2009

Evaluation of Nature-like and Technical Fish Passes for the Passage of Alewife (Alosa pseudoharengus) at Two Coastal Streams in New England

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EVALUATION OF NATURE-LIKE AND TECHNICAL FISH PASSES FOR THE PASSAGE OF ALEWIFE (ALOSA PSEUDOHARENGUS) AT TWO COASTAL STREAMS IN NEW ENGLAND

A Thesis Presented

by

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Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

February 2009

Wildlife and Fisheries Conservation

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DEDICATION

To my family.

ACKNOWLEDGMENTS

I wish to thank my advisor Alex Haro for his patience, insight, encouragement, and for being so generous with his time. Thanks go to Ted Castro-Santos for his patience, encouragement, statistical assistance, time, and for fun brainstorming sessions. I also wish to thank my committee members Martha Mather and Piotr Parasiewicz for their time and recommendations. Thanks go to Jim Turek and the NOAA Fisheries Office of Habitat Conservation for the funding of this study.

The field work would not have been possible without the help of my talented and knowledgable lunch buddies Steve Walk, John Noreika, and Phil Rocasah. Thanks also go to David Gould with the Town of Plymouth, Phil Brady of the Massachusetts Division of Marine Fisheries and Steve Gephard, Tim Wildman, and David Ellis of the Connecticut Department of Environmental Protection for logistical help with field work. I am particularly grateful to Timothy Hughes who provided invaluable help during the two field seasons and took photographs of the sites.

I thank my family for their love and support, especially my brother Jonathan who tolerated many late night phone calls and listened patiently while I explained my data and analyses to him. And lastly I wish to thank my fellow classmates in the Department of Natural Resources Conservation for their advice, editing and formatting help, and moral support.

ABSTRACT

EVALUATION OF NATURE-LIKE AND TECHNICAL FISH PASSES FOR THE PASSAGE OF ALEWIFE (ALOSA PSEUDOHARENGUS) AT TWO COASTAL STREAMS IN NEW ENGLAND

FEBRUARY 2009

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Nature-like fish passes have been designed with the intent to re-connect river corridors and provide passage for all species occurring in a system. Nature-like fish pass designs have been constructed in Europe and elsewhere with some success, but performance of these designs has not been evaluated for North American species. Re-establishing passage for adult anadromous clupeids to their spawning areas is critical considering their recent dramatic population declines. Two nature-like fish pass designs in New England were evaluated for passage of anadromous adult alewives (*Alosa pseudoharengus*) using passive integrated transponder (PIT) telemetry and showed differing results. At Town Brook in Plymouth, Massachusetts the 32 m long perturbation boulder rock ramp with a 1:24 slope passed 94% of attempting fish with most ascending in under 22 minutes. At East River in Guilford, Connecticut the 48 m long steppool bypass design with a 1:14 slope passed only 40% of attempting fish with a median transit time of 75 minutes. Two technical fishway designs at the field sites were also evaluated and showed contrasting performance. At Town Brook a 14 m long 1:7 slope pool and weir fishway exhibited attraction and passage deficiencies. At East River two 3.05 m long steeppass fishways both passed the majority of attempting fish but one steeppass fishway may have had poor attraction efficiency. At both sites tagged fish passed rapidly downstream through the fish passes after spawning. Nature like fish pass designs are suitable for the passage of alewife but further evaluations are required to more precisely identify the influence of vertical drop per pool and specific local hydraulics on behaviors and passage performance for this species.

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EVALUATION OF NATURE-LIKE AND TECHNICAL FISH PASSES FOR THE PASSAGE OF ALEWIFE (ALOSA PSEUDOHARENGUS) AT TWO COASTAL STREAMS IN NEW ENGLAND

1.1 Introduction

Dams limit or restrict habitat for migratory and resident fish. In response to these barriers upstream fish passage facilities have been constructed throughout the northeastern United States, primarily for anadromous species such as alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis)*, American shad (*Alosa sapidissima*), sea lamprey (*Petromyzon marinus*), and Atlantic salmon (*Salmo salar*). The goal of the construction of these fishways is to allow the fish to pass upstream as quickly as possible with a minimal amount of stress, injury, delay or mortality (Orsborn 1987). The most common fishways constructed are technical designs such as baffle type Denil or Alaska steepasses for small or low head (< 3 m height) dams, and pool-and-weir type such as Ice Harbor or vertical slot for larger rivers or higher head dams (Orsborn 1987, Larinier and Travade 2002). These designs are often built with only a few target species in mind and often do not pass all of the species historically present in the watershed (Parasiewicz et al. 1998).

Few quantitative field evaluations of passage through technical fishways have been conducted for species other than salmonids. Poor attraction efficiency and passage through Denil fishway designs has been documented for species such as white suckers

(*Catostomus commersoni*), smallmouth bass (*Micropterus dolomieu*), and walleye (*Stizostedion vitreum*) (Bunt et al. 1999, Bunt et al. 2000). Dominy (1973) quantified the mean entry rate of alewife at two entrance pool elevations in a pool and weir fishway and found that alewife passed at a greater mean rate at the lower elevation. Pool and weir designs have been constructed extensively on large northeast rivers for American shad, but an evaluation of an Ice Harbor fishway for the passage of that species documented poor passage (Quinn, 1994, Sullivan 2004). An evaluation of a Denil fishway for passage of alewife documented moderate to high percent passage, but low entry rate (Kleinschmidt 2005).

A new design called a nature-like fish pass has been developed in response to concerns with technical fishways, and a growing desire to re-establish stream continuity (Eberstaller et al 1998). These fish passes typically consist of a wide, low gradient channel with a concave stream channel cross-section, and natural cobble or boulder substrates to dissipate hydraulic kinetic energy and reduce channel velocities to levels that allow fish to pass at sustainable (i.e., aerobic) swimming speeds. The goal is to mimic the habitat conditions found within the river and so their design is site specific (Parasiewicz et al. 1998). Nature-like passes have been designed as bypass channels around dams and as roughened ramps constructed either immediately downstream of a dam or in association with a partially removed dam. Fish are believed to find natural substrates more acceptable than concrete channels or channels with baffles in technical fishways (Food and Agriculture Organization 2002). The low velocities at the margins and hydraulic boundary layers of this fish pass type have the potential to provide passage for very small or weakly swimming species. However, at this time no published quantitative data exists to provide evidence for either theory.

Evaluations of nature-like fish passes in Europe ranging in size from 30 m to 19 km long, 6 to 20 m wide and with slopes of 0.022% to 4.2% have been conducted and show varying results. Some researchers evaluated the fish passes by trapping, videorecording, or electrofishing fish below and above the bypass and using the ratio between the counts as a general indicator of passage efficiency. In this manner Santos et al. (2005) documented passage of four species of Cyprinids (.01-.57 electrofish to video ratios) at a nature-like bypass channel in Portugal but the most abundant species video recorded within the pass, striped mullet (*Mugil cephalus*), was never captured below the pass. Mader et al. (1998) documented 40 species, mostly cyprinids ascending a nature-like bypass channel in Austria by calculating for each species the ratio of number of fish trapped at the exit of the fishway to number of fish present below the fishway. These trap to weir catch ratios ranged from 0.1 to 456.0 (Mader et al.1998). Eberstaller et al. (1998) documented the use of a nature-like fish pass by brown trout (*Salmo trutta*), and rainbow trout *(Onchorhynchus mykiss)* as well as 17% of the population of European grayling *(Thymallus thymallus*) that occurred downstream of the fish pass. Although counts and ratios are useful for determining species composition within the fish pass, these methods do not provide information about attraction to or transit time through the fishway. Also, the ratio does not distinguish between fish that are moving downstream from above the pass or upstream from below the pass.

Evaluation of nature-like passes by telemetry of individual fish allows a more precise estimate of passage, as well as the quantification of transit time and the identification of attraction flow issues (Castro-Santos et al. 1996). By employing radio tags, Schmutz et al. (1998) were able to detect pike perch (*Stizostedion lucioperca*) approaching but not ascending a nature-like passage channel. Using passive integrated transponder (PIT) telemetry Aarestrup et al. (2003) showed that 90% of anadromous brown trout (*Salmo trutta*) located a nature-like fish pass in Denmark but only half completed the pass. Also employing PIT telemetry, Calles and Greenberg (2005) documented 89 to 100% passage efficiency of anadromous brown trout through two nature-like fish passes in Sweden, but only 50-53% attraction efficiency for the upper pass.

Nature-like fish passes have been constructed in Canada and in the northeastern states in the U.S.A. but to date none have been quantitatively evaluated for passage of northeastern diadromous species. Few river restoration projects, including those with the goal of fish passage, are monitored or assessed (Bernhardt et al., 2005). Monitoring the passage of different species through these existing nature-like fish passes will enable mangers and engineers to determine which designs are successful and which require modification. Evaluations will also aid efforts to form hypotheses about fishway performance and fish swimming abilities in the field, which will complement current models of swimming behavior that are generated using uniform hydraulic conditions in lab settings (Castro-Santos et al., 2008, Castro-Santos and Haro, 2008).

Along the eastern coast of the United States thousands of kilometers of historic anadromous alosine habitat have been highly modified or made inaccessible due to development of dams and other obstructions to migration (ASMFC 1999). Obstructions are created by large hydroelectric dams on mainstems of rivers, water storage and flood protection projects, small dams erected in tributaries to supply water to historic mills, and culverts at highway crossings (ASMFC 1999). River herring may be blocked by a structure only 20-30 cm above water and passage success at barriers often depends on the stream flow characteristics during the migration season (ASMFC 1999). In 15 rivers in Massachusetts managers believe that the major cause of *Alosa* stock decline is dams blocking upstream passage, and in a 2001-2002 survey of 215 coastal streams in the state a total of 380 obstructions to passage were catalogued (Rulifson 1994, Reback et al. 2004). The majority of these obstructions were dams that were no longer serving the purpose for which they were built.

Alewife (*Alosa pseudoharengus)*, also known as river herring along with the closely related blueback herring (*Alosa aestivalis*), are small anadromous, iteroparous fishes that migrate seasonally in rivers along the Atlantic Coast from northeastern Newfoundland to South Carolina (ASMFC 1999). Alewife spend most of their lives in the ocean but when they mature at three to five years they ascend their natal river to lay eggs in headwater ponds and other lentic areas. Migration and spawning is initiated by increasing water temperature in the spring months (Loesch 1987). The percentages of fish that move back downstream to the ocean or die within the ponds is unknown. The juveniles feed on zooplankton and migrate downstream to the ocean when water temperatures drop in autumn (Loesch 1987). River herring populations are culturally and economically important along the Atlantic Coast but their stocks have been declining due to several factors such as over harvest by river and ocean-intercept fisheries, biotic and abiotic environmental changes, loss of essential spawning and nursery habitat due to water quality degradation, and blockages of spawning reaches by dams and other impediments (AFSMC 1999, Belding 1920, ASMFC 1985).

The aim of this study is to quanitify passage of alewife at two existing nature-like fish passes at Town Brook in Plymouth, Massachusetts and East River in Guilford, Connecticut. The evaluation of Town Brook was conducted in 2006 and evaluation of East River in 2007. Both sites are habitat restoration projects of the National Oceanic and Atmospheric Administration Community-Based Restoration Program (Lenhart, 2003). The rock ramp design at Town Brook was constructed in conjunction with a dam removal project with the goal of creating a pool-riffle complex in the river and restoring passage of river herring. The site at East River is an adaptation of the dam bypass step pool design - the fish pass exit is at the dam itself instead of above the dam, and the passage channel was built into the existing grade with local materials (Food and Agriculture Organization 2002). It was built with the goal of restoring passage of river herring to the upstream ponds Evaluation metrics are attraction efficiency, proportion passing as a continuous function in relation to fish pass length and height, and transit time. PIT telemetry was chosen in order to collect a large sample, monitor small scale movements, and quantify transit time.

1.2 Methods

1.2.1 Study Area

1.2.1.1 Town Brook

Town Brook is a first order stream with a watershed of ten km^2 located in Plymouth, Massachusetts (Milone and MacBroom 2001). It flows 3 km from its source at a 109 hectare freshwater lake called Billington Sea to its mouth at Plymouth Harbor in Cape Cod Bay (Figure 1-1). The fourth dam upstream from the mouth of the river was removed in 2002 as part of an effort to reconnect the river corridor with the historic spawning grounds at Billington Sea. A 32m long, 8m wide nature-like fish pass with an overall 1:24 slope was constructed at the site. Migrating fish must ascend three technical fishways at the three lower dams and negotiate three small mill ponds before reaching the nature-like fish pass at river kilometer 1.6. (Reback et al 2004). A short distance upstream (154 m) of the nature like fishway is the 0.91m high "Off Billington St." dam with a small 14 m long pool and weir fishway with a slope of 1:7. Water flows both through this fishway and the spillway of the dam.

1.2.1.2 East River

East River is a second order stream with a watershed of 51.91 km^2 located in Guilford, Connecticut. Its source is the first order Iron Stream which originates in the town of Rockwell and flows into three impounded ponds called Upper Lake, Middle Lake, and Lower Lake, collectively known as "Guilford Lakes". East River then flows

10 km from the spillway of the Lower Guilford Lake dam to the mouth at Guilford Harbor in Long Island Sound (Figure 1-2). The Lower Guilford Lake Dam is divided into two concrete structures with an earthen impoundment in between. The western section is 3.35 m high, 35 m long and includes three 2.74 m wide spillways fitted with stoplogs and a 53.3 cm wide sluice gate. It has an elevation head of 3.66 m. The central earthen section is 25 m long. The eastern section is 1.32 m high, 12.20 m long**,** includes three 3.05 m long spillways fitted with stop logs, and has an elevation head of 0.61 m. Water flowed through the steeppass continually throughout the monitoring period. When the level of the pond rose, flow spilled over the western spillway first, and as leves rose, then over the weirs at the eastern spillway.

In 2001 the eastern channel was modified to create a fish passage channel including technical fishway and nature-like fish pass designs to provide access to 8.5 hectares of spawning habitat in the Lower and Middle Lakes. No fish passage is provided along the overflow channel at the western spillway. The eastern channel is 60 m long and the fish pass within it is 48 m long with a slope of 1:14. The nature-like portions are 7 to 9 m wide and constructed of 0.6-0.9 m rounded boulders that create 13 step pools. The substrate is bedrock granite and gravel. Two 3.05m long, 57.15cm wide, 68.6cm deep steeppass fishways are located within the fish pass (Ziemer 1962). The first steeppass is embedded at a 29.63% slope within a portion of ledge 20m downstream of the base of the dam, and the second is at a 9.59% slope at the dam itself. Migrating fish must pass through two ponds and one technical (Denil) fishway before reaching the entrances to the Lower Guilford Lake dam channels at river kilometer 9.

1.2.2 Passive Integrated Transponder Telemetry

Movements of alewife through the two nature-like fish passes were quantified using passive integrated transponder (PIT) telemetry (Castro-Santos et al. 1996). Instream antennas were constructed with single loops of four gauge welding wire and ranged from 4 to 8m wide. Antennas inside the technical fishways were constructed with 12 gauge THHN insulated copper wire encased in PVC tubing. All antennas were tuned to resonate at 132.4 kHz to maximize read range and were connected to Texas Instruments Radio Frequency Identification Systems Series 2000 readers enclosed in a weatherproof box. Readers were configured to gather data at a rate of 10 reads per second and were powered by a DC power supply. The distance a tag could be read from the antenna loop ranged from 20-30cm from the plane of the antenna loop. The date, time, fish identification number, and antenna numbers were recorded by a data logging computer at each site. Antennas were tested periodically with a test tag attached to the end of a pole. Detection records for each fish were examined and missed detections were identified if a fish was known to have passed at an antenna upstream of the antenna in question. Efficiency was calculated for each antenna by dividing the number of fish known to have passed the antenna (determined by detections at other antennas) by the number of fish that were actually detected at the antenna.

1.2.3 Antenna Placement

At Town Brook a 180 m stretch of river was monitored with eight antennas. Four antennas were placed within the rock ramp nature-like fish pass, two antennas were installed between the nature-like fish pass and the Off Billington St. dam and two antennas were placed inside of the pool and weir fishway weirs (Figure 1-1). At East River the approach to the lower Guilford Dam was monitored with ten antennas. A single antenna was placed at the entrances of the overflow channel and passage channel to monitor route choice. One antenna was installed at the entrance to the nature-like section and three others within. Four antennas monitored the entrances and exits of the two steeppass fishways (Figure 1-2).

1.2.4 Tagging

1.2.4.1 Town Brook

A total of four hundred alewife were collected and tagged with 23mm PIT tags (intra-peritoneal implantation; see Sullivan 2004 for methodology) at the Newfield Street weir over a period of 27 days from April 19 to May 15 during daylight hours (Figure 1-1). Fish were netted from an enclosed area by hand and for each fish the fork length, sex, and percentage of scale loss on the right and left side was recorded (Table 1-1). Fish with more than 50% scale loss on either side were released without a tag. On April 19th 100 fish were tagged and released. Subsequent tagging events were completed in batches of 50 fish on April 26, May 1, May 5, May 8, May 12, and May 15. Tagged fish were immediately released into the headpond above the Newfield Street Dam 914 meters from the entrance to the nature-like fishway and were allowed to enter the rock ramp volitionally.

1.2.4.2 East River

A total of three hundred and ninety three alewife were collected and tagged with 23mm PIT tags below the Capello Pond Dam over a period of 38 days from March 30 to May 7 during daylight and evening hours (Table 1-2). The same methodology as Town Brook was used.

Collections were made using a weir constructed of 1.9 cm square mesh Trical netting with steel rebar supports that was installed at a 45 degree angle across the full width of the river leading fish into a 4.57 m by 2.13 m trap box also constructed from netting and steel rebar supports. Trapped fish were then dip netted by hand, measured, and examined for sex and scale loss (Table 1-2). Fish with more than 50% scale loss were released without a tag. After being tagged, fish were transported approximately 50m by bucket and released at the base of Capello Pond 762 meters below the entrance to the nature-like fish pass (Figure 1-2). Released fish were allowed to enter the nature-like fish pass volitionally.

1.2.5 Data Collection

Data files produced by the datalogging computer were downloaded every day. At Town Brook the system began monitoring on April 19, 2006 but due to a computer malfunction stopped recording data for 117 hours from April 19, 2006 to April 24, 2006; antennas then operated continuously from April 24 to July 6, 2006. At East River the system began monitoring on March 23, 2007. Due to a computer malfunction the system stopped recording data for 60 hours from April 27 to April 30. The data loggers then operated continuously from April 30, 2007 to June 12, 2007.

Water level and temperature data were collected hourly at both sites using Onset HOBO ® U20-001-01 Water Level loggers. In order to derive absolute water level at each site a logger was installed above water to record atmospheric pressure. A total of three data loggers were installed at Town Brook: two underwater at the entrance and exit of the nature-like fish pass and one above water in the weathertight box containing the PIT readers. At East River three data loggers were installed: one in the headpond, one at the entrance of the passage corridor, and one in the weathertight box. As a reference, water temperature and relative level were measured manually using a digital thermometer and staff gauges. At East River hourly flow measured in $m^3 \cdot sec^{-1}$ over the eastern and western weirs and through the upper steeppass fishway was calculated using a formula that incorporated the hourly water level measurements in the headpond and the elevation of the weirs and fishway (Appendix C). The estimate of flow through the nature-like fish pass was arrived at by adding the flow through the upper steeppass to the flow over the eastern spillway. A gap is present between flows at 0.09 $m^3 \cdot sec^{-1}$ and 0.13 $m^3 \cdot sec^{-1}$ that reflects when the flow over the weir is added to the flow moving through the steeppass. Percent slope in between individual antennas was calculated using elevation measurements at each antenna measured with a rod and level.

1.2.6 Data Analysis

Text data files from the PIT recording system were imported into a Microsoft Access database. Readers had been configured to log 10-12 reads per second, so in order to reduce the size of the database consecutive reads of individual fish at individual antennas less than one second were defined as single presences. The time of the first and last observation for each presence was retained. For each site passage performance was evaluated by examining passage efficiency, attraction efficiency, number of attempts, and transit time. Percent passage was quantified as the number of fish that entered the fish pass that successfully passed. Ninety five percent confidence intervals for percent passage estimates were calculated using the binomial distribution and are parenthetically reported in the text with the estimates. Attraction efficiency for the East River fish pass was quantified as the percentage of fish that were detected at an antenna downstream of the entrance to the fish pass that were then detected at the entrance to the fish pass.

Detections of individual fish were grouped into "attempts" in order to quantify multiple efforts to ascend the fish pass as well as determine on what attempt the fish completed the fish pass. At both sites movement data were sorted by individual fish and time and then the lags (amount of time elapsed) between presences at the antennas monitoring the nature-like fish passes were calculated. The distribution of these lag times was then examined. At Town Brook it was determined that since most of the lag times were under 15 minutes, a lag of 15 min or more between presences at antenna 1 indicated that a fish likely had left the area of the ramp entrance and then returned to make another attempt. At East River a new attempt was assigned if a fish went undetected for more than 95 min between detections at antenna 3, or antenna 4 to accommodate the possibility of being missed at antenna 3 (Figure 1-2).

Transit times through the full length of the fish pass were calculated only for fish that successfully completed the fish pass. Transit times were calculated within successful attempts by subtracting the time of the last detection at the lower antenna from the time of the first detection at the upper antenna.

Multiple linear regression analysis was used at each site to examine how transit times through the nature-like passes were affected by fish length, proportion of scale loss, sex, time at liberty, and temperature when the attempt was begun. At Town Brook water level at the time the attempt was begun and the interaction between sex and length were also included in the model. At East River total flow through the fish pass and the interactions between temperature and flow and length and sex were included in the model. The distribution of transit times was skewed so transit times were transformed to their natural log. Time at liberty is defined as the amount of time that elapsed between when a fish was tagged and released and when it was first detected at an antenna. All variables were standardized to a mean of zero and a standard deviation of one and interaction terms are the product of the standardized variables. At each site the model with the lowest Aikaike Information Criterion (AIC) score was designated as the "top model" and all models with a difference in scores (ΔAIC) less than 2 are presented (Burnham and Anderson, 1998).

Transit times of fish through individual pairs of antennas were calculated by subtracting the last detection at the first antenna from the first detection at the next antenna. These are minimum times and can be representative of behaviors of fish traveling directly (without hesitation) or indirectly (hesitating or milling) from antenna to antenna. Horizontal and vertical (elevation gain) rate of travel were calculated by dividing the horizontal and vertical distance between antennas by the amount of time it took for the fish to pass in between those antennas.

Estimates of survivor functions and hazard rates for passage through the fishways were calculated using the Kaplan-Meier and life-table methods of event time analysis (Kaplan & Meier**,** 1958, Allison, 1995, Castro-Santos & Haro, 2003,). Cox's proportional hazards regression analyses was employed to examine the effects of sex, scale loss, and length on the maximum distance of ascent (Cox, 1972, Castro-Santos & Haro, 2003). In order to examine the effect of slope on failure rates through the nature-like and unmodified sections of the rivers linear regression analysis was performed on combined data from the two sites. The first analysis included data from all of the monitored sections. The second analysis included only nature-like and unmodified sections. Sections between antennas 1-6 at Town Brook and the antenna intervals 2-3, 3-4, 6-7, 7-8 at East River were included.

For the data from East River multiple logistic regression analyses were performed to examine the probability of passing or failing to pass at antennas 3 and 8 as a function of sex, length, proportion of scale loss, and temperature and flow at the time of first detection at the antenna. Analyses were performed for the first and second attempts at each antenna. At antenna 8 three flow variables were tested; steeppass flow, weir flow, and nature-like flow (Appendix C). Models tested include the full model with all variables, environmental effects (temperature and flow), fish characteristics (sex, length, proportion of scale loss), and each of the variables alone. For the first and second attempt at each antenna, the full model, and all significant models are presented. A loess smooth model was fitted to the data for the models with the lowest AIC score at each antenna for each attempt.

Downstream transit times were calculated by subtracting the time of the last presence at the most downstream antenna from the first presence at the most upstream antenna of the fishways. A fish was considered to be moving downstream if it was detected at the top and then bottom of the fish pass.

1.3 Results

1.3.1 Town Brook

Data were collected from 43% (175) of the 400 fish tagged (Table 1-1). However due to a monitoring system malfunction the movements of the first 100 fish tagged and released went unrecorded for 117 hours. Seventy two of those fish were detected once the system was turned back on and their passage success through the rock ramp was 98.61%. However a one way analysis of variance analysis of the movements of the six later releases showed that the fish staged significantly more attempts in the first 117 hours than the subsequent 117 hours (df=158 F=102.45, p=<.0001). Because transit time and attempt rate data are dependent on complete histories of transits through the rock ramp, data from the first 100 fish released were omitted from further analyses. Results discussed from this point forward are based on the sample of 103 fish that were detected from the releases made on April 26 through May 15.

Of the103 fish included in analyses, 54.43% (95% CI 44-63%) were male and 47.57% (95% CI 39-58%) were female, their lengths ranged from 212mm to 263mm and the total percentage of scale loss ranged from 0 to 27.5%**.** Forty days of movements were observed during the period between April 26, 2006 and June 4, 2006. Antenna efficiency during this period ranged from 99% to 100% (Table 1- 3). Water temperatures ranged from 9.96 to 24.64 °C and relative water levels at the upstream datalogger ranged from 0.234 to 0.343 m (Figure 1-4).

Passage success through the rock ramp was high. Ninety four percent (N=97, 89.1% - 97.8%) of fish that entered the rock ramp successfully completed their ascent through it (Figure 1-5). Only six fish failed within the rock ramp. Cumulative passage success remained high until the section between antennas 6 and 7, indicating a guidance or attraction problem below the upstream pool and weir fishway (Table 1-4). Sixty six percent of the fish (N=68) reached their maximum distance of ascent above the rock ramp at antenna 6. No significant relationship was found between failure rate and sex, length, or percentage of scale loss. Of the 97 successful fish, 51.55 % were male (95% CI 42-62%) and 48.45% were female (95% CI 39-59%).

Attraction efficiency could not be calculated because an antenna was not placed below the entrance of the fishway in order to detect the fish that were available to pass the nature-like rock ramp. However, given that 103 fish entered the fishway out of 300 fish tagged, attraction efficiency is between 34.33% and 100%.

Of the 97 successful fish, 91 (93.8%) completed the rock ramp on their first attempt (Figure 1-5). Five fish completed it on their second attempt and one fish on the third attempt. On the first attempt antenna 6 was the maximum distance of ascent for 63.11% (65) of the fish. Eighty nine percent of all fish (N=92) began their first attempt during day light hours.

Transit times of successful fish through the rock ramp ranged from 4.85 min to 44.08 min with a median time of 11.09 minutes (Figure 1-6). A one way analysis of variance analysis found no significant difference in transit times between males and females (df=1, F=.29 p=.5903). The top multiple regression model explained the variation in transit time as a function of length, temperature, scale loss, and time at liberty (Table 1-5). Longer fish and fish with a smaller proportion of scale loss traveled through the nature-like fish pass more quickly. Fish that had a short time at liberty traveled slower through the fishway and all fish traveled faster at warmer temperatures. The top model explained 12.42% of the variation and the standardized partial regression coefficients indicate that length had a greater effect than temperature, scale loss, and time at liberty. Eight models had a ΔAIC of less than 2.

Fish traveled the fastest horizontally through the first 17 m of the rock ramp and median travel rates through the fish pass ranged from 4.04 $m{\cdot}min^{-1}$ to 2.85 $m{\cdot}min^{-1}$ (Figure 1-7). Vertically, the fish ascended the fastest through the steepest part of the rock ramp and median travel rates ranged from .09 $m{\cdot}min^{-1}$ to .21 $m{\cdot}min^{-1}$ (Figure 1- 7).

At the upstream pool and weir fishway, 96 fish were detected at antenna 6 and were considered available to pass. Twenty eight of those fish found the entrance giving the fishway an attraction efficiency of 29.17%. Six fish successfully completed the fishway giving it a passage efficiency of 21.43%. Transit time from antenna 7 to 8 ranged from 11.9 to 30.5 seconds. On several days fish were visually observed congregating below the spillway of the dam and attempting to swim through the spillway flow.

Downstream movement through the rock ramp was observed after two different events. Including the first group of released fish, out of 16 fish that were known to have passed upstream of the technical fishway, 10 (62.5%) then moved back downstream 8 to 27 days later. The downstream transit times of these fish through the rock ramp ranged from 17 to 96 seconds. Downstream movements through the rock ramp were also observed from fish that only reached antenna 6 and then moved downstream. This behavior was recorded for 86 fish and their transit times through the rock ramp ranged from 17.23 seconds to 11.14 minutes with a median of 72.42 seconds. Transit times from the last detection at antenna 5 to the last detection at antenna 4 ranged from 94 seconds to 3.52 hours with a median of 4.95 minutes.

1.3.2 East River

Data were collected from 59.5% (234) of the fish tagged. Males made up 64.53% (95% CI 59-71%) of the sample and females 38.03% (95% CI 32-45%). Their lengths ranged from 201 to 271mm and total scale loss ranged from 0 to 20%. Fifty two days of movement were observed from April 22, 2007 to June 12, 2007. Antenna efficiency for this period ranged from 89.25 to 100% (Table 1- 3). Water temperatures from the downstream data logger ranged from 11.14 to 26.39 °C and water level from 0.131 to 0.544m (Figure 1-4).

The monitoring system did not operate for 60 hours from April 27 to April 30 during a high flow event that inundated the antennas and tuning boxes. When the system was repaired and turned back on again at 12:03 on April 30th, no fish were detected at any antennas. The first detections of fish after this event occurred several hours later and were below the nature-like fish pass at antennas 1 or 2. This was interpreted to mean that the fish pass contained no fish during the high flow event. The decision was made to retain all of the data from the 204 fish that were released before this high flow event. Over the entire monitoring period, of the 60 fish that did successfully ascend to the pond and were detected descending through the fish pass, only two fish spent less than three days in lower Guilford Lake before moving downstream. Considering this information it is unlikely that fish ascended and descended through the fish pass while the system was not operating.

Attraction efficiency of the passage channel was high. Of the 231 fish detected at the entrance of the passage channel at antenna 2, 90.6% (212) entered the nature-like fish pass at antenna 3. Ninety four percent of detected fish (221) were detected exploring the entrance of the overflow channel at antenna 1, but only three of those fish failed to locate the entrance to the passage channel.

Percent passage through the passage channel was modest. Of the 212 fish that entered the fish pass at antenna 3, 40.56% (N=86, 34.4% - 47.5%) completed the nature-like and steeppass sections and reached Lower Guilford Lake (Figure 1-8, Table 1-6). Of the 86 successful fish 77.91% were male (95%CI 70-86%) and 22.09% were female (95% CI 15-33%). Two sections of the nature-like fish pass had high failure rates (Table 1-13). Twenty five percent (54) of fish that entered the fish pass ascended no further than antenna 3. Twenty four percent (51) of fish reached their maximum antenna near the top of the fish pass at antenna 8.

Percent passage through the two individual steeppass sections was high. Of the 146 fish that entered the first steeppass at antenna 5, 141 (96.58%) completed it. Of the 91 fish that entered the second steeppass at antenna 9, 86 (94.51%) completed it. Given that the percentages for antenna efficiency at antennas 5 and 6 are less than the estimates of percent passage, it can be assumed that passage through the first steeppass was 100% (Table 1-3).

A positive relationship exists between both fork length and failure rate through the fish pass and percentage of scale loss and failure rate through the fish pass (Table 1-7). For every millimeter increase in length, the failure rate at each weir increases by 2%. For every percent increase in scale loss, the failure rate at each weir increases by 4%.

On the first attempt 64.62% (137) of fish ascended no further than the beginning of the nature- like fish pass at antenna 3 and only 8.96% (19) successfully ascended the entire passage channel (Figure 1-8). The fish that successfully ascended the passage corridor to Lower Guilford Lake (86) made between one and eight attempts to complete the passage channel. Seventy two percent (153) of fish approached the passage channel during daylight hours.

For the first attempts at antenna 3 the probability of a fish failing to pass increases with an increase in total flow through the nature-like fish pass (Table 1-8). On the second attempt the probability of a fish failing to pass decreases as temperature increases (Table 1-9). For the first attempts at antenna 8 the probability of a fish failing to pass increases with increasing flow through the upper steeppass fishway (Table 1-10). On the second attempt at antenna 8 the probability of a fish failing to pass decreases with rising temperature (Table 1-11).

Transit times of successful fish (86) through the entire fish pass (both nature-like and steeppass sections) ranged from 19.6 minutes to over 3 days (Figure 1-6). The median passage time was 75 minutes and ninety percent of the successful fish passed in seven hours. The only variable included in the top model is time at liberty (Table 1-12). In this model 9.9% of the variation is explained by the positive relationship between transit time and time at liberty. Eight models had a ΔAIC of less than 2 and the variable time at liberty is included at a significant level in all of them.

Median transit times between individual pairs of antennas through the nature-like section ranged from 44 seconds to 19 minutes (Figure 1-9). Median horizontal travel rates ranged from 0.099 $m \cdot min^{-1}$ to 7.94 $m \cdot min^{-1}$ (Figure 1- 9). Median vertical travel rates ranged from 0.003 $m \cdot min^{-1}$ to 0.328 $m \cdot min^{-1}$ (Figure 1-9). Median transit times through the steeppass sections were 1.7 seconds for the lower steeppass and 3.02 seconds for the upper (Figure B-1).

Sixty six percent (57) of the 86 fish that successfully ascended to the Lower Guilford Lake were detected moving downstream through the passage channel. Time spent in the lake ranged from 1 to 41 days with a median residence time of 16.5 days. Downstream transit times through the passage channel ranged from 1.7 minutes to 23.2 minutes with a median of 8.4 minutes. Median downstream transit times through the two steeppass sections were 2.28 seconds and 1.74 seconds. Median transit times for the nature-like sections ranged from 7.29 seconds (antennas 9 to 8) to 295.03 seconds (antennas 7 to 6). Six percent (5) of successful fish descended over the western spillway through the overflow channel and were detected at antenna 1; one of those fish was detected exploring downstream passage through the passage channel but then was detected descending through the overflow channel eight days later. Twenty eight percent (24) of successful fish were not detected again after the last upstream presence at antenna 10.

A significant linear relationship was not found between slope and failure rate at all of the monitored sections of Town Brook and East River (p=0.73) nor for the nature-like and un-modified sections of the two sites (p=0.09). In general, low slopes corresponded to low failure rates (Figure 1-10).

1.4 Discussion

The results of this study indicate that nature-like fish pass designs can be employed to pass alewife in coastal streams, but performance is variable. The rock ramp design at Town Brook was effective – it passed 94% of detected fish, most of them on their first attempt, and in a short period of time. The bypass design at East River was not as effective as Town Brook, it passed only 40.56% of detected fish, over a wide range of attempts, and with longer transit times. Most of the poor passage at the East River pass can be attributed to two specific sections at antennas 3 and 8.

The percentage of tagged fish that were detected was higher at East River than at Town Brook but both percentages fall in between the lowest (15.09% Calles and Greenberg (2005)) and highest (72.7% Aarstrup et al (2003)) reported for other nature-like fish pass evaluations. Considering that 22 fish were detected at East River only below the fish pass at antennas 1 and 2, an additional antenna placed below the rock ramp at Town Brook might have increased the proportion of fish detected at that site. The fate of undetected fish is not known at either site. Mortality could have occurred as a consequence of tagging, handling, or predation. Fish also could have spawned in a location downstream of the monitored area, or lost the tag before reaching the monitored area as well. Although mortality induced by the effects of tagging and handling was not evaluated for this particular study, it was assumed to be low based on results from other work. Kleinschmidt (2005) observed no mortality in a 48 hour observation period after implanting alewife with the same size PIT tag used for this study. Sullivan (2004) found no significant difference in survival times between American shad that had been tagged with 32mm x 3.8mm PIT tags, and those that had not been tagged. Smith et al. (2008) found no mortality associated with gastric tagging of alewives after a 14 day observation period. It is possible that some tags may have fallen out of fish but Sullivan (2004) documented only 2 lost tags out of 20 tagged American shad in 2000 and recorded no tag loss out of 30 tagged shad in 2001.

The sample of fish collected and tagged at Town Brook was composed of nearly equal numbers of males and females, but at East River was composed of more males. Loesch (1987) reports that males generally make up a larger proportion of the early run and that the proportion of females increases over time. It is possible that the sample from Town Brook is representative of the entire run and at East River only the beginning. The spawning run at Town Brook historically occurs over a period of 4-6 weeks. Tagging began approximately two weeks after the first alewife were seen in the river and continued at regular intervals over the next month. Little was known about the size and timing of the run at East River, so tagging began as soon as alewife were trapped and approximately half of the sample was tagged on one day.

Further evaluation is needed to more precisely identify the causes of poor passage at East River at antenna 3. Our antenna layout lacked the spatial resolution to detect whether fish were reluctant to enter the beginning of the fishway, or proceeded through the entrance but then encountered difficulties with a particular step pool. This section has the second highest slope of the nature-like portions, but further work is required to determine if the overall slope, the design, or number of steppools is the cause of the passage barrier.

Environmental factors, not fish characteristics were associated with the probability of a fish failing to pass at antenna 3 on the first and second attempts. The relationship with flow on the first attempt and temperature on the second could indicate that first attempts were exploratory and second attempts were related to increased motivation due to higher temperatures. However for the first attempt the AIC scores of the significant models are close enough to suggest that some combination of flow and temperature influenced failure to pass. A more thorough examination of the relationship could be accomplished by quantifying flow in increments of time less than one hour. The observation of successful passage being associated with warmer temperatures has been made at other fishways with different species and could reflect increased physiological capacity or increased motivation. Gowans et al (1999) reported that Atlantic salmon (*Salmo salar*) approached a dam but did not ascend through a pool and orifice fish ladder in Scotland until temperatures were above 8.5 °C. Haro et al. (1999) reported that the percent of American shad passed per unit time increased with temperature through a Denil fishway.

Two possible explanations exist for poor passage at the East River site at antenna 8. The section between antennas 8 and 9 has the highest slope of the nature-like sections and just upstream of antenna 8 is the narrow slot that leads to the final step pool. The velocities at this slot could have prevented fish from ascending into the steppool. The alternative explanation is that the poor passage was due to fish sensing competing flow from the first weir of the eastern spillway. Fish could have swum past antenna 8 and ascended into the final step pool, but then had difficulty locating the entrance of the steeppass fishway because of the competing flow. The fact that fish took the longest amount of time to ascend this section provides some evidence for this theory, but weir flow was not a significant variable in any models for either the first or second attempts.

At East River a smaller proportion of females completed the fishway than males. Libby (1981) also observed a difference in sex ratio at the bottom and top of a fishway and concluded that the fishway was selective against larger fish. At both sites length affected aspects of individual performance through the fishways. At Town Brook longer fish ascended the fishways faster than shorter fish and at East River longer fish had a smaller maximum distance of ascent. Sullivan (2004) also found an effect of length on percent passage for shad ascending a modified Ice Harbor fishway; for both males and females successful individuals were significantly smaller than unsuccessful individuals. This relationship deserves further exploration and additional data should be collected at a wide range of sites and fishway designs. Since larger herring have greater reproductive capacity, their possible exclusion from spawning grounds could have major population implications.

Attraction efficiency cannot be compared between the two sites. An antenna was not installed below the rock ramp at Town Brook to detect fish available to enter the fish pass. Attraction efficiency does not appear to be a problem at East River. Even though most fish explored the overflow channel, only three fish failed to enter the passage channel at antenna 2.

The behavior exhibited by the fish on their first attempts was markedly different at the two fish passes. A possible explanation is that the rock ramp at Town Brook spans the entire width of the river and fish were presented with no other alternative to progressing upstream. At East River the presence of the overflow channel may have prompted fish to make exploratory movements at the entrance to the fishway before making the choice to progress through it. Temperature is not a likely factor in explaining the differences in movements between the two sites; only a 0.19 degree difference exists in the range of temperatures experienced by the fish on their first attempts at the two sites and the distributions are similar. Also at both sites fish have access to suitable spawning sites both downstream and upstream of the fishways, so it is unlikely that fish at either site are more motivated to ascend on the first attempt due to lack of proper habitat downstream.

It appears that transit times at both Town Brook and East River are influenced by other variables in addition to the six measured – the best models at both sites explained very little of the variation. At Town Brook the positive relationship with temperature corresponds to the finding that American shad and blueback herring moved more quickly through a Denil and a steeppass fishway at higher temperatures (Haro et al. 1999).

At both sites the variable time at liberty influenced the transit times through the fish passes but with opposite effects and at a significant level only at East River. At East River the positive relationship could be interpreted as evidence that the level of motivation to move upstream is consistent through unmodified and modified sections of the river. Assuming that fish traveled directly from the release site to the fish pass, it could also reflect varying swimming abilities related to sex or length. At Town Brook the negative effect of time at liberty on transit time was small but could potentially be due to fish recovering from the capture and tagging event.

No clear patterns emerge from examining the rates of horizontal and vertical travel at the two sites. At Town Brook fish travelled both horizontally and vertically the fastest through the steepest sections of the fishway. This observation corresponds to the expectation that fish will increase their swim speed upon encountering higher velocities in order to continue to cover more distance over ground (Castro-Santos 2005). In contrast at East River fish traveled fastest horizontally through the lowest sloped nature-like section at antenna 7 to 8 and slowest through the steepest nature-like section between antennas 8 and 9. Vertically the fish ascended the fastest from antenna 7 to 8, due to them swimming very quickly through a shallow section. They travelled the slowest vertically between antennas 3 to 4, but because they had to ascend through five steppools in that section we cannot determine if the overall slope posed a challenge, or whether it was a localized issue particular to a specific steppool. Comparing the Town Brook rock ramp to the three sections of East River with slopes in the same range does not yield a consistent pattern either; East River fish traveled faster through one section than Town Brook fish and slower on the other two. This lack of a pattern might be explained by fish responding to localized hydraulic conditions that change with increases and decreases in flow, in addition to the overall slope.

The technical fishways at the two sites exhibited contrasting performance. At Town Brook the pool and weir fishway at the Off Billington St. Dam site had both low attraction and passage efficiency while the two technical steeppass sections in the East River passage corridor had high percent passage. Percent passage was higher at the East River 1:3.4 and 1:10 sloped steeppasses than what was observed for blueback herring ascending a longer and deeper (7.62m, 102 cm) steepass design tested at slopes of 1:8 (70% passage)and 1:6 (10-20% passage)(Haro et al.1999). The transition from a nature-like section to the first technical section within the fish pass did not create a passage barrier. Some evidence exists that the upper steeppass had attraction flow issues, but the placement of antennas at this section did not allow us to determine if this situation did occur.

Both fishways appear to provide successful downstream passage, although complete data on guidance to the fishways is lacking. At both sites downstream transit times were approximately nine times as fast as upstream times. At Town Brook the transit times observed between antennas 5 and 4 (median of 4.95 min) suggest that the fish may have delayed before moving downstream through the rock ramp, however this median downstream transit time is a third of the median upstream transit time at this section. No data were collected regarding downstream guidance to East River fishway. Median transit times between pairs of antennas were all short except upstream of the lower steeppass. After some rain events water flowed around the outside this steeppass. Fish could have delayed at this section while choosing to descend around the fishway or through the vanes of the steeppass.

Quantifying the percentage of alewife that move downstream after spawning and determining the amount of time they are resident in rivers before initiating downstream migration could provide useful information to managers. Until recently the available technology has not been adequate to quantitatively assess downstream migratory timing

(Saila et al. 1972). In Massachusetts the generally accepted belief is that most migrants move downstream approximately one to two weeks after spawning, although observations have been made of adults migrating downstream along with juveniles in the autumn months (Philips Brady, Massachusetts Division of Marine Fisheries, personal communication). PIT telemetry can be used for this application; both this study and a PIT study of a Denil fishway at Salmon Falls River in South Berwick, Maine quantified downstream movements of approximately 60% of the fish that successfully moved upstream (Kleinschmidt 2005). The residence times of fish detected at East River seem to provide evidence that most fish move downstream within a few weeks of arriving at the spawning area.

It is difficult to draw generalized conclusions about the design of nature like fish passes based upon single-season evaluations of only two sites. Sullivan (2004) observed variability in passage performance of American shad through technical fishways over four years of evaluation with a difference in percent passage estimates ranging from 8.2 to 17.2. However, by simply comparing the passage at the two field sites we observed that the sections that had slopes ranging from 1.01% to 5.43% had low failure rates indicating high passage. Sections with slopes ranging from 7.92% to 18.52% had higher failure rates indicating lower passage. The linear regression analysis of slope and hazard rates from both Town Brook and East River was not significant, but includes only nine data points. More evaluations of fish passes will be needed in order to thoroughly examine this relationship. A more conclusive study performed in a controlled laboratory setting found negative relationships between fishway slope and percent passage in American shad and blueback herring ascending technical steeppass and Denil designs (Haro et al. 1999), albeit at much higher slopes than the nature-like fish passes evaluated in this study. Because these nature-like fish pass evaluations were performed in the field in uncontrolled settings we cannot definitively conclude that the poor passage at the steeper slopes was due to the overall slope, or whether it was caused by a significant drop in elevation between steppools, or the hydraulic conditions experienced by the fish.

This study demonstrates that nature-like fish pass designs are suitable for the passage of alewife, but more evaluations must be performed both in the field and in controlled laboratory settings to generate more informative design criteria. Few evaluations of both technical and nature-like fishways have been conducted for non salmonid species. In order to validate the paradigm that nature-like designs are more effective at passing a wider range of species than technical designs, evaluations must be conducted for both designs that include estimates of guidance, attraction, and passage for the full complement of migratory fishes that ascend small coastal streams. Nature-like and technical designs should also be evaluated in the context of the full passage corridor in order to examine cumulative passage through multiple fishways.

Table 1-1. Sample size, sex ratio, length, scale loss and pecent detection data for release groups of tagged alewife at Town Brook. Release group number indicates date of release.

Release Group	Number Tagged	Males	Females	M/F Ratio	Range of Lengths	Median Length	Average Proportion of Scale Loss Left Side	Average Proportion of Scale Loss Right Side	Number; Percent Detected
19-Apr	100	67	33	1:0.49	222-260	240	0.07	0.08	72;72.0%
26-Apr	50	22	28	1:1.27	220-259	237.5	0.05	0.06	34;68.0%
1-May	50	15	35	1:2.33	214-263	235	0.05	0.06	21;42.0%
5-May	50	30	20	1:0.66	220-253	234.5	0.08	0.07	25;50.0%
8-May	50	14	36	1:2.57	212-259	234.5	0.05	0.05	10;20.0%
12-May	50	19	31	1:1.63	209-254	232	0.06	0.06	3;6.0%
15-May	50	36	14	1:0.39	207-247	228	0.07	0.08	10;20.0%

Table 1-2. Sample size, sex ratio, length, scale loss and pecent detection data for release groups of tagged alewife at East River. Release group number indicates date of release.

Release Group	Number Tagged	Males	Females	M/F Ratio	Range of Lengths	Median Length	Average Proportion of Scale Loss Left Side	Average Proportion of Scale Loss Right Side	Number; Percent Detected
30-Mar	7	5	2	1:0.4	210-229	218	0.17	0.18	0;0%
21-Apr	12	6	6	1:1	212-269	230	0.61	0.58	0;0%
22-Apr A	16	14	2	1:0.14	208-250	215.5	0.36	0.43	0;0%
22-Apr B	75	54	21	1:0.39	209-266	229	0.15	0.17	35;46.67%
23-Apr A	43	27	16	1:0.59	206-271	223	0.17	0.23	9;20.93%
23-Apr B	200	117	83	1:0.71	204-262	223	0.04	0.06	160;80.0%
4-May	34	21	13	1:0.62	201-248	220.5	0.08	0.06	24;70.59%
7-May	8	4	4	1:1	206-234	220.5	0.11	0.05	6;75.0%

Table 1-3 Antenna detection efficiency at Town Brook and East River.

Location	Antenna Number	Number of Exposures	Number of Detections; Efficiency (%)
Town Brook	1	312	312; 100
	2	258	257; 99.61
	3	254	253; 99.61
	4	254	253; 99.61
	5	276	274; 99.28
	6	68	68; 100
	7	21	21; 100
East River	2	703	676; 96.16
	3	252	236; 93.65
	4	214	191; 89.25
	5	268	246; 91.79
	6	200	179; 89.5
	7	227	227; 100
	8	98	98; 100
	9	86	83; 96.51

Table 1-4. Cumulative proportion of fish succeeding at each antenna on first attempt through monitored section of Town Brook, and over all attempts through monitored section of Town Brook. Proportion Suceeding (95% Confidence Interval).

Antenna Number	Proportion Succeeding on First Attempt	Proportion Succeeding over All Attempts
1	1.00 (1.00-1.00)	1.00 (1.00-1.00)
2	0.98 (0.92-1.00)	0.98 (0.92-1.00)
3	0.89 (0.82-0.94)	0.95 (0.89-0.98)
4	0.88 (0.80-0.93)	0.94 (0.87-0.97)
5	0.87 (0.79-0.92)	0.94 (0.87-0.97)
6	0.85 (0.77-0.91)	0.93 (0.86-0.97)
7	0.22 (0.15-0.31)	0.27 (0.19-0.36)
8	0.07 (0.03-0.13)	0.09 (0.04-0.15)

Table 1-5. Results from multiple linear regression analysis of variables affecting transit time through the nature-like fish pass at Town Brook. N=91. Coefficients (β) indicate effect of each variable on the natural log of transit time measured in minutes; scale refers to the error term.

	β±SE								
Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Full Model
Intercept	2.44±.04	2.44±0.04	2.44±0.04	2.44±0.04	2.44±0.04	2.44±0.04	2.44±0.04	2.44±0.04	2.42±0.06
p	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Length (mm)	-0.13±0.04	-0.13 ±0.04	-0.11±0.04	-0.13±0.04	-0.13±0.04	-0.12±0.06	-0.12±0.04	-0.12±0.06	-0.12±0.06
p	0.0026	0.0035	0.0104	0.0032	0.0032	0.0377	0.0060	0.0435	0.0500
Water Level (m)				0.03±0.05	-0.02±0.04				0.03±0.05
p				0.5938	0.6170				0.6011
Temperature ℃	-0.08±0.04	-0.08±0.04	-0.09±0.04	-0.08±0.04	-0.08±0.04	-0.08±0.04		-0.08±0.04	-0.08±0.04
p	0.0474	0.0539	0.0250	0.0474	0.0544	0.0465		0.0533	0.0496
Time at Liberty (min)	-0.06±0.04			-0.08±0.05		-0.06±0.04			-0.08±0.05
p	0.1637					0.1645			0.1674
Proportion Scale Loss	0.08±0.04	0.08±0.04		0.08±0.04	0.08±0.04	0.08±0.04	0.09±0.04	0.08±0.04	0.08±0.04
p	0.0484	0.0676		0.0692	0.0597	0.0501	0.0312	0.0696	0.0709
Sex									0.02±0.09
p									0.8429
Length*Sex						-0.03±0.09		-0.02±0.09	-0.02±0.09
p						0.7771		0.7977	0.8079
AIC	-168.968	-168.902	-167.386	-167.275	-167.169	-167.055	-166.991	-166.972	-163.390
ΔAIC	0	0.066	1.582	1.693	1.799	1.913	1.977	1.996	5.578
Adjusted r^2	.1242	0.114	0.090	0.117	0.107	0.115	0.106	0.105	0.096

Table 1-6. Cumulative proportion succeeding at each antenna on first attempt through monitored section of East River, and over all attempts through monitored section of East River.

Antenna Number	Proportion Succeeding on First Attempt	Proportion Succeeding over All Attempts
3	1.00 (1.00-1.00)	1.00 (1.00-1.00)
4	0.35 (0.29-0.42)	0.75 (0.68-0.80)
5	0.28 (0.22-0.34)	0.70 (0.63-0.76)
6	0.26 (0.20-0.32)	0.68 (0.62-0.74)
7	0.26 (0.20-0.32)	0.67 (0.61-0.73)
8	0.24 (0.19-0.30)	0.67 (0.61-0.73)
9	0.10 (0.06-0.14)	0.43 (0.36-0.49)
10	0.09 (0.06-0.13)	0.41 (0.34-0.47)

Table 1-7. Results of Cox's proportional hazards regression analysis of variables affecting failure rate at East River fish pass. N=231, 86 observations censored.

Variable	DF	Parameter Estimate	Standard Error	Chi-Square	Pr > ChiSquare	Hazard Ratio
Percentage of Scale Loss	1	0.04	0.02	5.16	0.02	1.04
Length (mm)	1	0.02	0.01	5.69	0.02	1.02
Sex	1	-0.22	0.20	1.20	0.27	0.80

Table 1-8. Results of logistic regression analysis of variables affecting failure to pass at East River on the first attempt at antenna 3. N=212. Coefficients indicate effect on probability of failing to pass; scale refers to the error term. AIC score of intercept only model is 275.002.

	β±SE		
Variables	Model 1	Model 2	Model 3
Intercept	-1.44±.53	1.70±2.34	-1.40±4.15
p	0.0068	0.4677	0.7360
Length (mm)			0.01±.02
p			0.3692
Odds Ratio			1.01
Odds Ratio Interval			.68-1.07
Sex			-0.06±.19
p			0.7466
Odds Ratio			0.89
Odds Ratio Interval			.42-1.85
Scale Loss (Proportion)			-0.93±1.66
p			0.5767
Odds Ratio			0.4
Odds Ratio Interval			.02-10.26
Temperature °C		-0.16	-0.16±.12
p		0.468	0.17
Odds Ratio		0.85	0.85
Odds Ratio Interval		.68-1.07	.68-1.07
Nature-Like Flow (m3•sec-1)	21.45±5.51	16.04±6.71	15.42±6.70
p	<.0001	0.0168	0.0221
Odds Ratio	>999.99	>999.99	>999.99
Odds Ratio Interval	>999.99 - 999.99	18.12 - >999.99	9.25 - >999.99
AIC	258.3	258.382	263.333
ΔAIC	0	0.082	5.033
Hosmer Lemeshow GOF	15.47 df=8 p=.0506	8.16 df=7 p=.3188	11.30 df=8 p=.1850
Likliehood Ratio	p<.0001	p<.0001	p=.0006

Table 1-9. Results of logistic regression analysis of variables affecting failure to pass at East River on the second attempt at antenna 3. N=147. Coefficients indicate effect on probability of failing to pass; scale refers to the error term. AIC score of intercept only model is 207.063.

	β±SE		
Variables	Model 1	Model 2	Model3
Intercept	6.46±1.74	7.04±2.53	9.82±4.87
p	0.0002	0.0055	0.0440
Length (mm)			-0.001±.02
p			0.6114
Odds Ratio			0.99
Odds Ratio Interval			.96-1.03
Sex			0.01±.23
p			0.9568
Odds Ratio			1.03
Odds Ratio Interval			.42-2.49
Scale Loss (Proportion)			2.40±2.20
p			0.2758
Odds Ratio			11.04
Odds Ratio Interval			.15-829.88
Temperature (°C)	-0.38	-0.4	-0.45±.13
p	0.0002	0.0009	0.0008
Odds Ratio	0.68	0.67	0.64
Odds Ratio Interval	.56-.83	.53-.85	.49-.83
Nature-like Fish pass Flow (m3•sec-1)		-0.02	-0.03±.08
p		0.7549	0.7240
Odds Ratio		0.98	0.97
Odds Ratio Interval		.84-1.14	.83-1.14
AIC	192.753	194.656	199.286
ΔAIC	0	1.903	6.533
Hosmer Lemeshow GOF	8.97 df=7 p=.2550	6.10 df=8 p=.6359	7.40 df=8 p=0.4947
Likliehood Ratio	<.0001	0.0003	0.0032

Table 1-10. Results of logistic regression analysis of variables affecting failure to pass at East River antenna 8 on the first attempt at antenna 8. N=142.Coefficients indicate effect on probability of failing to pass; scale refers to error term. AIC score of intercept only model is 191.580.

	β±SE				
Variables	Model 1	Model 2	Model 3	Full Model 1	Full Model 2
Intercept	-6.98±2.62	-13.69±6.34	-6.56±2.82	-18.84±7.67	-4.10±4.80
p	0.0077	0.0309	0.0201	0.0140	0.3933
Length (mm)				0.02±.02	0.02±.002
p				0.3673	0.3202
Odds Ratio				1.02	1.02
Odds Ratio Interval				.98-1.06	0.98-1.06
Sex				-0.19±.24	-0.18± 0.24
p				0.4384	0.4492
Odds Ratio				0.69	0.7
Odds Ratio Interval				.27-1.76	0.28-1.76
Scale Loss (Proportion)				2.17±2.25	0.69±2.14
p				0.3349	0.7474
Odds Ratio				8.73	1.99
Odds Ratio Interval				.11-712.67	0.03-131.75
Temperature °C		0.18		0.18±.16	-0.08±0.11
p		0.2427		0.2382	0.4808
Odds Ratio		1.20		1.20	0.93
Odds Ratio Interval		.89-1.61		.89-1.63	0.75-1.15
Steeppass Flow (m3•sec-1)	0.95	1.41	0.89±0.36	1.51±.55	
p	0.0046	0.0068	0.0141	0.0061	
Odds Ratio	2.59	4.09	2.44	4.54	
Odds Ratio Interval	1.34-4.99	1.48-11.34	1.19-4.98	1.54-13.35	
Weir Flow (m3•sec-1)			0.05±0.13		
p			0.6998		
Odds Ratio			1.05		
Odds Ratio Interval			0.82-1.35		
Nature-like Flow (m3•sec-1)					0.17±0.12
p					0.16
Odds Ratio					1.19
Odds Ratio Interval					0.93-1.52
AIC	185.202	185.823	187.049	189.868	195.483
ΔAIC	0	0.621	1.847	4.666	10.281
Hosmer Lemeshow GOF	7.10 df=8 p=.02	2.73 df=7 p=.07	.82 df=8 p=0.03	8.62 df=8 .3770	99 df=8 p=0.434
Likliehood Ratio	0.0077	0.0309	0.014	0.0390	0.2969

Table 1-11. Results of logistic regression analysis ofvariables affecting failure to pass at East River on the second attempt at antenna 8. N=54. Coefficients indicate effect on probability of failing to pass; scale refers to the error term. AIC score of intercept only model is 191.580.

	β±SE			
Variables	Model 1	Model 2	Full Model 1	Full Model 2
Intercept	8.33±3.64	-6.34±12.87	-14.76±15.66	-13.82±15.90
p	0.0220	0.6225	0.3460	0.3850
Length (mm)			0.04±.04	0.04±0.04
p			0.3194	0.339
Odds Ratio			1.04	1.04
Odds Ratio Interval			0.96-1.13	0.96-1.13
Sex			0.20±.42	0.2±0.41
p			0.6324	0.6222
Odds Ratio			1.49	1.5
Odds Ratio Interval			0.29-7.57	0.29-7.63
Scale Loss (Proportion)			2.1±3.6	2.02±3.60
p			0.5584	0.5732
Odds Ratio			8.22	7.58
Odds Ratio Interval			.01-999.99	0.01-999.99
Temperature °C	-0.45±.20	-0.17±.30	-0.20±.31	-0.20±0.31
p	0.0223	0.5637	0.5293	0.517
Odds Ratio	0.64	0.84	0.82	0.82
Odds Ratio Interval	0.44-0.94	0.47-1.51	0.45-1.52	0.44-1.51
Steeppass Flow (m3•sec-1)		1.28±1.11	1.27±1.15	
p		0.2485	0.2693	
Odds Ratio		3.6	3.55	
Odds Ratio Interval		0.41-31.60	0.38-33.58	
Nature-like Fishway Flow (m3•sec-1)				1.20 1.16
p				0.3027
Odds Ratio				3.31
Odds Ratio Interval				0.34-32.23
AIC	72.801	73.393	77.281	77.126
ΔAIC	0	0.592	4.48	4.325
Hosmer Lemeshow GOF	5.09 df=8 p=0.7478	6.23 df=8 p=0.6211	11.68 df=9 p=0.2318	11.57 df=9 p=0.2385
Likliehood Ratio	p=0.0220	p=0.0248	p=0.0905	0.0855

Table 1-12. Results of multiple linear regression analysis of variables affecting transit time through the fish pass at East River. N=76. Coefficients (β) indicate effect of each variable on the natural log of transit time; scale refers to the error term.

	β±SE								
Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Full Model
Intercept	4.58±0.12	4.53±0.14	4.58±0.12	4.58±0.12	4.60±0.13	4.52±0.26	4.58±0.12	4.58±0.12	4.32± 0.42
p	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Length (mm)				0.08±0.13					0.08±0.35
p				0.535					0.813
Nature-Like Flow (m3•sec-1)			0.11±0.13						0.09±0.26
p			0.4128						0.7212
Temperature ℃							0.02±0.12		0.08±0.17
p							0.8818		0.6438
Time at Liberty (min)	0.38±0.12	0.41±0.13	0.41±0.13	0.39±0.13	0.39±0.13	0.38±0.13	0.38±0.13	0.38±0.13	0.45±0.14
p	0.0033	0.0021	0.0025	0.0029	0.0029	0.0034	0.0035	0.0046	0.0023
Proportion Scale Loss								0.003±0.13	0.006±0.13
p								0.9795	0.964
Sex						0.08±0.30			0.29±0.43
p						0.7912			0.501
Length*Sex					0.09±0.16				0.02±0.39
p					0.5495				0.95
Temperature*Flow		-0.11±0.11							-0.08±0.18
p		0.3101							0.6484
AIC	13.026	13.946	14.323	14.622	14.650	14.952	15.002	15.025	24.635
ΔAIC	0	0.920	1.297	1.597	1.625	1.927	1.977	1.999	11.609
Adjusted r2	0.099	0.099	0.095	0.091	0.091	0.087	0.087	0.086	0.035

Table 1-13. Failure rate at each antenna interval over all attempts at Town Brook and East River.

Location	Antennas	Failure Rate	95% Lower Confidence Limit	95% Upper Confidence Limit
Town Brook	1-2	0.02	0.00	0.05
	2-3	0.03	0.00	0.06
	3-4	0.01	0.00	0.03
	4-5	0.01	0.00	0.03
	5-6	0.00	0.00	0.00
	6-7	1.10	0.88	1.31
	7-8	1.03	0.63	1.42
East River	2-3	0.09	0.05	0.12
	3-4	0.29	0.21	0.37
	4-5	0.07	0.02	0.11
	5-6	0.02	0.00	0.04
	6-7	0.01	0.00	0.03
	7-8	0.01	0.00	0.02
	8-9	0.44	0.32	0.56
	9-10	0.06	0.01	0.11

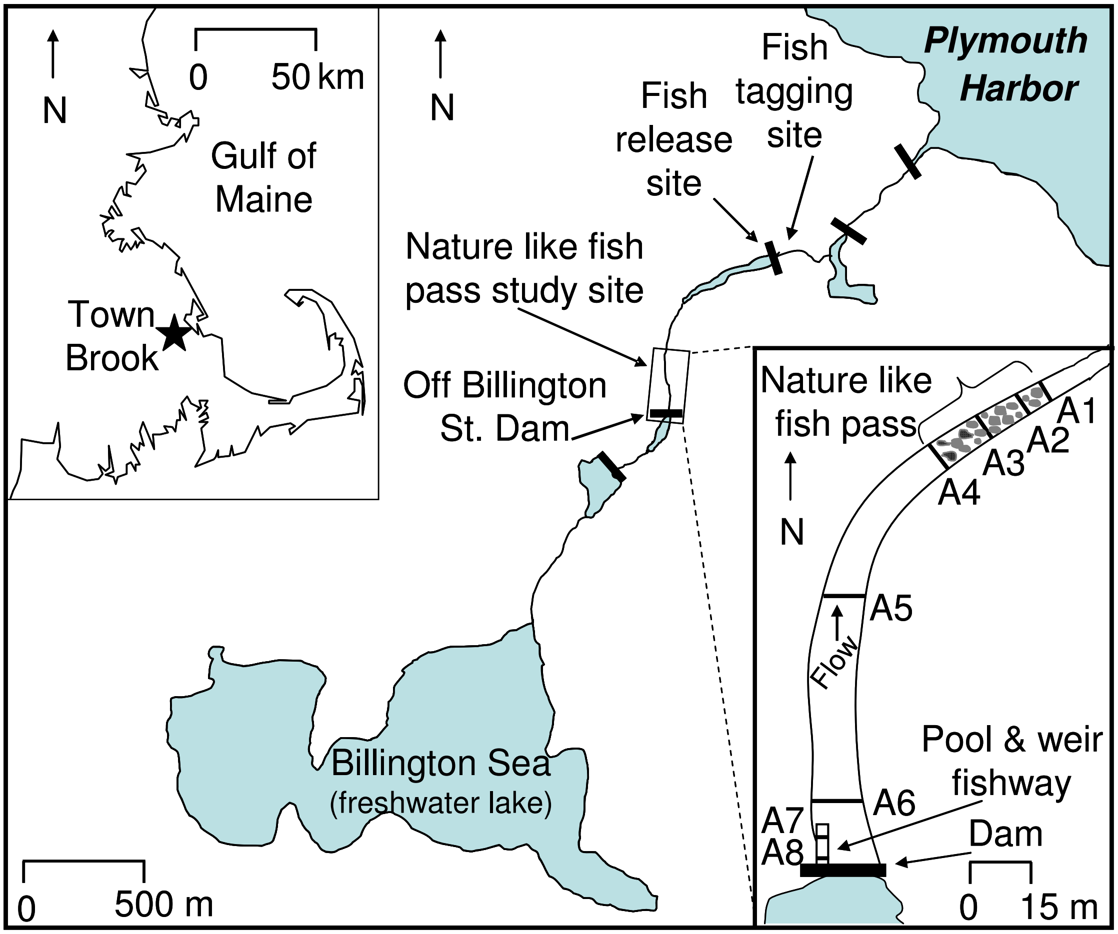


Figure 1-1. Location of Town Brook in Plymouth, Massachusetts, and the layout of PIT monitoring antennas (A1-A8) at the nature-like fish pass study site. Black rectangles indicate dams.

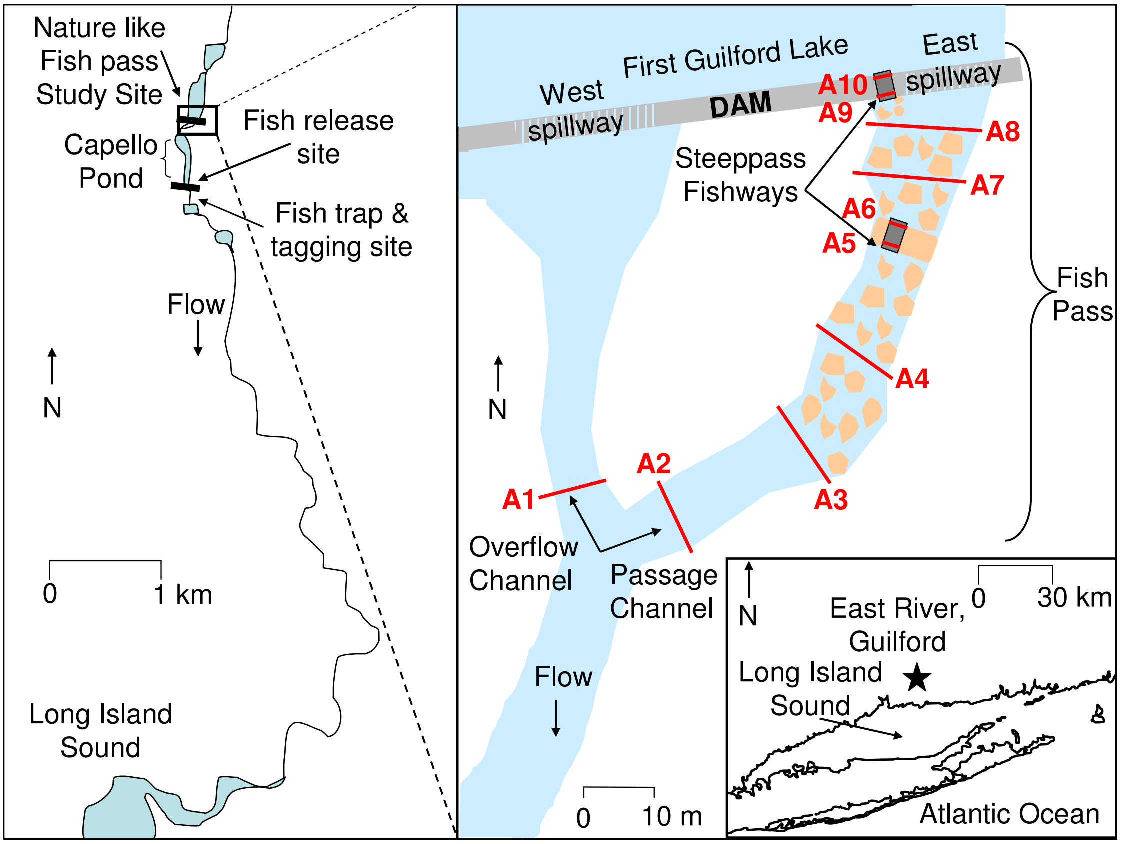


Figure 1-2. Location of East River in Guilford, Connecticut and layout of PIT monitoring antennas (A1-A10) at the nature-like fish pass study site. Black rectangles indicate dams.

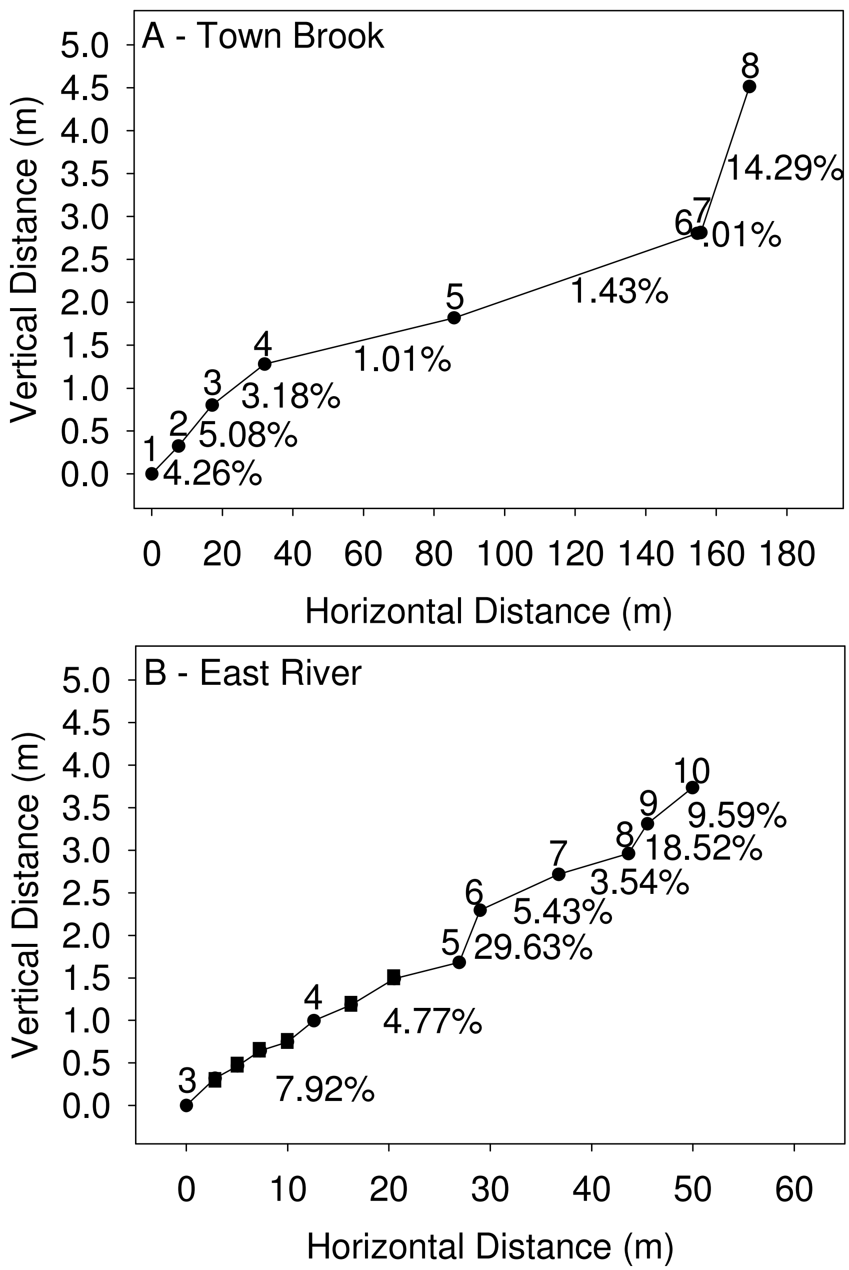


Figure 1-3. Water surface gradelines for Town Brook (A) and East River (B). Numbers above data points indicate antennas, percentages between antenna intervals indicate slopes. Squares between antenna intervals at East River indicate drops between steppools. Note different horizontal distance scales.

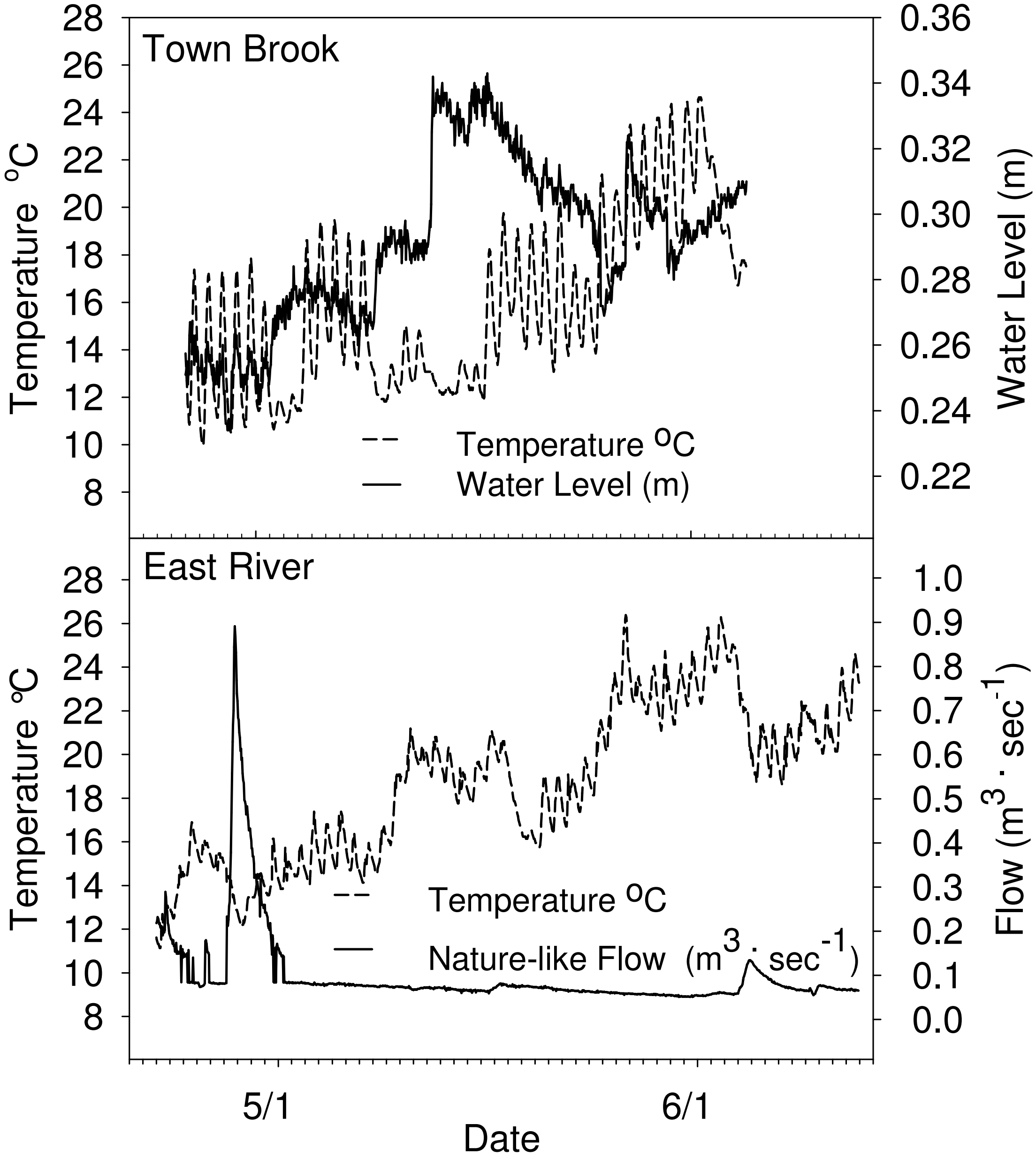


Figure 1-4. Temperature and water level (Town Brook, upper panel) or flow (East River, lower panel) during the monitoring periods.

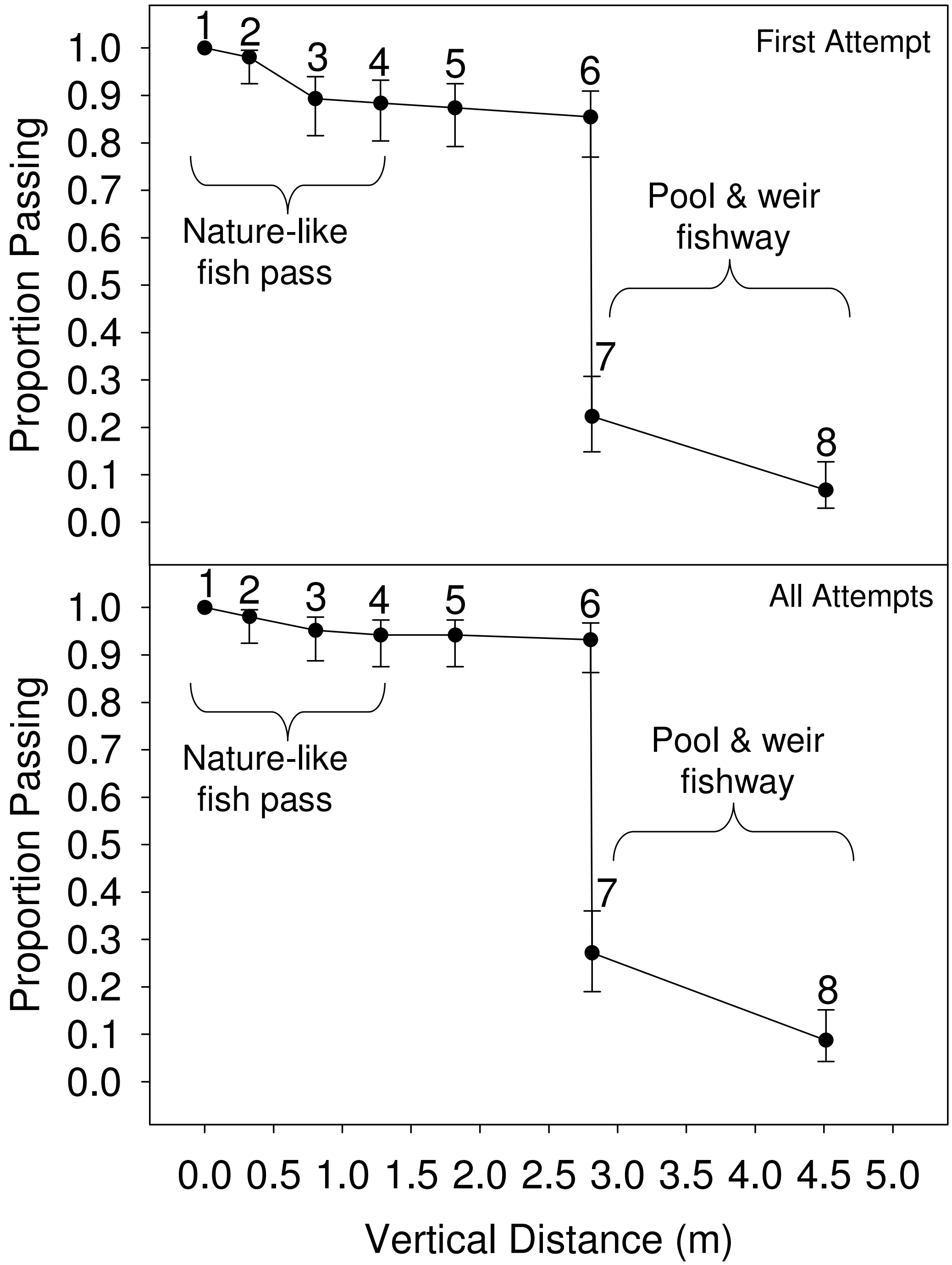


Figure 1-5. Proportion of fish ascending over vertical distance for first attempt and over all attempts through the monitored section of Town Brook. Numbers at data points indicate antennas, bars indicate 95% confidence intervals.

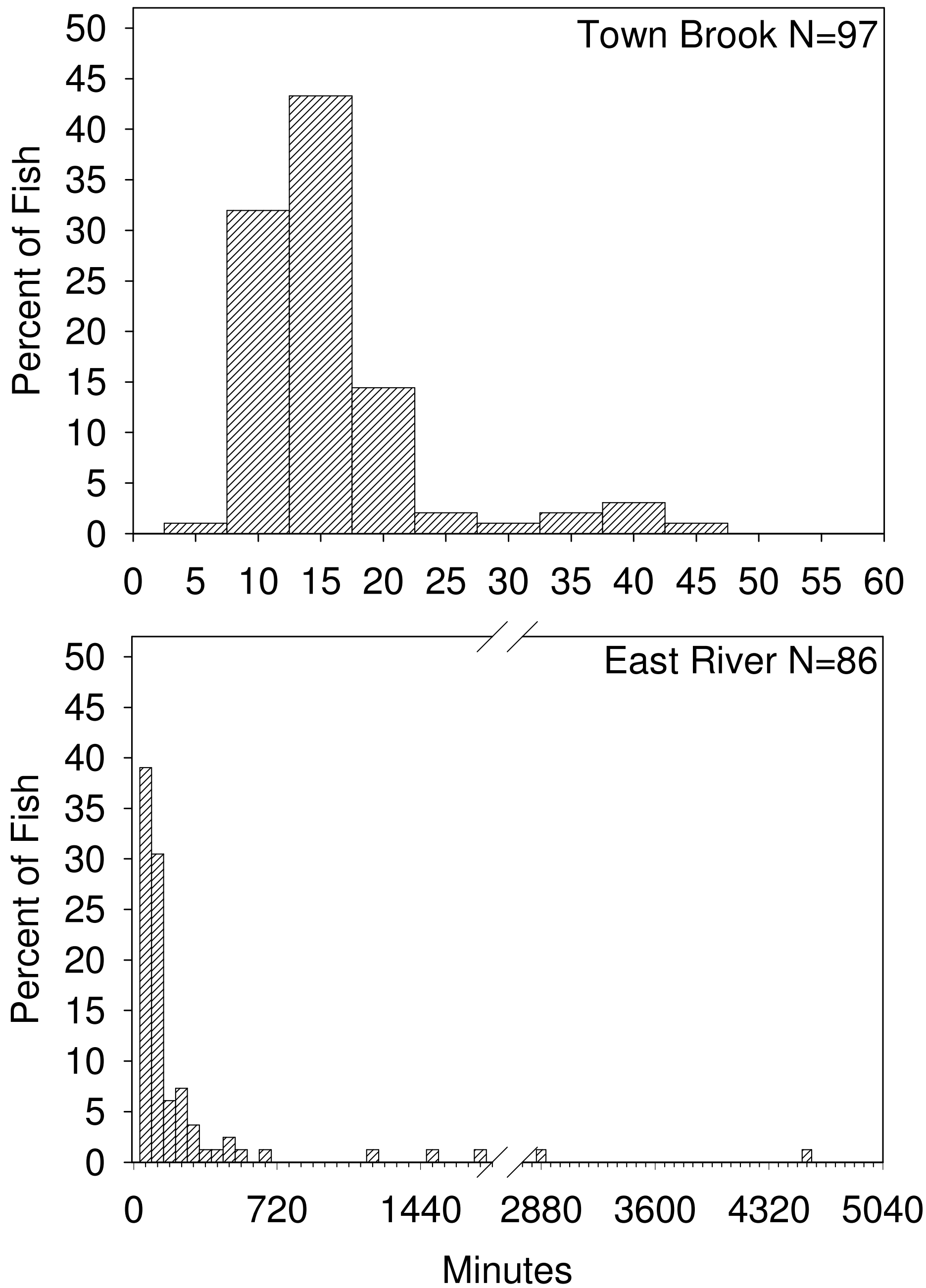


Figure 1-6. Minimum transit times through fish pass sections at Town Brook (antennas 1-4) and East River (antennas 3-10). Note difference in x-axis scales.

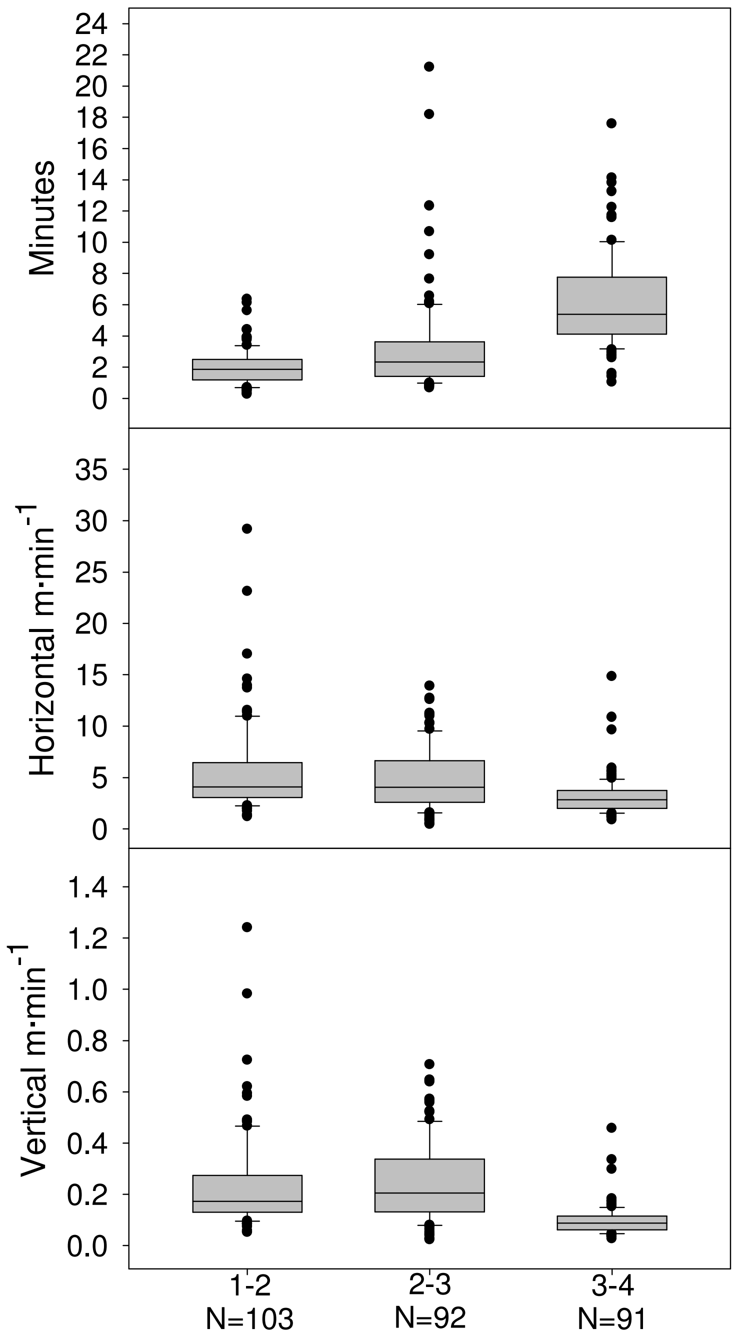


Figure 1-7. Minimum transit time, rate of horizontal travel, and rate of vertical travel in between nature-like fish pass antennas at Town Brook. Box lines are 25th, 50th, and 75th percentiles. Whiskers are 5th and 95th percentiles.

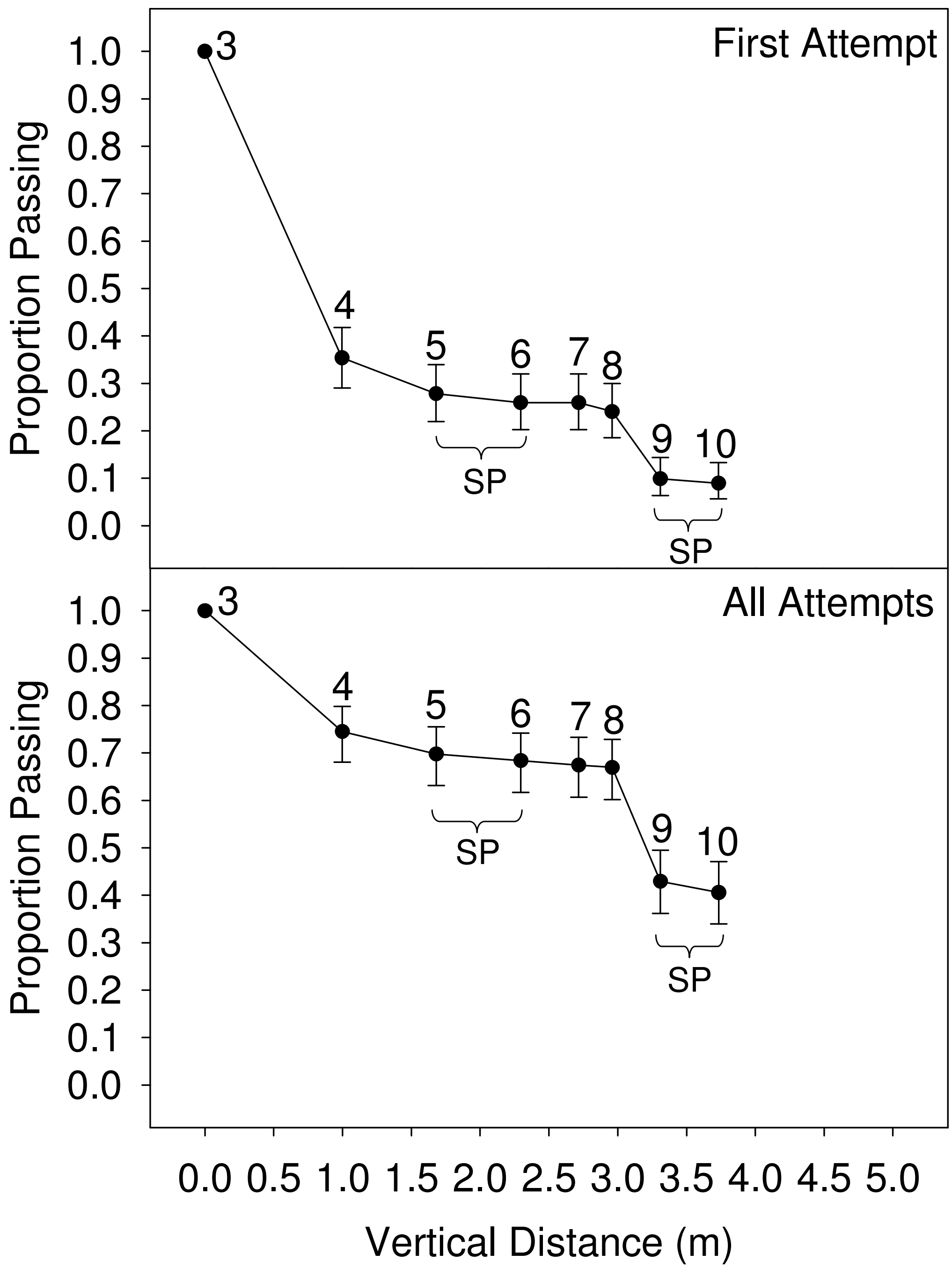


Figure 1-8. Proportion of fish ascending over vertical distance for first attempt and over all attempts through the fish pass section of East River. Numbers at data points indicate antennas, bars indicate 95% confidence intervals. SP = steeppass fishway.

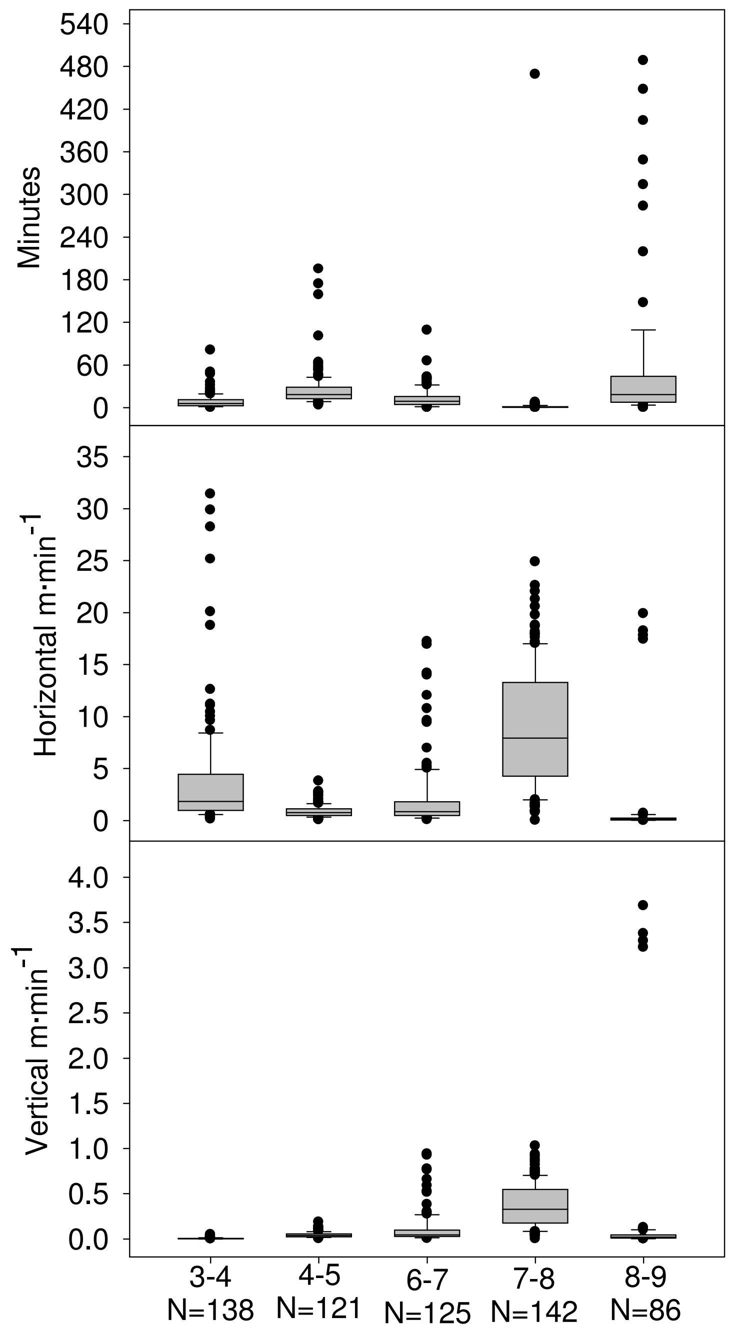


Figure 1-9. Minimum transit times, horizontal rate of travel, and vertical rate of travel in between nature-like fish pass antennas at East River. Box lines are 25th, 50th, and 75th percentiles. Whiskers are 5th and 95th percentiles. Outliers 1221.43, 1406.77 minutes omitted from antenna interval 8-9.

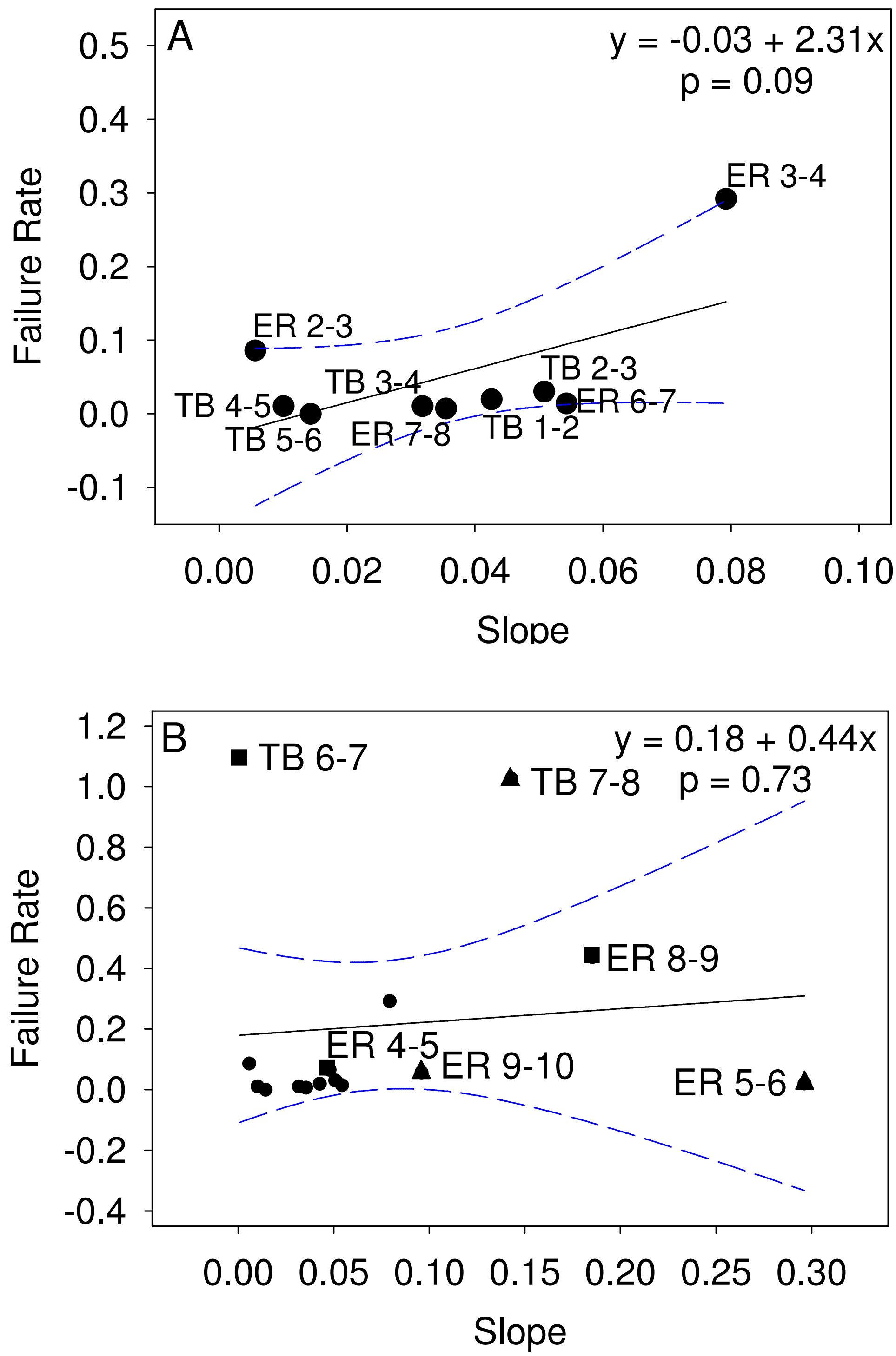


Figure 1-10. A. Linear relationship between slope and failure rate of nature-like and unmodified sections of East River (ER) and Town Brook (TB). Numbers refer to antenna interval. B. Linear relationship of slope and failure rate of sections shown in A (●), sections that transition from nature-like to technical fishway (■), and sections of technical fishway (▲).

CHAPTER 2

OBSERVATIONS OF ALEWIFE (ALOSA PSEUDOHARENGUS) MOVEMENTS BELOW BARRIERS TO PASSAGE IN TWO COASTAL STREAMS IN NEW ENGLAND.

2.1 Introduction

The damming of rivers has provided economic and safety benefits to humans for generations, but has also impacted riverine ecosystems by modifying biogeochemical cycles, changing water temperatures, and creating barriers to the movement of organisms and nutrients (Poff and Hart 2002). Dams particularly affect populations of diadromous fish by blocking access to spawning habitat. This effect is mitigated by the construction of fishways which ideally should allow fishes to pass upstream or downstream of a barrier successfully without causing stress, injury, delay, or mortality (Castro-Santos et al. 2008).

Theoretically, the amount of time it takes for a fish, or a population of fish, to swim through a fishway should be no longer than the amount of time it would have taken to ascend that section of river before a barrier was constructed. Migratory delay can be said to occur when additional time is taken to travel past the barrier. But because information about passage success through unobstructed sections before the construction of barriers is not available, migratory delay can rarely be identified definitively (Castro-Santos et al. 2008).

Migratory delay can potentially occur when a fish has difficulties identifying the entrance to a fishway, or in the case of upstream migration, when the design of a fishway creates hydraulic conditions that prevent the fish from ascending. Insufficient attraction flow or poor placement of a fishway can cause delay in locating the fishway (Clay 1995). Ignorance of the physiological capabilities or behavioral tendencies of a species can lead to ineffective fishway designs (Castro-Santos et al. 2008).

Alewife (*Alosa pseudoharengus)*, are small anadromous, iteroparous fishes that migrate seasonally in rivers along the Atlantic Coast from northeastern Newfoundland to South Carolina and frequently encounter human constructed barriers to passage while migrating (ASMFC 1999). Alewife population decline has been documented since the early 20th century and more dramatic declines have been observed more recently (Belding1920, CRASC 2004). Barriers are known to have a negative effect on populations of diadromous fish and efforts have been made to quantify the number of dams affecting passage in New England. In Massachusetts a survey of 215 coastal streams catalogued 175 fish passage structures and a total of 380 obstructions to passage, the majority of which were no longer serving the purpose for which they were built (Reback et al. 2004). In Connecticut 77 barriers to passage exist on the 43 lower tributaries of the Connecticut River (CRASC 2004).

Since it is no longer possible to evaluate migratory delay on these rivers by comparing the transit times of fish before and after the construction of these dams and fishways, one approach is to observe movements of alewife within and below the many existing fishways in order to identify a range of possible movements. Once a range of transit times and behaviors is established future evaluations can be placed in context. Knowing how alewife respond to obstacles to passage will aid in the design of more efficient attraction and conveyance systems.

Movements of alewife were observed below two dams while conducting a study on the efficacy of two nature-like fishways in New England using PIT telemetry. The goal in examining these movements is to quantify how many times and for how long alewife will attempt to ascend past a barrier or through a fishway, as well as to describe their movements both before and between attempts. The transit time from the release site to the beginning of the fishways in both rivers is also quantified and analyzed.

2.2 Methods

2.2.1 Study Areas

Town Brook is a first order stream with a watershed of ten km^2 located in Plymouth, Massachusetts (Milone and MacBroom 2001). It flows 3 km from its source at a 109 hectare freshwater lake called Billington Sea to its mouth at Plymouth Harbor in Cape Cod Bay (Figure 2-1). Migrating fish must ascend three technical fishways, travel through three small mill ponds, and ascend a 32m long full river width nature-like fish pass before reaching the 0.91m high “Off Billington St.” dam at river kilometer 1.8.

A 14 m long pool and weir fishway with a slope of 1:7 is located on the northern side of the dam. Water flows both through this fishway and the spillway of the dam.

East River is a second order stream with a watershed of 51.91 km^2 located in Guilford, Connecticut. Its source is the first order Iron Stream which originates in the town of Rockwell and flows into three impounded ponds called Upper Lake, Middle Lake, and Lower Lake, collectively known as "Guilford Lakes". East River then flows 10 km from the spillway of the Lower Guilford Lake dam to the mouth at Guilford Harbor in Long Island Sound (Figure 2-2). The Lower Guilford Lake Dam is divided into two concrete structures with an earthen impoundment in between. The western section is 3.35m high with an elevation head of 3.66m. The eastern section is 1.32m high with an elevation head of .61m. The eastern channel is 60 m long and contains a 48 m long fish pass with a slope of 1:14 made of two 3.05m long, 57.15cm wide, 68.6cm deep steeppass fishways and 13 nature-like steppools. Migrating fish must pass through two ponds and one technical (Denil) fishway before reaching the entrances to the Lower Guilford Lake dam channels at river kilometer 9.

Fish tagging methods and PIT telemetry and temperature and water level monitoring methods are described in Chapter 1.

2.2.2 Data Analysis

Detections of individual fish were grouped into "attempts" in order to quantify multiple efforts to ascend past the barrier as well as determine on what attempt the fish successfully ascended past the barrier. At Town Brook the number of attempts quantifies how many times a fish tried to locate an avenue to pass beyond the Off Billington St. dam. An attempt was assigned when a fish moved from downstream of the Off Billington St. dam at antenna 5 to directly below the dam at antenna 6.

At East River the number of attempts quantifies how many times a fish tried to ascend the fish pass in order to ascend past the First Guilford Lake dam. An attempt was assigned if a fish moved from the staging area below the fish pass (detected at antenna 2) to the entrance of the fish pass at antenna 3. For both sites the total number of attempts made, and on what attempt the fish successfully passed are reported.

At both sites the time elapsed between attempts one and two was calculated by subtracting the time of the last detection of attempt one from the first detection of attempt two. At both sites the movements of fish during the time between attempts are reported. At East River the number of times a fish moved back and forth between antennas 1 and 2 during the time between attempts one and two was quantified. A "switch" is defined as a movement from either antenna 2 to 1, or antenna 1 to 2.

Passage efficiency was quantified as the percentage of fish that entered the fish pass (East River) or pool and weir fishway (Town Brook) that successfully ascended it. Fish that ascended the fish pass or fishway and were detected at the uppermost antenna are assumed to have reached the pond upstream and are referred to as "successful" fish. Fish that attempted to ascend the fish pass or fishway but did not reach the upper most antennas are referred to as "unsuccessful".

At Town Brook during the migration season hundreds of fish were observed swimming directly below the Off Billington Dam, upstream of the entrance to the pool and weir fishway. Quantifying the amount of time between the first detection at antenna 6 and the last detection at antenna 6 for unsuccessful fish on the first attempt can give some indication as to how long fish were delayed at this location. For successful fish the time elapsed between being first detected at antenna 6 and last detected at antenna 8 was also quantified.

When fish arrive at the upstream portion of Capello Pond, they encounter a fork in the river and must make a decision to swim left towards the overflow channel, or right into the passage channel. These movements were monitored by antennas placed at the entrances of the overflow channel (antenna 1) and the passage channel (antenna 2). Two observations were made of fish spending time in this area. First, the amount of time the fish spent at the fork before making an attempt at the fish pass was quantified by subtracting the time of the first detection at antenna 1 or antenna 2 from the time of the first detection at antenna 3. Second, the number of times a fish "switched" back and forth between antennas 1 and 2 before deciding to ascend to antenna 3 was counted.

In order to determine if a difference existed in the amount of time successful fish and unsuccessful fish spent trying to ascend past the barriers, a Kruskal-Wallis test was used to look for a difference in median residence times. At Town Brook the amount of time between encountering the Off Billington dam and either successfully ascending past it, or leaving the area for the last time was quantified. For unsuccessful fish this "residence time" is defined as the time elapsed between the first detection at antenna 6 and the last downstream detection at antenna 5. For successful fish it is defined as the amount of time elapsed between the first detection at antenna 6 and the last upstream detection at antenna 8. At East River the amount of time between encountering the fish pass and either successfully ascending it or leaving the area was quantified. Residence time for unsuccessful fish is defined as the time elapsed between the first detection at antenna 3 and the last detection in the PIT monitoring system. For successful fish it is defined as time elapsed between the first detection at antenna 3 and the last upstream detection at antenna 10.

Passage time through the section of river inbetween the release site and the first antenna was quantified at both Town Brook and East River. At Town Brook this section is 914 m long, begins at the base of the Newfield St. pond, and ends at the entrance to the nature-like fish pass at antenna 1 (Figure 2-1). The transit time through this section was quantified by subtracting the time of tagging from the first detection at antenna 1. At East River this section is 762 meters long, begins at the base of Capello Pond, and ends at the entrance of the two dam channels (Figure 2-2). The transit time through this section was quantified by subtracting the time of tagging from the first detection at either antenna 1 or 2.

Event time-analysis was employed to examine the relationship between transit time through these sections and the constant variables of sex, length, and percentage of scale loss, and the time-varying covariates of daylight, temperature, and water level (Castro-Santos and Haro 2003). At Town Brook the interactions between length and sex, length and scale loss, and temperature and daylight were also included in some models. At East River the interactions between length and sex, length and scale loss, water level and temperature, and water level and daylight were included in some models.

For each site a set of candidate models were chosen consisting of one to ten predictor variables for East River and one to nine variables for Town Brook. For each site the model with the lowest Aikaike Information Criterion (AIC) score was designated as the "top model" and all models with a difference in scores (ΔAIC) less than 2 are presented (Burnham and Anderson 1998).

2.3 Results

2.3.1 Town Brook

Alewife made between one and five attempts to ascend past the Off Billington St. dam at Town Brook (Figure 2-3). Out of 103 fish, 69 (67.37%) fish made only one attempt. Ninety six fish were detected at antenna 6 and were considered available to pass. Twenty eight fish entered the fishway at antenna 7. Six fish successfully completed the fishway giving it a percent passage of 21.43%. Of the six successful fish, three were successful on first attempt, two fish on their second attempt, and one on the third attempt (Figure 2-3).

Of the 32 fish that made multiple attempts, the amount of time that elapsed between their first and second attempts ranged from 21.6 minutes to 19 days (Figure 2-4). Out of those 32 fish almost half of them (46.88%) returned to the obstruction for a second attempt within 6 hours. In between attempts one and two, fifteen fish traveled downstream through the nature-like fish pass (180m from antenna 6) and perhaps further before ascending again. The other 19 traveled downstream as far as antenna 4 (69 m) or 5 (122 m) before re-ascending.

For both successful and unsuccessful fish the time spent directly below the dam at antenna 6 on the first attempt ranged from 2.48 seconds to 10.08 days. Twenty nine fish (31.18%) spent under an hour and 51 fish (54.83%) spent between 1 and 48 hours below the dam (Figure 2-5).

The residence times of unsuccessful fish (N=87) ranged from 6.9 minutes to 26 days with a median of 22.9 hours. The residence times of successful fish (N=6) ranged from 3.96 minutes to 2.76 days with a median of 21.08 hours. No significant difference exists between the medians of the two groups (Chi-square=0.94 df=1 p=0.33).

The transit times of fish through the section between the release site and first antenna ranged from 35.4 minutes to 29.75 days with a median 9.87 hours (Figure 2-8). Temperatures for this period ranged from 11.3 to 22.3 °C and water level from 23.7 to 33.6 centimeters. The Cox's proportional hazards regression top model indicates that all measured variables influenced passage rate, but only length, percent scale loss, water level, and the interaction between scale loss and length at a significant level (Table 2-1). A 20% decrease in passage rate is associated with a 1 cm increase in water level. A 4.5% decrease in passage rate is associated with a millimeter increase in size, and a 75.9% decrease in passage rate is associated with a one percent increase in scale loss.

2.3.2 East River

At East River fish made between one and twelve attempts to ascend the fish pass. Out of the 212 fish that made an attempt to ascend the fishway, 44 fish (20.8%)

made one attempt, and 49 fish (23.1%) made two attempts (Figure 2-6). Of those 212 fish, 86 (40.6%) successfully ascended the passage corridor. Of those 86 successful fish, 14 (16.28%) were successful on the first attempt and 21 fish (24.42%) were successful on the second attempt (Figure 2-6).

Of the 168 fish that made a second attempt the time in between attempts one and two ranged from 3.17 minutes to 18 days with a median of 3.97 hours (Figure 2-7). Of those 168 fish, 48 (28.57%) made another attempt within one hour and 127 (75.6%) made another attempt within 24 hours.

Between attempts one and two**,** 117 fish made between 2 and 24 switches between antennas 1 and 2 (Table 2-2). Fifty one fish (30.36%) did not explore the overflow channel. Ninety seven (57.74%) fish left the staging area for a period ranging from one hour to 17 days (median 10 hours) in between detections at antenna 1 or 2.

The residence times of unsuccessful fish (N=126) ranged from 1.96 minutes to 23.74 days with a median of 1.74 days. Residence times of successful fish (N=86) ranged from 19.6 minutes to 24 days with a median of 9.59 days. No significant difference exists between the medians of the two groups (Chi-square=2.29, df=1 p=0.13).

The amount of time elapsed from when the fish first encounter the staging area to when they attempt to ascend the fish pass ranged from 39.7 seconds to 18 days with a median of 1.17 hours (Figure 2-8). One hundred and ten fish (47.17%) spent less than an hour at the fork before making an attempt. One hundred and eighty six fish (79.72%) spent under 24 hours before making an attempt.

Almost half (45.85%) of the fish that made an attempt to ascend the fish pass either identified the passage corridor on the first try or began at the overflow channel and then proceeded to the passage channel with no further movements between the lower antennas (Table 2-3). The remaining 111 fish (54.15%) made between 3 and 22 switches between antennas 1 and 2 before being detected at antenna 3. The residence times of the 54 fish that identified the passage channel on the first try ranged from 36 seconds to 10 days with a median time of 6 minutes. The residence times of the 40 fish that first travelled to the overflow channel and then proceeded to the passage channel ranged from 4 minutes to 15 days with a median time of 24 minutes.

Passage times through the unobstructed section ranged from 3.14 hours to 12.08 days with a median of 21.92 hours (Figure 2-10). Temperatures during this period ranged from 12.2 to 20.5 °C and water level ranged from 18.5 to 35.9 centimeters. The Cox's proportional hazards regression top model contained the variables scale loss, daylight, temperature, water level, and the interaction of water level and temperature. A 287.3% increase in passage rate through the unobstructed section is associated with a 1°C increase in temperature, and a 95.4% increase in passage rate with a 1 cm increase in water level. A 1% increase in scale loss is associated with a 5.6% decrease in passage rate.

2.4 Discussion

These observations indicate that alewife will make multiple attempts to ascend past barriers and that a wide range of movements exist in response to these barriers. Some of the potential causes of variation in passage time of successful and unsuccessful salmonids through the Columbia and Snake River dams outlined by Caudill et al. (2006) could be applicable to alewife as well. The variation observed at Town Brook and East River in number of attempts made, time elapsed between attempts, and movement between attempts could be influenced by environmental conditions during the migration, genetic differences among individuals, or the physiological condition of individuals. Interactions among these factors are possible as well.

Alewife respond to flow and temperature when entering natal rivers as adults and leaving ponds as juveniles, so it is likely that environmental conditions would also affect their behavior at barriers (Loesch 1987). Before humans began changing the course of rivers, barriers to migration in New England would have been created under certain flow conditions by beaver dams or fallen trees and leaves. Maintaining station below a barrier while waiting for higher or lower flows may have been a successful strategy for reaching upstream spawning areas. Fish with long residence times below the

Off Billington St. Dam may have been following this strategy. The results of the analysis of passage rate through the unobstructed sections indicate that fish were being influenced by water level and temperature in these rivers.

The variation in number of attempts, time elapsed between attempts, and movement between attempts could be evidence of multiple spawning strategies within the two populations. Spawning habitat exists downstream of both barriers and alewife are iteroparous batch spawners. Variation in movements could be evidence of multiple bet hedging strategies, mechanisms to maintain a strong population in response to variable environmental conditions. The unsuccessful fish that attempted to ascend only once or twice, or the fish with small residence times may have been following a theoretical, "quick in quick out" strategy. These fish may have chosen to spawn in a suboptimal site with easy access in order to retain enough energy for the return migration downstream. But a possible risk of this strategy is that rain events or extreme temperature conditions may render that one spawning area unsuitable for egg survival or larval or juvenile development.

Another theoretical strategy is to spawn in multiple sites along the river in order to spread out the risk of egg or juvenile mortality due to unfavorable environmental conditions. The fish that made multiple attempts and took long periods of time inbetween attempts may have been spawning in Capello and Newfield St. ponds before returning to the barriers to try to ascend again. A potential risk associated with this strategy is that spending more time in the river increases the chances of energy depletion or predation. Although multiple spawning strategies could explain the variation in movements observed, they will remain theoretical until a large scale study analyzing the effects of age, size, sex, and condition on spawning activity across several rivers can be carried out.

Alewife in poor physiological condition may not have the energy to make multiple attempts to ascend a fishway or to remain below an obstruction for a long period of time. Percentage of scale loss was used as an indicator of fish condition for this study and increase in scale loss was associated with faster passage rate through the unobstructed sections at both sites. Fish in poor condition might spend as little time in the river as possible in order to migrate back to the ocean faster.

At most sites it is no longer possible to discover the amount of time fishes took to ascend a section of river before a dam was constructed. Dams were often built at sites of natural falls or rapids where sudden drops in elevation exisited already. It is important to consider that in an unmodified river a proportion of the population might have had long residence times or made multiple attempts to ascend sections. But in order to evaluate passage and attempt to identify migratory delay in the absence of pre-dammed condition data, one approach is to assume that an ideal fishway would allow fishes to enter and proceed through the fishway with no delay (Castro-Santos et al. (2008).

Identifying migratory delay due to poor fishway design or placement is important in the context of managing fish populations for sustainability. Given that alewife populations have been declining, every human activity that could potentially affect the chances of fish returning to spawn in subsequent years needs to be explored. Energy expended trying to ascend an inefficient fishway could reduce energy available for spawning or the return migration to the ocean. The longer a fish remains in the river or crowded with other fish below an obstruction, the greater the chances of being predated from above or below become. The outlier values in the distribution of time spent below Off Billington Dam could be evidence of predation. The alewife that spent 2.48 seconds below the dam and was never detected again could have been eaten by a heron or racoon. The alewife that spent multiple days below the dam could potentially have been in the stomach of a piscivorous fish that then chose to remain at the dam where abundant food was available.

Identifying migratory delay by comparing present day passage behavior with pre-impact conditions is not possible for most rivers, so other methods of identifying migratory delay should be explored. Monitoring the movements of alewife through entire river corridors, including tributaries containing suitable spawning habitat, could help to place residence times at fishways and dams in context and begin to answer some questions about spawning strategies. Comparing transit times of alewife through rivers of similar size with and without fishways is another possible method. Hundreds of fishways exist in New England and opportunities to explore their effects on migratory transit time are plentiful.

Table 2-1. Results from Cox's proportional hazards regression of effects of constant and time varying covariates on passage rate through an unobstructed section of Town Brook. N=103.

	β±SE		
Variable	Full Model	Model 2	Model 3
Length (mm)	-0.046±0.02		
p	0.0237		
Sex	-5.576±5.15		
p	0.2786		
Scale Loss (%)	-1.425±0.54		
p	0.0082		
DayNight	3.229±7.24	-3.780±0.71	2.865±7.16
p	0.655	<.0001	0.6893
Water Level (cm)	-0.224±0.05	-0.215±0.05	-0.214±0.05
p	<.0001	<.0001	<.0001
Temperature °C	0.062±0.05	0.031±0.05	0.036±0.05
p	0.2284	0.5149	0.4473
LengthXSex	0.026±0.02		
p	0.2294		
TemperatureXDayNigh	-0.519±0.56		-0.495±0.56
p	0.3555		0.3736
ScaleLossXLength	0.006±.002		
p	0.008		
AIC	1148.654	1151.823	1152.627
ΔAIC	0	3.169	3.973

Table 2-2. Number of switches made by alewife at antennas 1 and 2 between attempts one and two at East River.

Number of Switches	Number of Fish	Percent of Fish
0	51	30.36
2	51	30.36
4	27	16.07
6	13	7.74
8	6	3.57
10	9	5.36
12	3	1.79
14	4	2.38
16	1	0.60
18	2	1.19
20	0	0.00
22	0	0.00
24	1	0.60

Table 2-3.Number of switches at antennas 1 and 2 made by alewife before attempting to ascend fish pass and amount of time spent in vicinity of fork at East River.

Number of Switches	Number of Fish	Percent of Fish	Minimum Time at Fork	Median Time at Fork	Maximum Time at Fork (Hours)
0	54	26.34	0.66 min	6.27 min	251.43
1	40	19.51	4.29 min	24.74 min	371.86
2	30	14.63	5.55 min	48.87 min	413.40
3	19	9.27	13.60 min	12.14 h	301.94
4	17	8.29	20.28 min	8.78 h	112.33
5	8	3.90	34.29 min	4.60 h	140.84
6	9	4.39	1.88 h	11.90 h	362.27
7	6	2.93	3.83 h	15.76 h	68.24
8	2	0.98	6.31 h		88.02
9	3	1.46	1.97 h	17.70 h	42.62
10	3	1.46	11.69 h	95.57 h	22.26
11	2	0.98	24.87 h		336.98
12	3	1.46	7.53 h	17.89 h	199.33
13	1	0.49			12.47
14	2	0.98	2.81 h		10.24
15	1	0.49			137.25
16	0	0.00			
17	0	0.00			
18	2	0.98	17.84 h		395.44
19	0	0.00			
20	1	0.49			17.35
21	1	0.49			360.20
22	1	0.49			166.68

Table 2-4. Results from Cox's proportional hazards regression of effects of constant and time varying covariates on passage rate through an unobstructed section of East River. N=205.

	β±SE		
Variable	Model 1	Model 2	Full Model
Length (mm)			0.013±0.013
p			0.2974
Sex			4.046±3.437
p			0.2392
Scale Loss (%)	-0.058±0.019	-0.061±0.019	0.286±0.304
p	0.0018	0.0012	0.3464
DayNight	-0.505±0.297		-0.806±1.629
p	0.0889		0.6206
Water Level (cm)	0.669±0.325	0.778±0.306	0.640±0.516
p	0.0393	0.011	0.2147
Temperature °C	1.354±0.545	1.540±0.513	1.294±0.817
p	0.013	0.0027	0.1132
LengthXSex			-0.018±0.015
p			0.2312
LengthXScaleLoss			-0.001±0.001
p			0.2688
TemperatureXWater Level	-0.055±0.022	-0.062± 0.021	-0.054±0.033
p	0.0139	0.0035	0.1044
DayNightXWater Level			0.008±0.071
p			0.9117
AIC	1684.885	1685.796	1691.072
ΔAIC	0	0.911	6.187

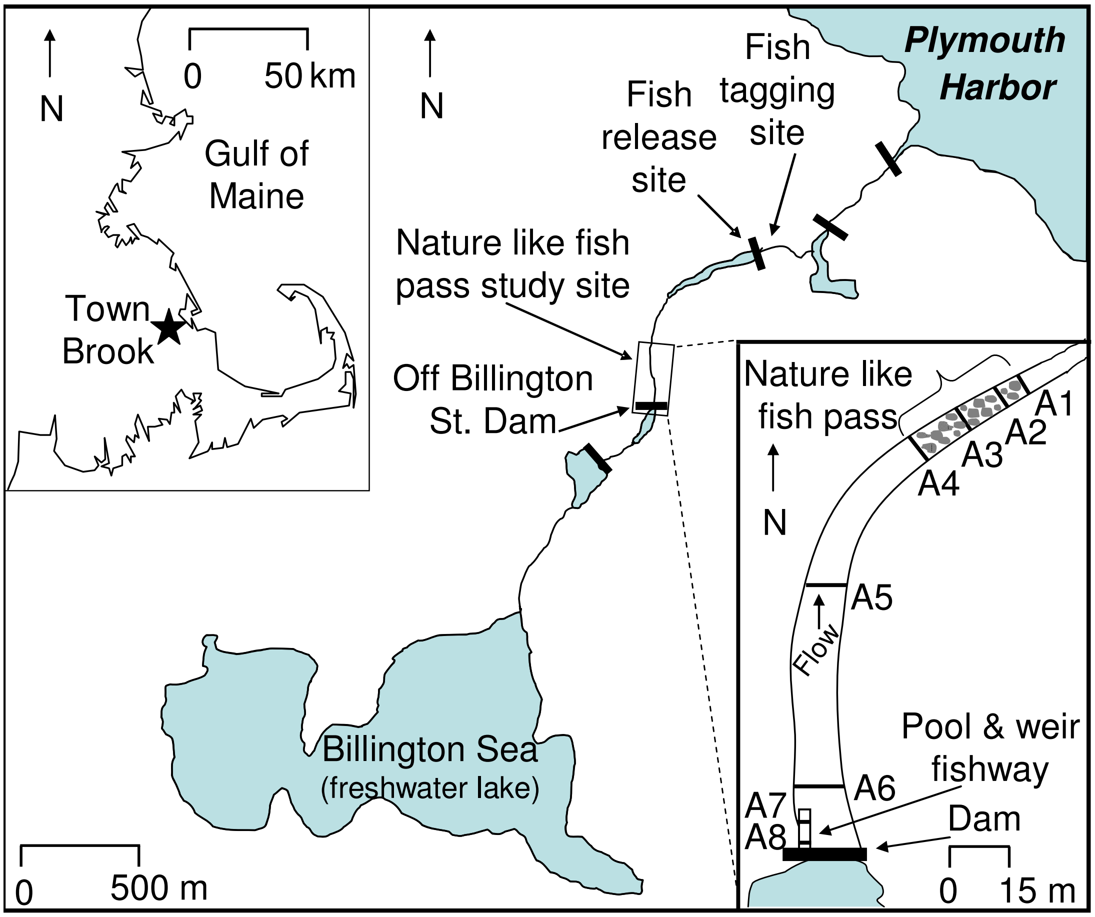


Figure 2-1. Location of Town Brook in Plymouth, Massachusetts and the layout of PIT monitoring antennas (A1-A8) at the study site. Black rectangles indicate dams.

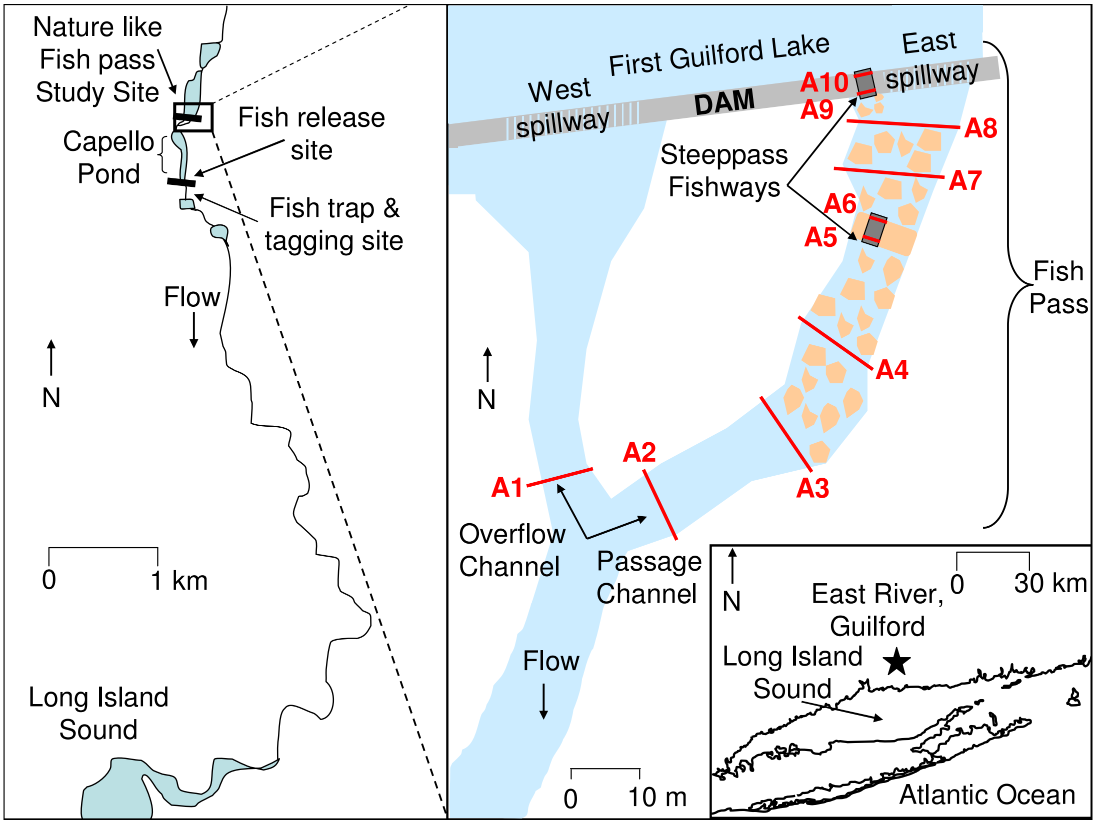


Figure 2-2. Location of East River in Guilford, Connecticut and layout of PIT monitoring antennas (A1-A10) at study site. Black rectangles indicate dams.

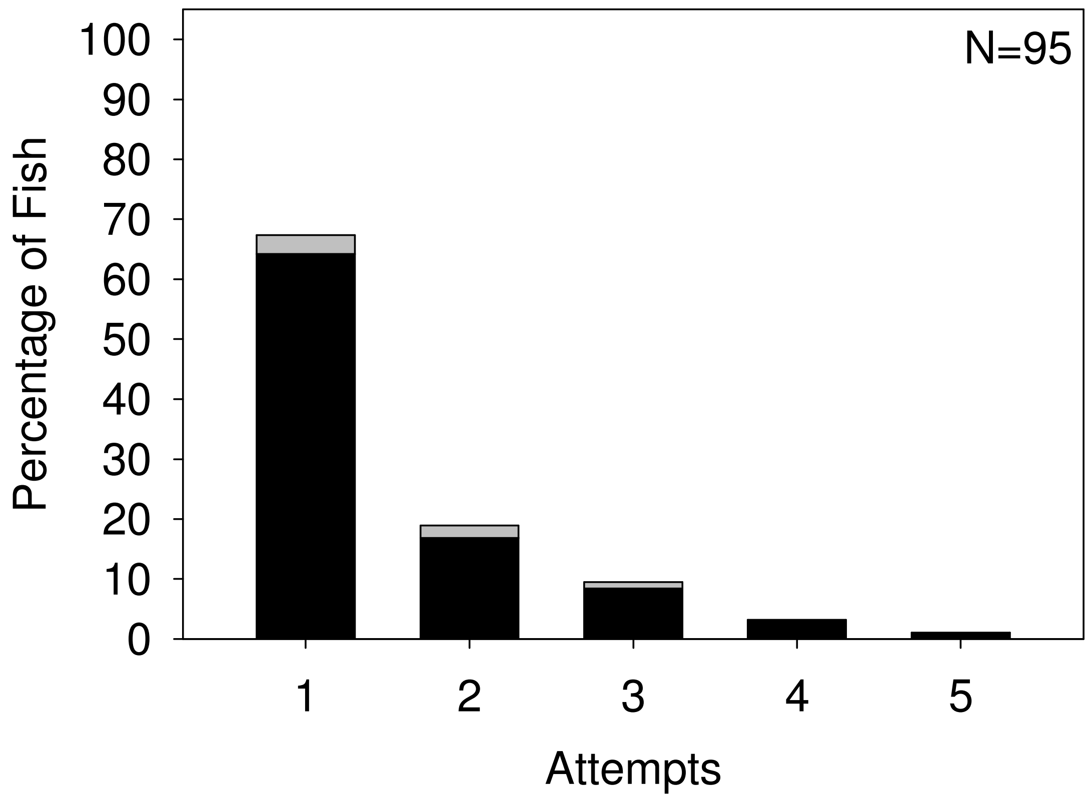


Figure 2-3. Number of attempts made to ascend past Off Billington Dam at Town Brook. Black portion of bar indicates percentage of fish that made unsuccessful attempts, grey portion indicates percentage of fish that made successful attempts.

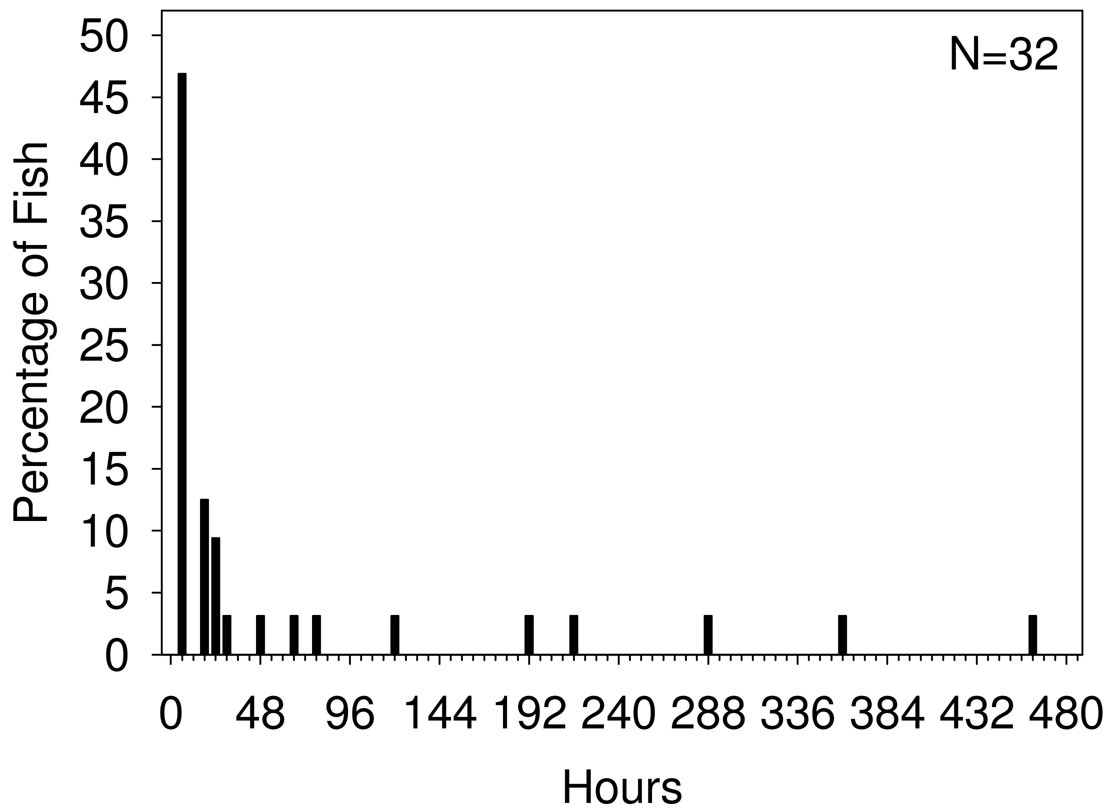


Figure 2-4. Distribution of time elapsed between end of attempt one and beginning of attempt two at Town Brook.

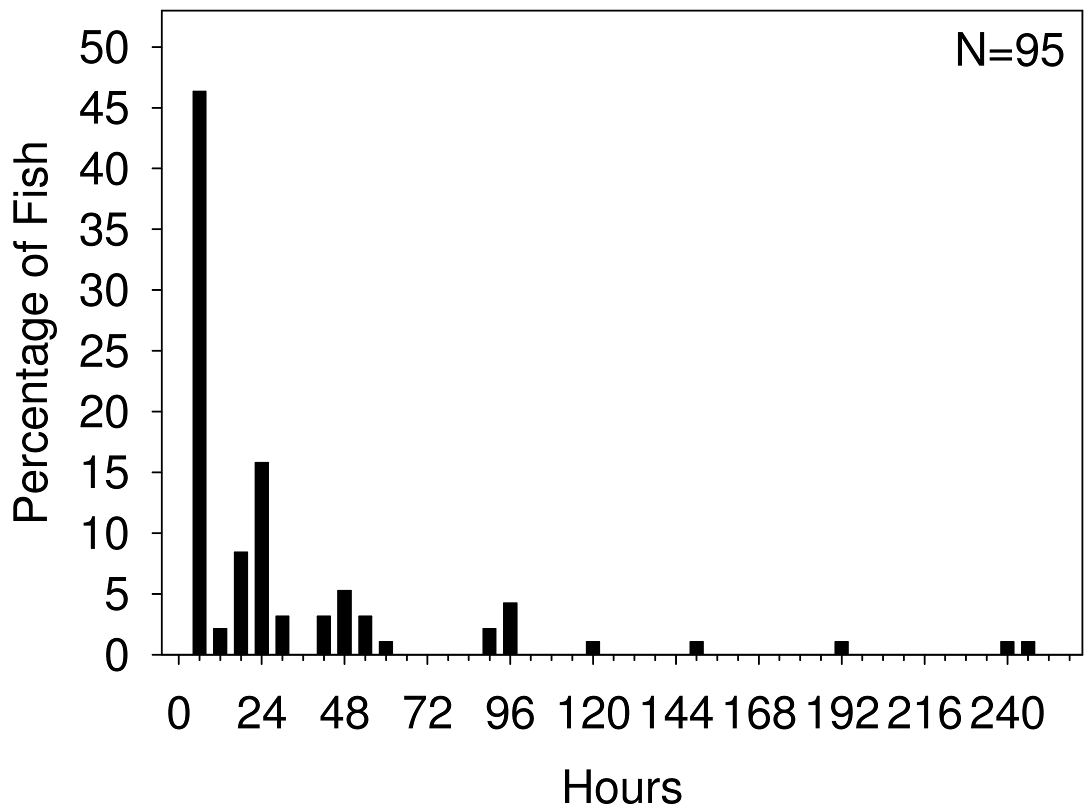


Figure 2-5. Distribution of hours spent below the Off Billinton St. Dam at Town Brook on the first attempt.

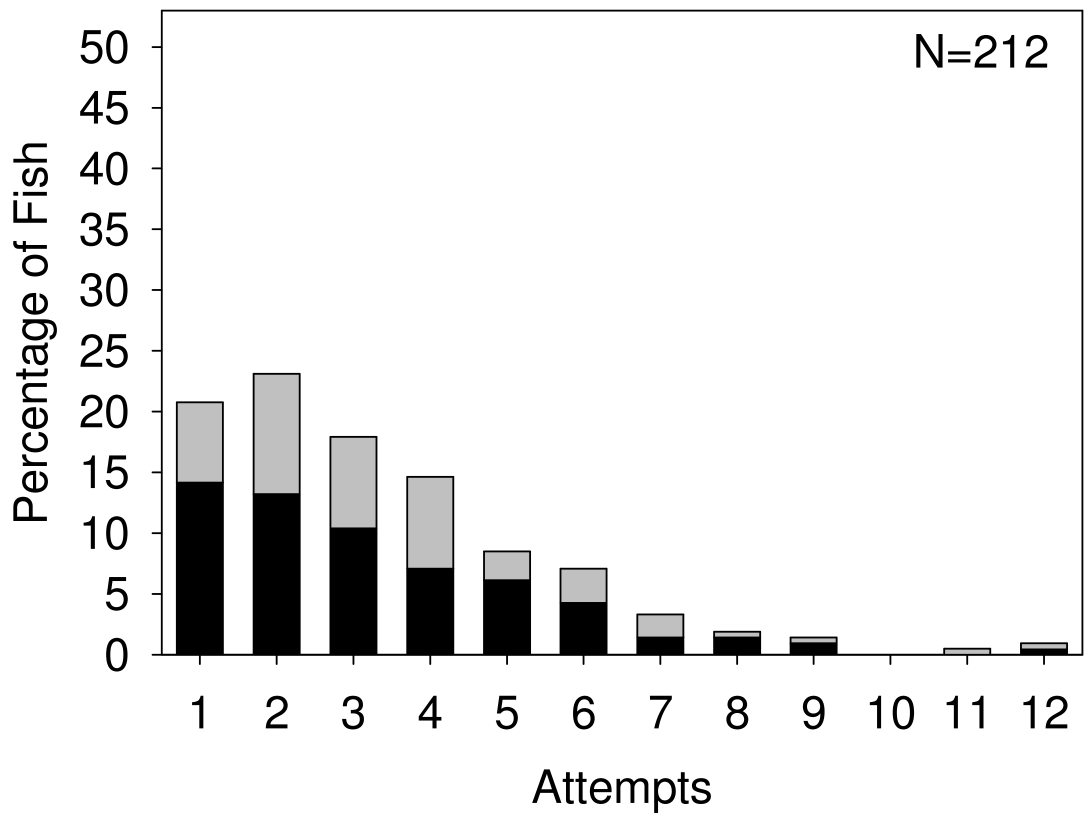


Figure 2-6. Number of attempts made to ascend fish pass at East River. Black portion of bar indicates percentage of fish that were unsuccessful on that particular attempt, grey portion indicates percentage of fish that successfully ascended the fishway on that particular attempt.

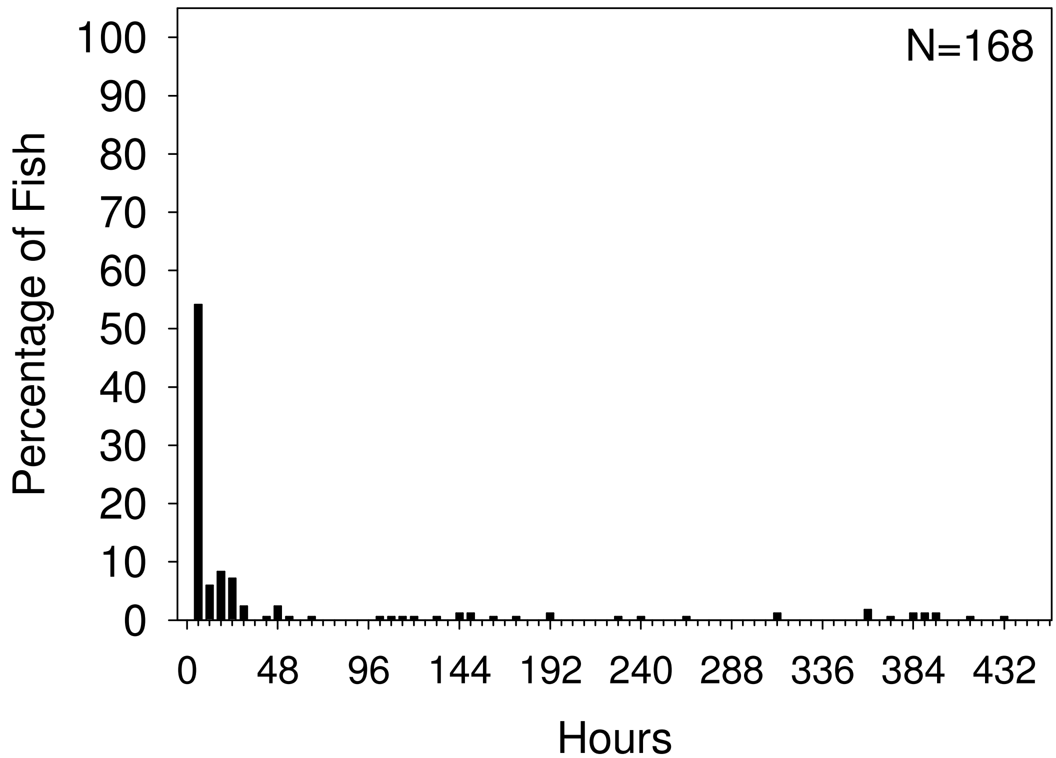


Figure 2-7. Distribution of time elapsed between attempts 1 and 2 at East River.

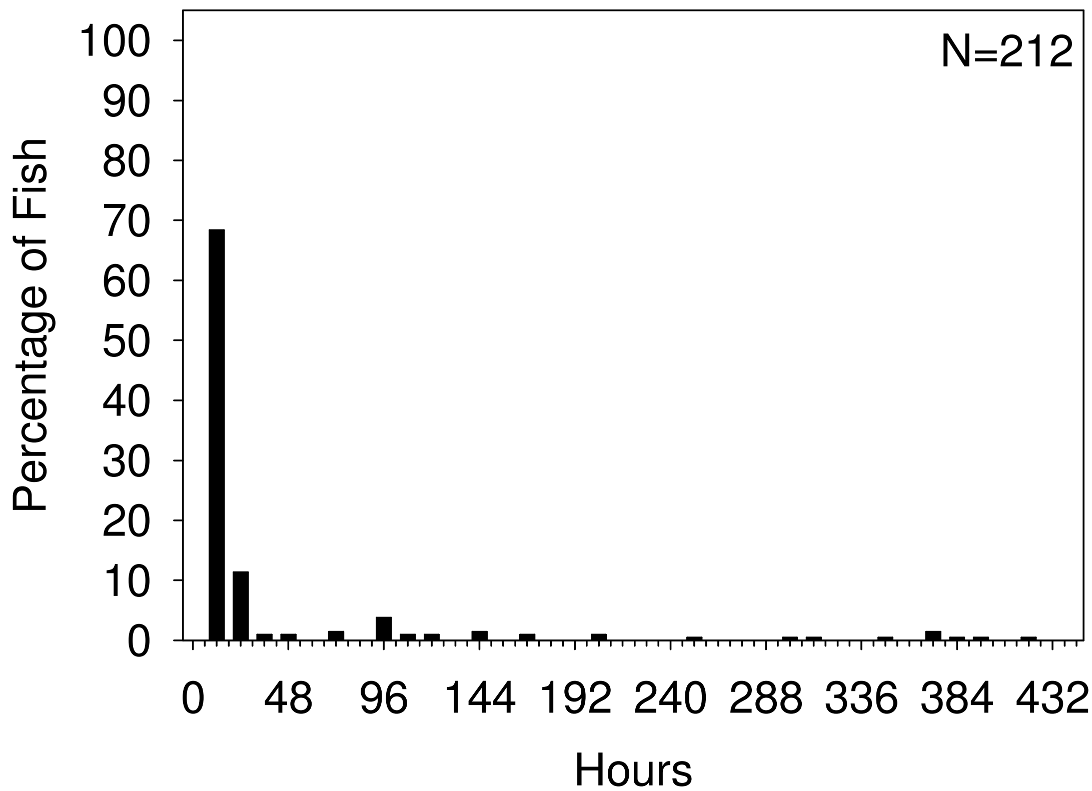


Figure 2-8. Distribution of hours spent below First Guilford Lake Dam at the fork monitored by antennas 1 and 2 at East River before making an attempt to ascend the fish pass.

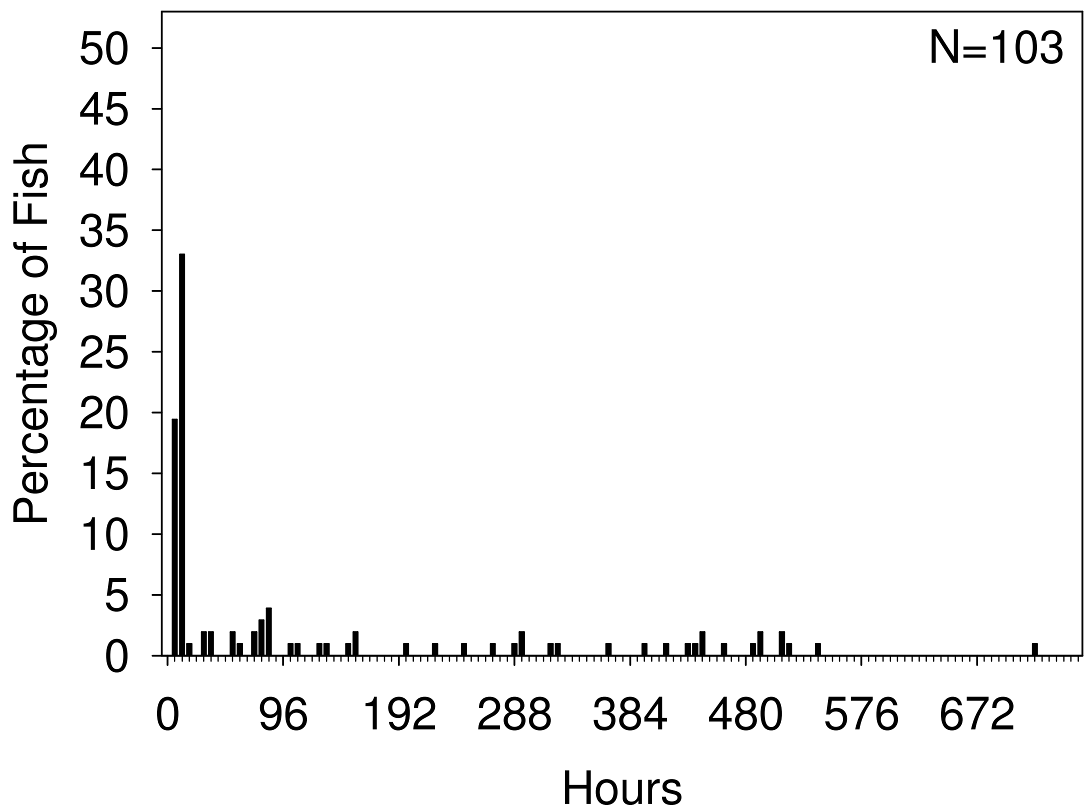


Figure 2-9. Distribution of transit times through the unobstructed section at Town Brook.

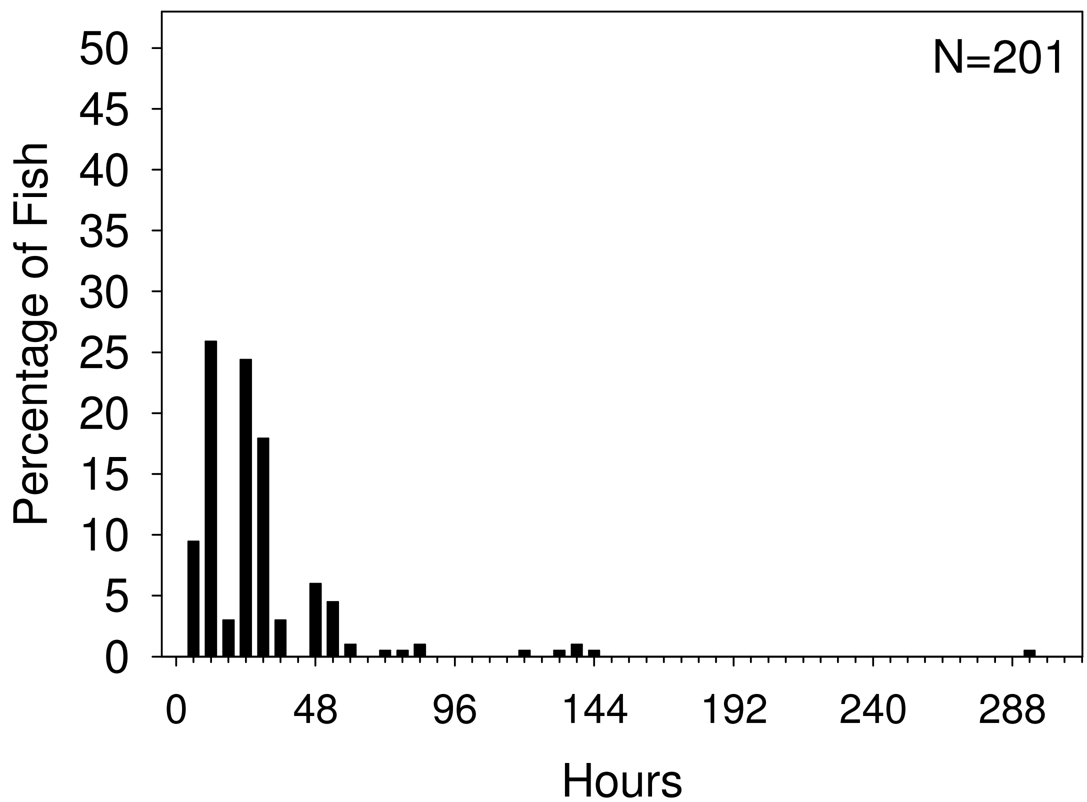


Figure 2-10. Distribution of transit times through the unobstructed section of East River.

APPENDIX A

LOESS SMOOTHING FUNCTION FIGURES OF PASSAGE OR FAILURE AT

EAST RIVER ANTENNAS 3 AND 8

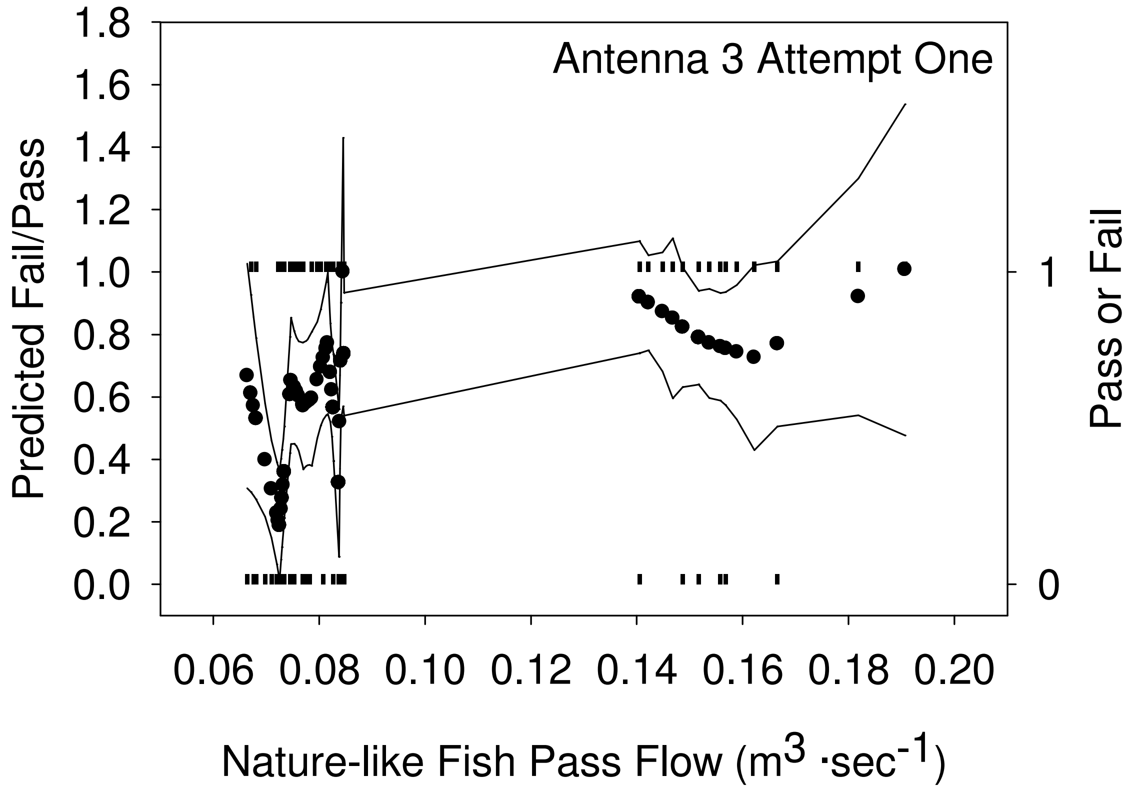


Figure A-1. Loess smoothing function applied to data on passage failure and flow through the nature-like fish pass on the alewives' first attempt at East River antenna 3. N=212. Smoothing parameter = 0.18. Circles indicate predicted value generated by smoothing function, rectangles indicate passage (0) or failure (1), solid lines represent 95% confidence intervals.

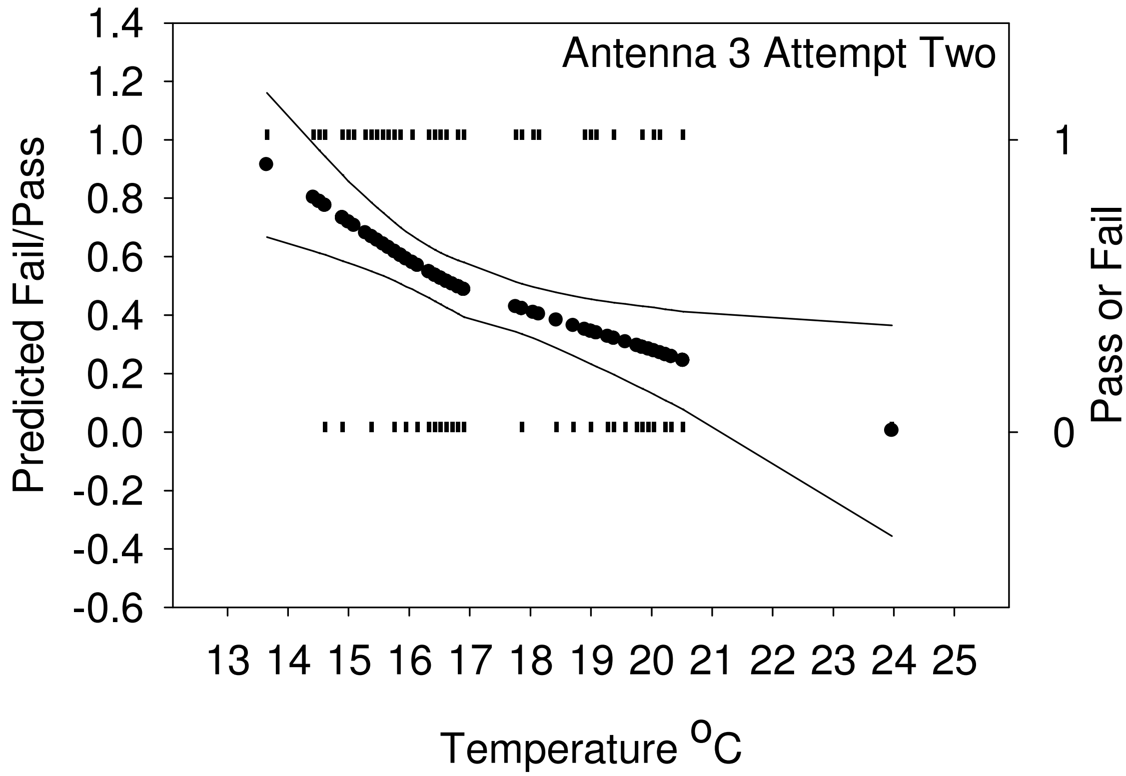


Figure A-2. Loess smoothing function applied to data on passage failure and temperature on the alewives' second attempt at East River antenna 3. N=147. Smoothing parameter = 0.95. Circles indicate predicted value generated by smoothing function, rectangles indicate passage (0) or failure (1), solid lines represent 95% confidence intervals.

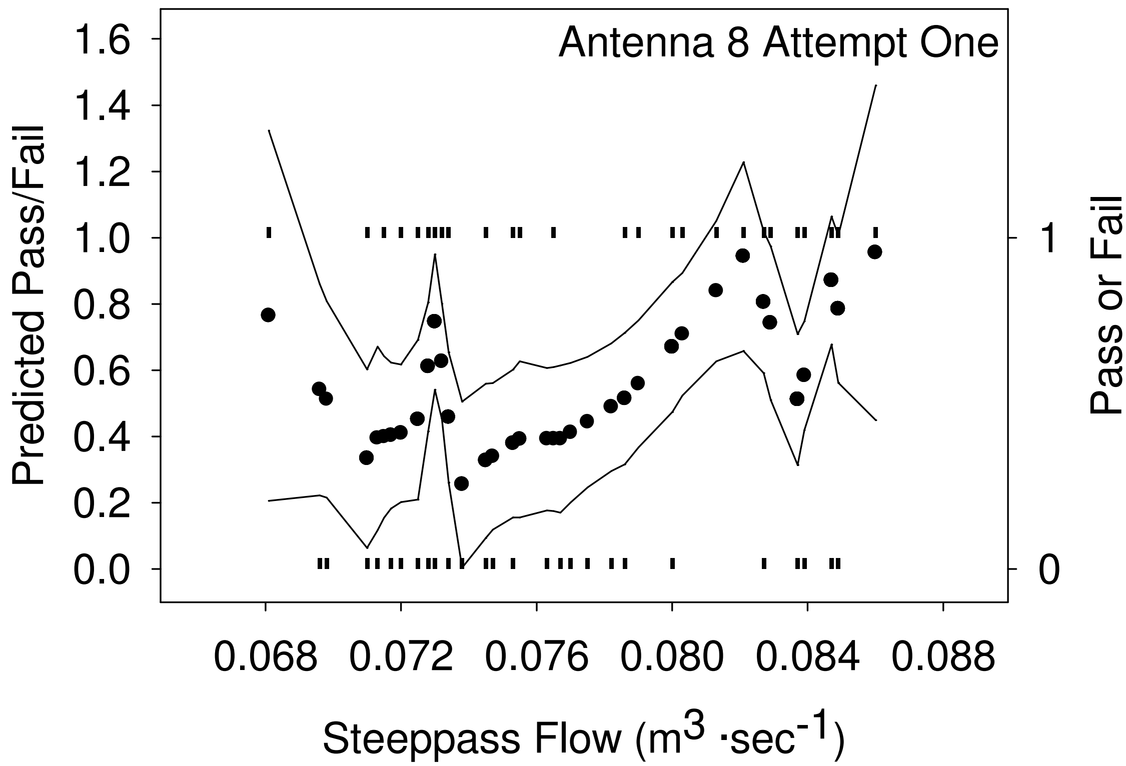


Figure A-3. Loess smoothing function applied to data on passage failure and flow through the upper steeppass fishway on the alewives' first attempt at East River antenna 8. N=142. Smoothing parameter = 0.24. Circles indicate predicted values generated by smoothing function, rectangles indicate passage (0) or failure (1), solid lines represent 95% confidence intervals.

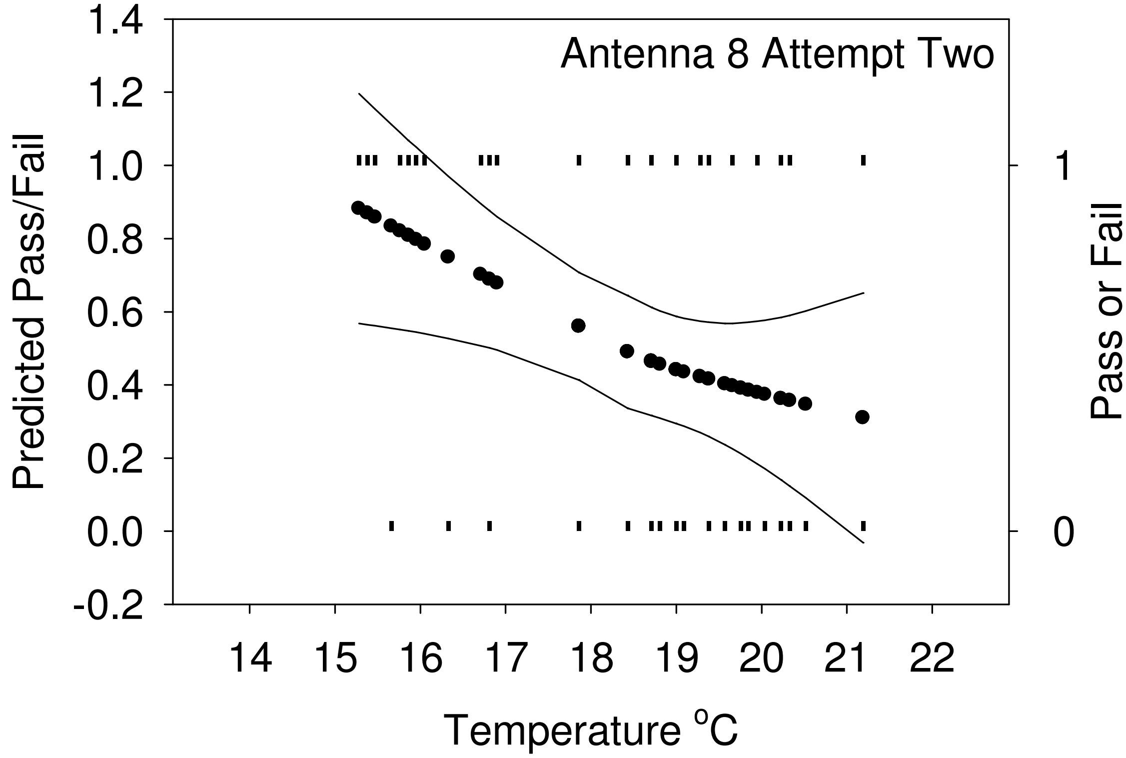


Figure A-4. Loess smoothing function applied to data on passage failure and temperature on the alewives' second attempt at East River antenna 8. N=54. Smoothing parameter = 1.0. Circles indicate predicted value generated by smoothing function, rectangles indicate passage (0) or failure (1), solid lines represent 95% confidence intervals.

APPENDIX B

EAST RIVER STEEPPASS FISHWAYS

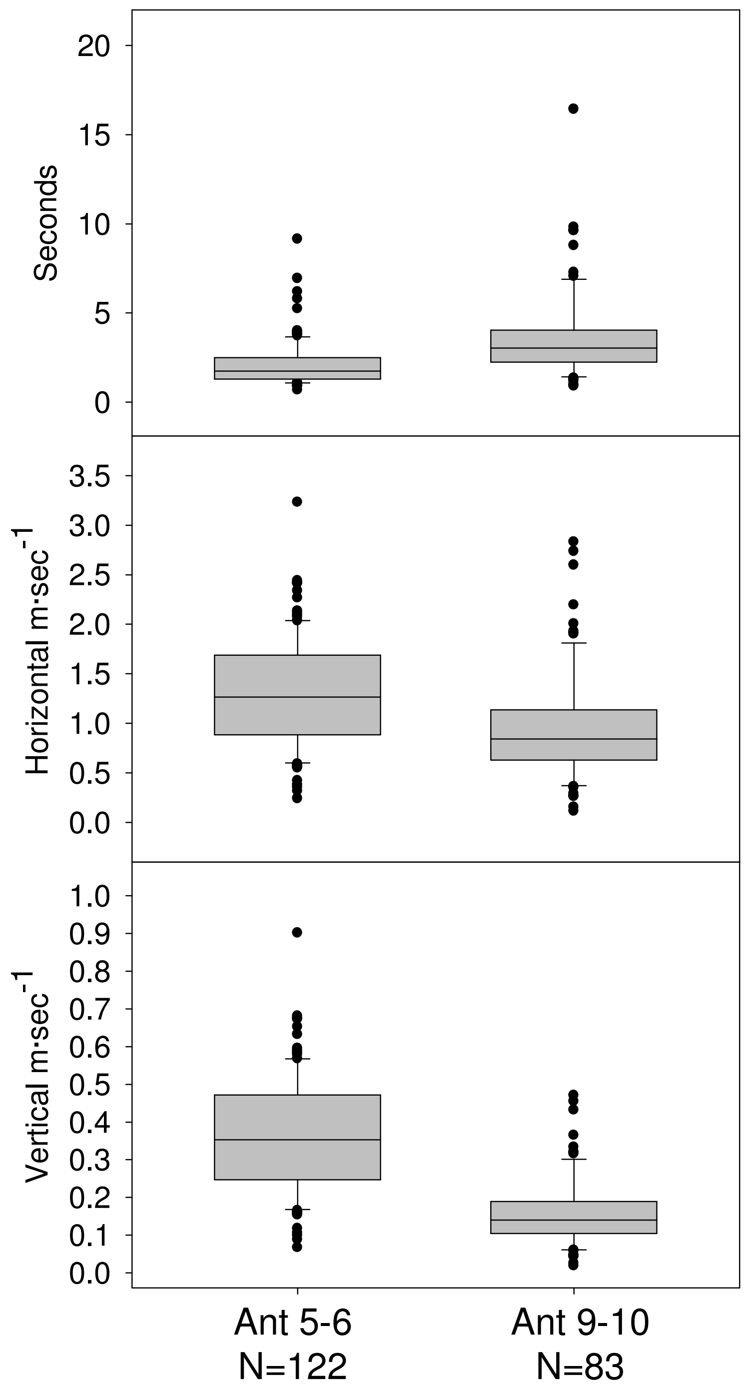


Figure B-1. Minimum transit time, rate of horizontal travel, and rate of vertical travel between steeppass antennas at East River

APPENDIX C
STEEPPASS AND WEIR FLOW FORMULAS

East Spillway Flow = Q WeirI + Q Weir II + Q Weir III + Q Upper Steeppass

Steeppass

$Q\ (m^3/sec) = (bh)^{1.508} - 0.12$ (Odeh and Haro, 1996) *Eq (1)*
$b = [\ 0.826 + .115\ (\ln(s)]^2$ (Odeh and Haro, 1996) *Eq (2)*

s = slope of steeppass = 0.18
b = 0.395
h = water elevation above invert of steeppass (m)

$Q\ (m^3/sec) = (0.395*h)^{1.508} - 0.12$ (Odeh and Haro, 1996) *Eq (3)*

Weirs I, II, III

$Q=cLH^{3/2}$ *Eq (4)*

L = length of weir
H = height of water over weir

For a weir with end contractions, c is determined by the ratio L/B and H/P where

B= channel width
P= depth of weir

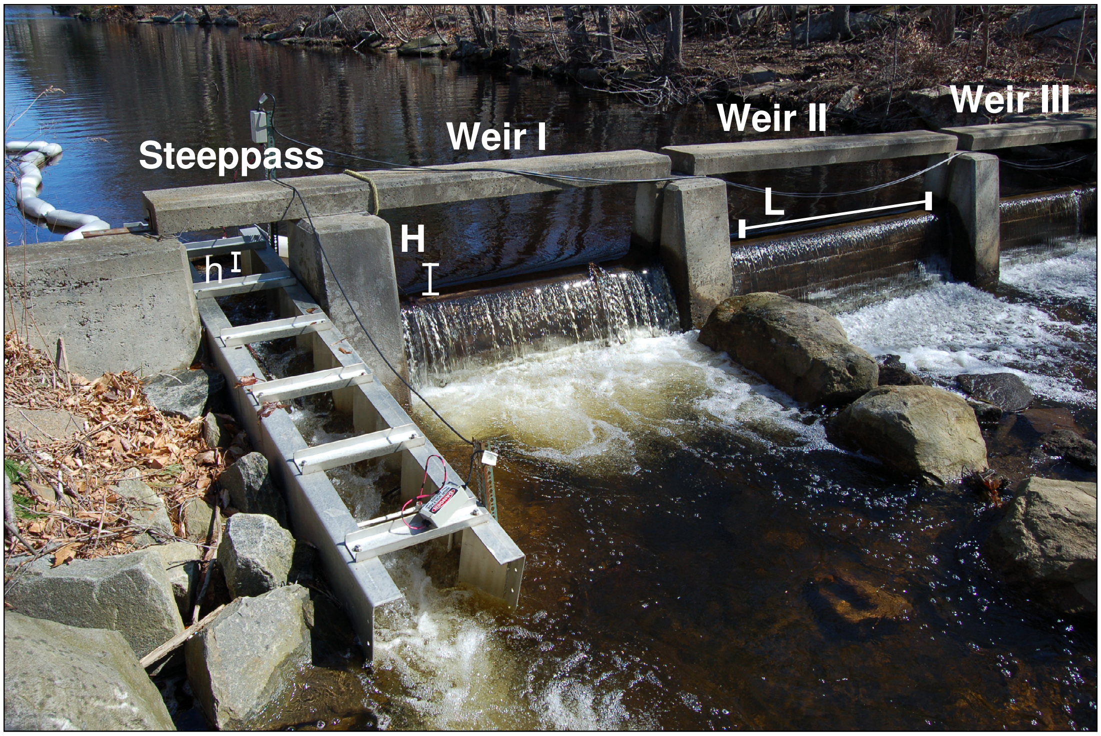
Based on Figure 5.3 in Brater and King 1976

c = weir coefficient = 3.3

Flowrate of weir I $(m^3/sec) = (3.3*6.65*H^{3/2})/\ 35.29$ *Eq (5)*

Flowrate of weirs II and III $= (3.3*26.92*\ H^{3/2})/35.29$ *Eq (6)*

APPENDIX C
STEEPPASS AND WEIR FLOW FORMULAS



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