from scientific literature for target fish species

Common Name	Size potentially encountered the region (in)	Size included in burst speed estimate based on data availability	Burst Speed (fps) at minimum size[5]	Burst Speed (fps) at median size[5]	Burst Speed (fps) at maximum size[5]
American Shad (Juvenile)	2-6[1]	2-6	5.2	8.4	11.2
American Shad (Adult)	15-23[2]	10-15	16.2	19.0	21.5
River Herring (Juvenile)	1.25-6[1]	1.25-6	3.6	7.8	11.2
River Herring (Adult)	9-13[3]	9-12	15.1	16.7	18.4
American Eel	25-41[4]	21-45	11.0	14.9	18.4

1 Upper end of range based on 145 juvenile alosines handled as part of the Juvenile Alosine Downstream Passage Assessment; Lower end of range adopted from species review (Normandeau, 2021)

2 Based on 544 adult American Shad handled as part of the Upstream and Downstream Adult Alosine Passage Assessment (Normandeau, 2025a, 2025b)

3 Based on 914 adult river herring handled as part of the Upstream and Downstream Adult Alosine Passage Assessment (Normandeau, 2025a,2025b)

4 Based on 162 adult eels handled as part of the Downstream American Eel Passage Assessment (Note Soucook River origin eels ranged 27-34 inches; St. Croix River origin eels ranged 24-41 inches)(Normandeau, 2019b)

5 Katopodis, C, and R Gervais. 2016. Fish Swimming Performance Database and Analyses. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/002., 550.

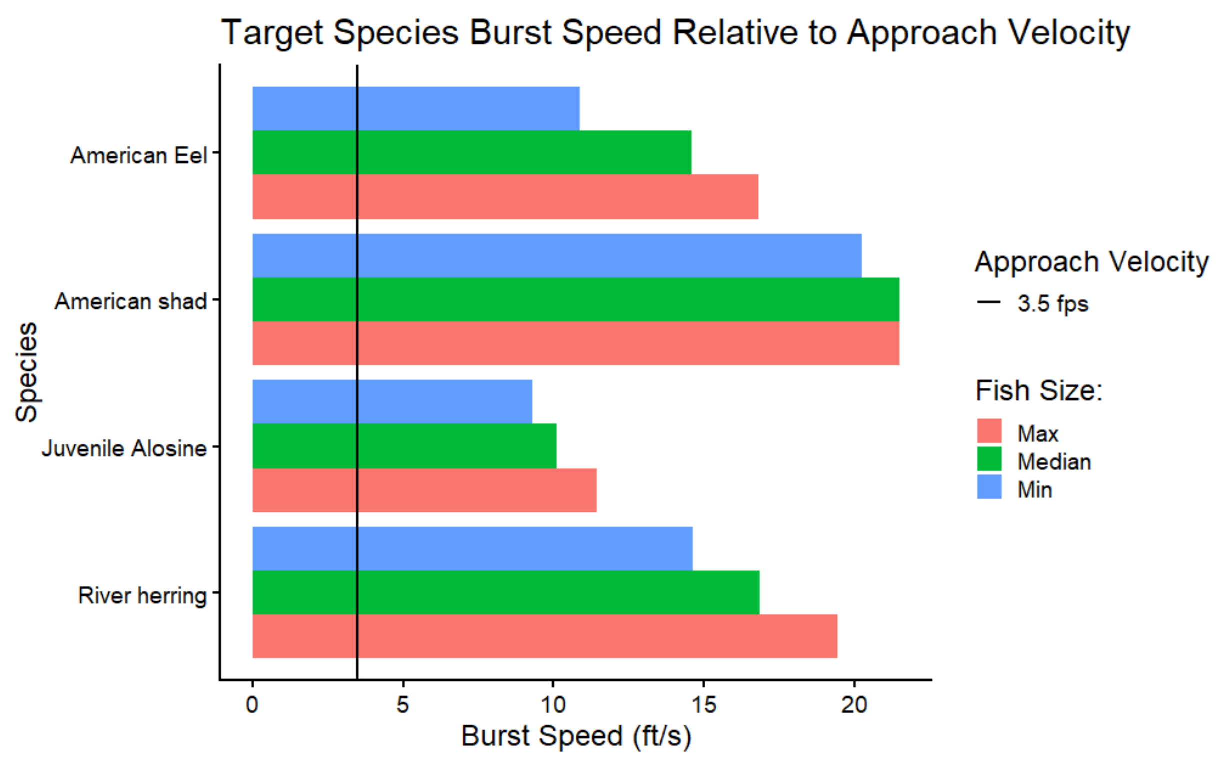

Figure 4-2. Burst swim speed of target fish species compared to the calculated approach velocity at the Lawrence intake when the Project is operating at maximum capacity.

4.4 Qualitative Assessment of Entrainment and Turbine Survival Potential

Evaluating entrainment potential for the target fish species required combining and synthesizing the species-specific behavioral traits, life stages, and swimming capabilities and comparing them to the Project's unique intake, water conveyance and infrastructure characteristics. The blending of these factors yielded a qualitative assessment of whether or not a target fish species will potentially entrain through the Project's intakes. This qualitative assessment took into consideration and summarized all of the factors that influenced entrainment and is presented in Table 4-7.

When the life history characteristics, behavior, and habitat use are considered, all species considered during this analysis (American Eel, American Shad, and river herring) are obligatory diadromous migrants. As such, they are required to pass the Project as part of their life cycle resulting in the classification of "high" entrainment potential for that category. All species/life stages considered in this assessment have the potential to become entrained through the existing 6.0-inch spaced racks because their body dimensions will permit them to fit through those openings. When the median burst swim speed rates are considered, each species/life stage approaching the Project intakes are expected to be physically capable of avoiding involuntary entrainment for a short duration due to their burst swimming capability relative to the intake velocity. Entrainment potential overall for the target species considered under this assessment will be “high” due to their life histories, requiring upstream and downstream passage to complete various phases of their life cycle.

Table 4-7. Qualitative entrainment potential for target fish species at the Lawrence Project

Species and Life Stage	Entrainment Potential		
	Behavior, Habitat and Life History	Trash rack Clear Spacing	Swim Speed compared to Lawrence Units
		6.0 inches	(3.5 fps)
American Shad			
Adult	H	H	L
Juvenile Alosines			
Juvenile	H	H	L
River Herring			
Adult	H	H	L
American Eel			
Adult (silver)	H	H	L

4.5 Total Project Survival Estimates

4.5.1 Literature Review

Eleven previously conducted passage studies focused on the target species of interest at Lawrence and informing on passage route utilization and associated survival rates were evaluated to determine representative survival estimates for the spillway and bypass passage routes at Lawrence. These sources included previously completed HI-Z tag-recapture and radio-telemetry mark-recapture studies. Tables 4-8 through 4-11 summarize the final set of previously conducted passage studies used to inform estimates of total project survival at Larwence. Where multiple estimates were available, values were averaged and used as spillway and bypass route probability metrics for the TBSA model.

Table 4-8. Derived bypass and spillway route survival rates for juvenile alosines.

Juvenile Alosine				
Project	**Year**	**Spill**	**Bypass**	**Citation**
Crescent Hydroelectric Project (HI Z)	1991	0.940	NA	Mathur et al. (1996a)
Juvenile Alosine Downstream Passage Assessment, Lawrence Hydroelectric Project (HI Z)	2025	NA	0.900	Normandeau, 2026a
Determined Route Survival Rates for TBSA model		**0.940**	**0.900**	

Table 4-9. Derived bypass and spillway route survival rates for adult American Shad.

Adult American Shad				
Project	**Year**	**Spill**	**Bypass**	**Citation**
Lawrence Hydroelectric Project (radio-telemetry)	2020	NA	0.959	*Normandeau, 2021a*
Lowell Hydroelectric Project (radio-telemetry)	2019	0.892	0.826	*Normandeau 2021c*
Penobscot River Projects - West Enfield (radio-telemetry)	2018	0.980	1.000	*Normandeau, 2018a*
Penobscot River Projects - Milford - Bay 2 (radio-telemetry)	2018	0.900	0.970	*Normandeau, 2018a*
Penobscot River Projects - Milford - Bay 7 (radio-telemetry)	2018	0.900	0.770	*Normandeau, 2018a*
Pejepscot Hydroelectric Project (radio-telemetry)	2019	0.890	NA	*Normandeau, 2020a*
Determined Route Survival Rates for TBSA model		**0.912**	**0.905**	

Table 4-10. Derived bypass and spillway route survival rates for adult river herring.

Adult River Herring				
Project	**Year**	**Spill**	**Bypass**	**Citation**
Briar Hydroelectric Project - Penacook Lower (radio-telemetry)	2021	NA	0.895	*Normandeau,2022a*
Briar Hydroelectric Project - Penacook Upper (radio-telemetry)	2022	1.000	0.953	*Normandeau,2022a*
Briar Hydroelectric Project – Rolfe (radio-telemetry)	2022	0.980	NA	*Normandeau, 2022a*
Mine Falls Hydroelectric Project (radio-telemetry)	2020	NA	0.924	*Normandeau, 2021b*
Lawrence Hydroelectric Project (radio-telemetry)	2020	NA	0.413	*Normandeau, 2021a*
Lowell Hydroelectric Project (radio-telemetry)	2019	NA	0.878	*Normandeau, 2021c*
Little Falls Hydroelectric Project (HI Z)	1996	NA	0.990	*Normandeau, 1997a*
Penobscot River Projects - Milford - Bay 2 (radio-telemetry)	2018	NA	0.930	*Normandeau, 2018a*
Penobscot River Projects - Milford - Bay 7 (radio-telemetry)	2018	NA	0.580	*Normandeau, 2018a*
Penobscot River Projects - Orono (radio-telemetry)	2018	1.00	0.900	*Normandeau, 2018a*
Penobscot River Projects - West Enfield (radio-telemetry)	2018	0.950	0.890	*Normandeau, 2018a*
Pejepscot Hydroelectric Project (radio-telemetry)	2020	0.850	1.000	*Normandeau, 2020a*
Determined Route Survival Rates for TBSA model		**0.956**	**0.850**	

Table 4-11. Derived bypass and spillway route survival rates for adult American Eels.

Adult American Eel				
Project	**Year**	**Spill**	**Bypass**	**Citation**
Briar Hydroelectric Project - Penacook Lower (radio-telemetry)	2021	1.000	NA	*Normandeau, 2022b*
Briar Hydroelectric Project - Penacook Upper (radio-telemetry)	2021	0.951	NA	*Normandeau, 2022b*
Briar Hydroelectric Project – Rolfe (radio-telemetry)	2021	1.000	NA	*Normandeau, 2022b*
Lawrence Hydroelectric Project (radio-telemetry)	2019	0.982	1.000	*Normandeau, 2020b*
Determined Route Survival Rates for TBSA model		**0.983**	**1.00**	

4.5.2 Turbine Blade Strike Analysis (TBSA)

Table 4-12 presents the minimum, maximum, median and mean lengths for target species and life stages used in the TBSA model. These representative fish lengths for adult Alewife, Blueback Herring, and American Shad were based on data collected from studies conducted downstream of Lawrence Project in 2025. Length statistics for juvenile herring were derived from a 2019 study using in-basin fish completed at Lowell Hydroelectric Project while adult American Eel lengths were based on the 2019 passage assessment at Lowell using eels from the St. Croix River in Maine.

Table 4-12. Mean length determined by representative species lengths based on prior studies occurring in the vicinity of Lawrence Project.

Species	Minimum (in)	Median (in)	Maximum (in)	Average (in)	Standard Deviation (in)
Juvenile Alosine[1]	4.6	5.3	6.1	5.3	0.3
Adult River Herring[2]	8.8	10.6	13.1	10.8	1.0
Adult American Shad[3]	13.9	18.8	22.4	18.8	1.4
American Eel[4]	21.0	32.1	45.0	32.5	3.4

1 Range is based on 145 juvenile alosines handled as part of the Juvenile Alosine Downstream Passage Assessment at Lowell Hydroelectric Project (FERC No. 2790) in fall of 2019; (Normandeau, 2020a)
2 Based on 640 adult river herring handled as part of the Phase II Behavior Study and Radio Telemetry Study at Lawrence Project in spring of 2025; (Normandeau, 2026a)
3 Based on 406 adult American Shad handled as part of the Phase II Behavior Study and Radio Telemetry Study at Lawrence Project in spring of 2025; (Normandeau, 2026b)
4 Based on 160 adult eels handled as part of the Downstream American Eel Passage Assessment at Lowell Project in fall of 2019; (Normandeau, 2019b)

4.5.3 Total Project Survival Estimates

<u>Spring Passage Season – Hypothetical Operating Regimes</u>

Table 4-13 presents the four hypothetical operating regimes defined at the Lawrence Project for the spring passage season (i.e., April 1 to July 15; Figure 3-1). Regimes were based on the presence and relative abundance of spill flows ranging from none (i.e., regime #1) to full (i.e., regime #4). During the spring passage season, inflow was initially allocated to the upstream and downstream fishways (360 cfs combined), leakage to the North and South Canal (100 cfs) and then to the capacity of the powerhouse (8,000 cfs). As inflow increased and exceeded the hydraulic capacity of those routes, spill was added through one or more crest gate section until all sections of the inflatable crest dam were lowered.

Spring Passage Season – Passage Route Usage and Survival Rates

Table 4-14 summarizes the route-specific passage survival rates for adult river herring and American Shad utilized during the development of the total project survival estimates for those species at Lawrence. Estimates for individuals using the downstream bypass and spill flows were derived from the existing studies assessed as part of this evaluation (see Section 4.6.1) and were estimated within the TBSA Tool for fish using the turbine units. For all theoretical operating regimes, fish were allocated proportional to flow volumes.

Spring Passage Season – Calculated Operating Regime Survival Rates

Table 4-15 summarizes the resulting project survival rates associated with each of the four theoretical operating regimes defined for Lawrence during the spring fish passage season. Operating regime estimates ranged from 94.0 to 95.3 for adult river herring and 90.1 to 90.9 for adult American Shad.

Spring Passage Season – Total Project Survival Estimate

The total survival estimates for outmigrating adult river herring and American Shad, when considering the full range of operational conditions occurring during the course of the outmigration season (i.e., April 1 to July 15) are presented in Table 4-16. When the regime-specific estimates provided are weighted for their proportional occurrence throughout the length of the passage season, the total project survival estimate for adult river herring is 93.6% and for adult American shad is 89.4%.

Table 4-13. Theoretical operating regimes developed for the Lawrence Project to estimate total passage survival during the spring migration period (April 1 – July 15).

Operating Regime	River Flow (cfs)	Fish Passage Flow	Kaplan (Unit 1/2)	Crest Gate Spill	Spill
1	8,460	US/DS	On	Closed	No
2	12,500	US/DS	On	Partially Open	Low
3	32,250	US/DS	On	Partially Open	Medium
4	52,000	US/DS	On	Full Open	High

Table 4-14. Proportional route utilization and associated survival rate for outmigrating alosines during the spring migration period (April 1 to July 15).

Species/Life Stage	Operating Regime	Route Proportion (%)			Route Survival Rate (%)		
		Bypass	Spill	Turbine	Bypass	Spill	Turbine
Adult River Herring	1	2.0	0	98.0	85.0	95.6	94.2
	2	1.3	33.1	65.6	85.0	95.6	94.0
	3	0.5	74.5	25.0	85.0	95.6	95.2
	4	0.3	84.3	15.4	85.0	95.6	95.0
Adult American Shad	1	2	0	98.0	90.0	91.2	90.0
	2	1.3	33.1	65.6	90.0	91.2	90.0
	3	0.5	74.5	25.0	90.0	91.2	90.5
	4	0.3	84.3	15.4	90.0	91.2	89.4

Table 4-15. Operating regime-specific survival estimates for adult river herring and American Shad at Lawrence during the spring migration period (April 1 to July 15).

Species/ Life stage	Operating Regime	River Flow (CFS)	River Flow to DS Bypass (%)	River Flow to Turbines (%)	Spill Flow (%)	TBSA Survival (%)
Adult River Herring	1	8,460	2.0	98.0	0.0	94.0
	2	12,500	1.3	65.6	33.1	94.3
	3	32,250	0.5	25.0	74.5	95.4
	4	52,000	0.3	15.4	84.3	95.3
Adult American Shad	1	8,460	2.0	98.0	0.0	90.1
	2	12,500	1.3	65.6	33.1	90.2
	3	32,250	0.5	25.0	74.5	90.4
	4	52,000	0.3	15.4	84.3	90.9

Assumes full generation; $\lambda = 0.2$

Table 4-16. Total project survival estimates for adult river herring and American Shad at Lawrence during the spring migration period (April 1 to July 15).

Species / Life stage	Operating Regime	River Flow (CFS)	TBSA Survival (%)	Weight of Survival Estimate based on Flow Exceedance[1]	Weighted Value (%)	Total Project Survival (%)
Adult River Herring	1	8,460	94.0	46	43.2	93.6
	2	12,500	94.3	17	16.0	
	3	32,250	95.4	32	30.5	
	4	52,000	95.3	4	3.8	
Adult American Shad	1	8,460	90.1	46	41.4	89.4
	2	12,500	90.2	17	15.3	
	3	32,250	90.4	32	28.9	
	4	52,000	90.9	4	3.6	

[1] Based on flow duration curves for spring migration period from 1995-2025 data.

Fall Passage Season – Hypothetical Operating Regimes

Table 4-17 presents the four hypothetical operating regimes defined at the Lawrence Project for the fall passage season (i.e., September 1 to November 15; Figure 3-2). Regimes were based on the presence and relative abundance of spill flows ranging from none (i.e., regime #1) to full (i.e., regime #4). During the fall passage season, inflow was initially allocated to the downstream fishway (160 cfs), leakage to the North and South Canal (100 cfs) and then to the capacity of the powerhouse (8,000 cfs). As inflow increased and exceeded the hydraulic capacity of those routes, spill was added through one or more crest gate section until all sections of the inflatable crest dam were lowered.

Fall Passage Season – Passage Route Usage and Survival Rates

Table 4-18 summarizes the route-specific passage survival rates for juvenile alosines and silver-phase American Eel utilized during the development of the total project survival estimates for those species at Lawrence. Estimates for individuals using the downstream bypass and spill flows were derived from the existing studies assessed as part of this evaluation (see Section 4.6.1) and were estimated within the TBSA Tool for juvenile alosines using the turbine units. Turbine survival for silver-phase American Eel were determined using the multiple linear regression model described by Alden (2017). For all theoretical operating regimes, fish were allocated proportional to flow volumes.

Fall Passage Season – Calculated Operating Regime Survival Rates

Table 4-19 summarizes the resulting project survival rates associated with each of the four theoretical operating regimes defined for Lawrence during the fall fish passage season. Operating regime estimates ranged from 93.9 to 97.2 for juvenile alosines and 55.7 to 92.1 for silver-phase American Eel.

Fall Passage Season – Total Project Survival Estimate

The total survival estimates for outmigrating adult river herring and American Shad, when considering the full range of operational conditions occurring during the course of the outmigration season (i.e., September 1 to November 15) are presented in Table 4-20. When the regime-specific estimates provided are weighted for their proportional occurrence throughout the length of the passage season, the total project survival estimate for juvenile alosines is 96.8% and for silver-phase American Eel is 60.4%.

Table 4-17. Theoretical operating regimes developed for the Lawrence Project to estimate total passage survival during the fall migration period (September 1 – November 15).

Operating Regime	River Flow (cfs)	Fish Bypass System	Kaplan (Unit 1/2)	Crest Gate Spill	Spill
1	8,260	DS	On	Closed	No
2	12,500	DS	On	Partially Open	Low
3	32,250	DS	On	Partially Open	Medium
4	52,000	DS	On	Full Open	High

*no generation due to inflow only available for bypasses, was not included as there are no records of the lowest hypothetical operating regimes in the fall (687 cfs and 860 cfs) occurring in the last 30 years during each respective migratory period and were therefore excluded flows with no generation from modeling and total project survival estimates.

Table 4-18. Proportional route utilization and associated survival rate for outmigrating juvenile alosines and adult American Eel during the fall migration period (September 1 to November 15).

Species/Life Stage	Operating Regime	Route Proportion (%)			Route Survival Rate (%)		
		Bypass	Spill	Turbine	Bypass	Spill	Turbine
Adult River Herring	1	2.0	0.0	98.0	90.0	94.0	97.3
	2	1.3	34.2	64.5	90.0	94.0	97.1
	3	0.5	74.6	24.9	90.0	94.0	97.6
	4	0.3	84.3	15.4	90.0	94.0	97.5
Adult American Shad	1	2.0	0.0	98.0	100	98.0	54.8
	2	1.3	34.2	64.5	100	98.0	54.8
	3	0.5	74.6	24.9	100	98.0	54.8
	4	0.3	84.3	15.4	100	98.0	54.8

Table 4-19. Operating regime-specific survival estimates for juvenile alosines and adult American Eels at Lawrence during the fall migration period (September 1 to November 15).

Species/ Life stage	Operating Regime	River Flow (CFS)	River Flow to DS Bypass (%)	River Flow to Turbines (%)	Spill Flow (%)	TBSA Survival (%)
Juvenile Alosines	1	8,260	2.0	98.0	0.0	97.2
	2	12,500	1.3	64.5	34.2	95.9
	3	32,250	0.5	24.9	74.6	94.6
	4	52,000	0.3	15.4	84.3	93.9
Silver-phase American Eel	1	8,260	2.0	98.0	0.0	55.7
	2	12,500	1.3	64.5	34.2	70.4
	3	32,250	0.5	24.9	74.6	87.3
	4	52,000	0.3	15.4	84.3	92.1

Table 4-20. Total project survival estimates for juvenile alosines and adult American Eels at Lawrence during the fall migration period (September 1 to November 15).

Species / Life stage	Operating Regime	River Flow (CFS)	TBSA Survival (%)	Weight of Survival Estimate based on Flow Exceedance[1]	Weighted Value (%)	Total Project Survival (%)
Juvenile Alosines	1	8,260	97.2	81	78.7	96.8
	2	12,500	95.9	8	7.7	
	3	32,250	94.6	10	9.5	
	4	52,000	93.9	1	0.9	
Silver-phase American Eel	1	8,260	55.7	81	45.1	60.4
	2	12,500	70.4	8	5.6	
	3	32,250	87.3	10	8.7	
	4	52,000	92.1	1	0.9	

[1] Based on flow duration curves for fall migration period from 1995-2025 data.

5 Summary

Interactions with the Lawrence Project for each of the species and life stages considered during this assessment are unavoidable based on their obligatory seasonal movements to complete portions of their life cycles. The adult and juvenile life stages of all three alosine species (i.e. American Shad, Alewife and Blueback Herring) migrate from upstream portions of the Merrimack River watershed and as a result must pass downstream of the Project in order to complete their life history. For this assessment, American Eel was only considered as an entrainment/impingement risk during the adult life stage when they are actively out-migrating. Project interactions for alosines occur most frequently during the spring/early summer when post-spawn adults return downstream and during the fall/early winter when juveniles are migrating to the marine environment. Similar to juvenile alosines, the outmigration period for adult eels occurs during the fall time period.

Although each of the target species and life stages possess burst swim speeds capable of overcoming intake velocities and temporarily avoiding entrainment at the Project, the necessity to eventually pass downstream as part of their life cycle results in an increased probability of interaction with the Essex powerhouse turbines and resulted in an entrainment potential classification of “high” as part of this assessment. The existing 6.0-inch rack spacing is not exclusionary to any of the species or life stages considered as part of this analysis. The overall entrainment potential for the target species considered under this assessment is “high” due to their life histories, requiring upstream and downstream passage to complete various phases of their life cycle. Turbine entrainment of each of the target species has been previously documented during route of passage telemetry studies conducted at the site: American Eel (51.4% of individuals passing; Normandeau 2020b), river herring (16%; Normandeau 2021a), and American Shad (4%; Normandeau 2021a).

A desktop approach utilizing a blend of field-derived and calculated parameter values was used to develop estimates of total project survival for target species at Lawrence. Estimates of survival were developed for a series of operational regimes representative of the fish passage seasons at the Project (i.e., spring: April 1 to July 15, and fall: September 1 to November 15). Each of the estimates were developed using the TBSA Tool and incorporated a mix of user-entered route-specific survival estimates and calculated turbine blade strike probabilities to develop a predicted total project survival rate specific to a singular operational condition. Passage route selection was assumed to be proportionate to the amount of flow dedicated to each passage route under each scenario. Following development of the set of representative survival estimates, site-specific flow duration curves were used to quantify the proportion of a passage season during which each hypothetical operating regime was occurring. This allowed for the associated estimates from each regime to be proportioned such that the sum provided an estimate of total project survival over the course of the full passage season.

This approach resulted in estimates of total project survival of 93.6% for adult river herring, 89.4% for adult American Shad, 96.8% for juvenile alosines, and 60.4% for adult American Eels. It is important to note that for all estimates of survival associated with each operational scenario considered in this assessment, fish route utilization was proportional to flow discharge (e.g., if 50% of inflow was being passed via spill then 50% of fish would pass via spill). This approach assumes that fish passage at the Project is proportional to the distribution of inflow among potential passage routes. Prior passage route results associated with the downstream passage of adult herring and shad at Lawrence do not support this assumption as under the flow conditions present during the 2020 radio telemetry assessment, 67% of tagged herring and 92% of tagged shad were determined to have passed downstream via the bypass despite that route conveying only 160 cfs (Normandeau 2021a).

In the 2021 Merrimack River Watershed Comprehensive plan for Diadromous Fishes (Technical Committee 2021), Objective 14 states “Improve passage efficiency at all fish passage facilities in the watershed to achieve safe, timely and effective passage that meets or exceeds the following performance criteria”. Relative to downstream passage, Objective 14 stated that “*For alosines and American Eel, achieve and maintain a minimum of 95 percent downstream passage survival*”. When the total project survival rates estimated in this desktop assessment are compared to the “performance criteria” of 95% downstream passage survival for alosines and American Eel, only juvenile alosines met the criteria.

The total project survival estimates for adult river herring and adult American Shad both approached the 95% criteria with estimates of 93.6% and 89.4%, respectively. The desktop estimate for adult river herring was greater than that estimated during the single season downstream telemetry study conducted under inflow conditions during the spring of 2020 (38.7%; Normandeau 2021a). The field-based estimate of herring passage survival was not corrected for background mortality (i.e., predation) and as a result was very likely impacted by the known presence of Striped Bass in the reach immediately downstream of the Project. The field-based estimate for adult American Shad obtained during the single season downstream telemetry study conducted under inflow conditions during the spring of 2020 (94.8%) was comparable to that estimated via this desktop approach. The desktop total project survival estimate for silver-phase American Eel (60.4%) did not attain the written passage criteria and was also lower than that estimated during the single season downstream telemetry study conducted under the available set of inflow conditions during the fall of 2019 (90.3%; Normandeau 2020b).

6 Variances from FERC-Approved Study Plan

The Desktop Entrainment, Impingement, and Turbine Passage Survival Assessment was conducted following the methodologies identified within the FERC-approved study plan.

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