# Design and Evaluation of Nature-Like Fishways for Passage of Northeastern Diadromous Fishes

# Final Report

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## Executive Summary

Several nature-like fishway designs have been constructed in the northeastern US, but none of these fishways have been quantitatively evaluated for passage of northeastern diadromous species.  This report summarizes data on passage performance from two studies of nature-like fishway designs for passage of river herring in the field (Town Brook, Plymouth, Massachusetts, and East River, Guilford, Connecticut), and from two years of tests of generic nature-like fishway designs (perturbation boulder and rock weir) in a semi-controlled laboratory environment.  The field studies focused on passage of anadromous alewife (*Alosa pseudoharengus*); laboratory studies tested American shad (*A. sapidissima*), blueback herring (*A. aestivalis*), white sucker (*Catostomus commersoni*), white perch (*Morone americana*), striped bass (*M. saxatilis*), and smaller numbers of other nonanadromous riverine species.  Nature-like fishways tested ranged in overall slope from 1:20 (laboratory and Town Brook site) to 1:15 (East River site).

Overall passage performance through nature-like sections of fishways at the field sites was modest (40.6%; East River) to good (94%; Town Brook), and transit times through the fishways were relatively rapid (median transit times of 11 to 75 min).  Most fish ascended the Town Brook

fishway in one attempt, but only 22% of fish at the East River fishway ascended in a single attempt; most other fish required two or three attempts to pass the entire East River fishway.

In the experimental laboratory fishways, overall percent passage of American shad and white sucker over the two year test period ranged from 40% to 90%. There was no significant effect of fishway design, rock configuration, or flow depth on percent passage, although there may have been interactions between effects. Percent passage of alewife and river herring was lower (0% to 40%) than for shad or suckers, and contrasted with results from the field sites; handling and transport may have affected motivation and performance of alewife and blueback herring. Passage performance of other species (smallmouth bass, yellow perch, black crappie, channel catfish, common carp, fallfish) tested was variable; however, low sample sizes (number of fish tested of each species) made these results statistically inconclusive.

## Introduction

Upstream fish passage facilities have been constructed extensively throughout the northeastern United States, primarily for anadromous species such as American shad (*Alosa sapidissima*), alewife (*A. pseudoharengus*), blueback herring (*A. aestivalis*), sea lamprey (*Petromyzon marinus*), and Atlantic salmon (*Salmo salar*). Most pass designs are structural fishways of the baffle or "Denil" type (Denil or Alaska steepass) for small or low head (< 3 m height) dams, and pool-and-weir (i.e., Ice Harbor or vertical slot) type for larger rivers or higher head dams (Orsborn 1987, Larinier and Travade 2002). Although the baffle-type fishways can pass large numbers of some northeastern species at low head dams, many of both the Denil and larger structural fishways have poor or unknown overall effectiveness for passing larger anadromous clupeids, and their efficiency can decrease dramatically at dams of heights over 3 m (Sullivan 2004). Structural fishways also frequently require substantial maintenance (e.g., regular debris removal, replacement of baffles) throughout the operational season.

Recently, nature-like fishways (e.g., roughened ramps, bypass channels) have been developed and shown to pass a wide variety of species at low-head dams in Europe (FAO/DVWK 2002, Jungwirth et al. 1998). These fishways typically consist of a wide, low gradient channel (usually less than 1:20 slope) 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 are generally below sustained (i.e., aerobic) swimming speeds of target species. Nature-like fishway designs have typically included bypass channels around dams and roughened ramps constructed either immediately downstream of a dam or in association with a partially removed dam, creating a new hydraulic control upstream of the former dam. Fish are believed to find natural substrates more acceptable than concrete channels or channels with baffles in structural fishways (FAO/DVWK 2002). The lower velocities at the boundary layers and flow refugia resulting from high roughness of nature-like fishways (generally less than 0.3 $m \cdot sec^{-1}$) also allow for greater potential passage of very small or weakly swimming species such as rainbow smelt (*Osmerus mordax*), juvenile American eel (*Anguilla rostrata*), and even benthic invertebrates.

Although they show promise as effective fishway structures for low head dams, few nature-like fishways have been constructed in the northeastern US, and none of these fishways have been quantitatively evaluated for passage of northeastern diadromous species. Only a few evaluations of nature-like fishways have been performed in Europe, which have been shown to be qualitatively efficient for passing larger-sized European species (Eberstaller et al. 1998, Mader et al. 1998), but quantitative data on passage efficiency for these structures is generally lacking, except for larger European salmonids (Aarestrup et al. 2003).

In addition, some species such as American shad migrate and spawn in large rivers but rarely enter small tributaries, and thus may be reluctant to enter traditional nature-like fishway designs, which are relatively shallow with many obstructions (i.e., large boulders) and turbulent flow (Haro 2002). Design of nature-like fishways for shad thus presents a special challenge in that the fishway must possess sufficient depth (both over boulder weirs and within pools) and flow to be attractive to shad, yet velocities and turbulence must be low enough to allow shad to progress efficiently up the fishway within a reasonable timeframe. In addition, large eddies and pools of high volume may induce shad to mill or stall within the fishway, increasing transit time, as has been seen in large structural pool and weir fishways. These hydraulic characteristics also must be maintained over a reasonable range of operational flow to ensure functionality of the fishway under fluctuating headpond conditions, such that the fishway is not starved for flow, fish are not stranded or exposed to predators, and have sufficient flow depth for swimming . The design must also be able to withstand anomalous high storm flows without displacement of substrate or embedded large keystone boulders.

We propose that current nature-like fishway designs can be advanced to accommodate the preferences and swimming behavior of American shad, river herring, and other species to derive one or more generic designs that will pass a variety of diadromous and resident fish species in the northeastern region and other localities, for sites with a variety of river sizes and hydraulic heads. Our studies aim to collect data on passage performance from existing nature-like fishway designs under a range of natural flow conditions, and to modify these designs to increase performance of passage for northeastern species.

This report summarizes results from two studies of nature-like fishway designs for passage of river herring in the field (Town Brook, Plymouth, Massachusetts, and East River, Guilford, Connecticut), and from two years of laboratory tests of generic nature-like fishway designs river herring, American shad, and other species.

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## Study Objectives

1. Evaluate passage performance of alewife and blueback herring in an existing nature-like fishway site at Town Brook in Plymouth, Massachusetts.

2. Evaluate passage performance of alewife in an existing spillway bypass channel with nature-like fishway features site at the East River, Guilford, Connecticut.

3. Evaluate two full-scale prototype nature-like fishway designs (perturbation boulder and rock weir; each 10 ft width) in the Conte Anadromous Fish Research Laboratory

(CAFRL) flume complex under varying flow depths or a variety of test species, including American shad, alewife, blueback herring, white sucker, and other species, over two study years.

# PART I - Field Studies

## I. 1. – Field Site Descriptions

### I. 1. 1. Town Brook Field Site

Town Brook is a first order stream with a watershed of 10 $km^2$ located in Plymouth, Massachusetts (Milone and MacBroom 2001). It flows 3 km from its source at a 109 ha freshwater lake called Billington Sea to its mouth at Plymouth Harbor in Cape Cod Bay (**Fig. I-1**). In 2003 as part of an effort to reconnect the river corridor with the historic spawning grounds at Billington Sea, the fourth dam upstream from the mouth of the river was removed and a 32 m long, streamwide (8 m) nature-like fishway of a rock ramp design with an overall 1:20 slope was constructed at the site. Migrating fish must ascend three structural fishways (small pool-and-weir, Denil and Alaska steeppass fishways) at the three lower dams and negotiate three small mill ponds before reaching the nature-like fishway at river kilometer 1.6. (Reback et al 2004). A short distance upstream (154 m) of the nature like fishway is the 0.91 m high "Off Billington St." dam with a small 14 m long pool-and-weir fishway with a slope of 1:7.

### I. 1. 2. East River Field Site

East River is a second order stream with a watershed area of 53.1 $km^2$ located in Guilford, Connecticut. Its source is the first order Iron Stream which originates in the village 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 Lower Guilford Lake Dam to the mouth at Guilford Harbor in Long Island Sound (**Fig. I-2**). The Lower Guilford Lake Dam is divided into two concrete spillway structures with an earthen "island" in between. The west spillway is 3.35 m high, includes three 2.74 m wide spill gates fitted with stoplogs and a 53.3 cm wide sluice gate. It has an elevation head of 3.66 m. The east spillway includes three 3.05 m long spill gates fitted with stop logs, and has an elevation head of 0.61 m. The river below Guilford Lake Dam is therefore split by the two spillways into the passage channel below the east spillway and the overflow channel below the west spillway, which rejoin 60 m below the dam.

In 2001 the passage channel was field-modified to include fish passage including structural fishway and nature-like fishway features to provide access to spawning habitat in the Lower and Middle Lakes. The passage channel is 60 m long and the fish passage structures within the channel collectively are 48 m long with an average slope of approximately 1:15. The nature-like portions are 7 to 9 m wide and constructed of 0.6-1.0 m (2-3 ft) diameter boulders that create 13 step pools. The substrate is bedrock granite and gravel. Two 3.1 m long, 0.6 m wide Alaska steeppass fishway sections are located within a steep portion of ledge 20 m downstream of the base of the dam, and at the dam itself. One section of steeppass fishway is embedded in bedrock halfway up the fishway (this area presented difficulties in establishment of nature-like features due to the bedrock substrate and localized excessively steep slope). The other section of steeppass fishway is located at the dam at the top of the bypass channel, and provides the final passage reach from the top of the bypass into the headpond, and maintaining passability under fluctuations in headpond level of approximately 0.5 m. Additional flow into the bypass channel comes from spill over the dam crest, which is regulated by 0.23 m (9 in) high stoplogs. Fish are unable to pass directly from the bypass channel over the dam crest due to the 0.61 m (24 in) vertical drop below the dam crest; all fish must exit the channel via the steeppass fishway section (which was installed to provide adequate passage conditions under varying headpond conditions from presence/absence of dam crest stoplogs). Downstream of the study area, migrating fish encounter two ponds and one structural (Denil) fishway before reaching the entrance to the Lower Guilford Lake Dam and passage channel at river kilometer 9. No fish passage is provided over the west spillway of the Guilford Lake Dam.

## I. 2. Methods

### I. 2. 1. PIT System

Movements of alewife through the two study sites were quantified using passive integrated transponder (PIT) telemetry as described by Castro-Santos et al. (1996). Instream antennas were constructed with single loops of 4-gauge insulated welding wire and ranged from 4 to 8 m in length across each study passageway. Antennas inside the structural 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 System Series 2000 readers enclosed in a weatherproof box. Readers were configured to gather data at a rate of 10-12 reads per second and were powered by a DC power supply. The maximum distance a tag could be read from the antenna loop ranged from 30-40 cm from the plane of the antenna loop. When a fish was detected by an antenna, the date, time, fish identification number, and antenna number was recorded by a data logging computer. Antennas were tested periodically with a test tag attached to the end of a hand-held 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.

### I. 2. 2. Antenna Placement

At Town Brook a 180 m stretch of river was monitored with eight antennas. Four antennas were placed across the width of the nature-like fishway, two full-channel-width antennas were installed between the nature-like fishway and the Off Billington St. Dam and two antennas were placed at the entrance and exit weirs of the pool-and-weir fishway. (**Fig. I-1**). At East River the approach to the lower Guilford Lake Dam was similarly monitored with ten full-channel-width antennas. Antennas were placed across the entrances of the overflow channel and passage channel to monitor route choice. One antenna was placed at the entrance of the nature-like section and three others at other points along the nature-like section of the passage channel. Four antennas monitored the entrances and exits of the two steeppass fishways (**Fig. I-2**).

### I. 2. 3. Fish Collection and Tagging

At Town Brook, a total of 400 alewife were collected and tagged with 23 mm PIT tags (internal implantation; see Sullivan 2004 for methodology) at the commercial fish weir at Newfield Street Dam (914 m downstream from the entrance to the nature-like fishway) over a period of 27 d during daylight hours. Fish were netted from an enclosed area by hand and for each fish the fork length, sex, and percentage of scale loss was recorded. Fish with more than 50% scale loss 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 4/26, 5/1, 5/5, 5/8, 5/12, and 5/15. Tagged fish were immediately released into the headpond above the Newfield Street Dam and were allowed to enter the nature-like fishway volitionally. The PIT tags were numbered from 20063000 to 20063399.

At the East River site, a total of 393 alewife were collected and tagged with 23mm PIT tags using the same methodology as for Town Brook below the Capello Pond Dam over a period of 38 days during daylight and evening hours. 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 netted by hand, tagged, measured, examined for sex and scale loss, transported by bucket and released at the base of Capello Pond 762 meters below the entrance to the nature-like fishway. Fish with more than 50% scale loss were released without a tag. Released fish were allowed to enter the nature like fishway volitionally. On March 30 seven fish were tagged and released. Due to weather conditions the next tagging event did not occur until April 21. Between April 21 and April 23, 344 fish were tagged and released. An additional 34 fish were tagged on May 4 and 8 fish on May 7$^{th}$. The PIT tags were numbered from 20073000 to 20073392.

### I. 2. 4. Data Collection

Water level and temperature data were collected hourly at both sites using Onset HOBO Model U20-001-04 water level dataloggers. A total of three data loggers were installed at Town Brook at the entrance and exit of the nature-like fishway and above water in the weathertight box containing the PIT readers. The lower East River bypass channel was monitored by three data loggers installed in the headpond, at the entrance of the passage corridor, and in the weathertight box. The loggers installed in the weathertight enclosures were used to record atmospheric pressure that was later used to derive absolute water level. As a reference, water temperature and relative level were measured manually using a digital thermometer and staff gauges at weekly intervals. At East River hourly flow through the passage channel was calculated using a formula that incorporated the hourly water level measurements in the headpond and water level at the eastern and western weirs and the upper steeppass fishway. Hydraulic gradelines at both sites and elevations of individual antennas were measured with a rod and level.

Tag detection data files produced by the datalogging computer were downloaded every few days. At Town Brook the system began monitoring on April 19, 2006 but due to a computer malfunction stopped recording data for 117 h 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 h from April 27 to April 30. The antennas then operated continuously from April 30, 2007 to June 12, 2007.

### I. 2. 5. Data Analysis

Telemetry data files from the PIT recording system were imported into a Microsoft Access database and condensed by converting consecutive reads at individual antennas of under a second to single presences. For each site passage performance was evaluated by examining passage efficiency, attraction efficiency, number of attempts, and transit time. Passage efficiency was quantified as the percentage of fish that entered a structure or river reach that successfully passed the entire structure or reach. Ninety-five percent confidence intervals for percent passage estimates at each antenna were calculated using the binomial distribution. Attraction efficiency for the East River passage channel was quantified as the percentage of fish that were detected at the first antenna of the passage channel (Antenna 2) that were subsequently detected at the entrance to the lower nature-like fishway section (Antenna 3).

Detections of individual fish were grouped into "attempts" in order to quantify multiple efforts to ascend a fishway structure or reach as well as determine on what attempt the fish completely passed the entire structure or reach. At both sites movement data was 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 because more than 50% 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 fishway entrance and then returned to make another attempt. At East River the lag time distribution was more right-skewed (longer average lag times), therefore 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 were then calculated within attempts.

Transit times through fish passage structures or reaches were defined as the amount of time it took for a fish to travel through the structure or reach as delimited by upper and lower antennas, calculated by subtracting the time of the first detection at the lower antenna from the time of the first detection at the upper antenna. Transit times through passage structures or reaches were calculated only for fish that successfully completed the structure or reach. Because transit times were right skewed, median values are reported. A one-way analysis of variance (ANOVA) was used to test for differences between the natural log of transit times for males and females.

Multiple linear regression analysis was used at each site to examine how transit times through the nature-like passes were affected by fish length, scale loss, time at liberty, water level, temperature, and the interaction between scale loss and length. 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. Length and scale loss were standardized to a mean of zero and a standard deviation of one and the interaction term is the product of the two standardized variables. This was done to minimize the correlation between the single variables and the interaction of length and scale loss. An arcsine square root transformation was applied to the proportion of scale loss. The top five models chosen by Aikake's Information Criterion (AIC) are reported**.**

First attempts of successful and unsuccessful 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, milling) from antenna to antenna. Horizontal and vertical (elevation gain) rate of travel was calculated by dividing the horizontal and vertical distance in meters between antennas by the amount of time it took for the fish to pass between those antennas.

Estimates of survivor functions and hazard rates for passage through the fishways were calculated using the Kaplan-Meier method of event time analysis (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 (Castro-Santos & Haro 2003). In order to examine the effect of slope on hazard rates through individual sections of passage structures or reaches a linear regression analysis was performed.

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, temperature at the time of first detection at the antenna, and flow at the time of first detection at the antenna. At each antenna analyses were performed for the first and second attempts. Models that included all covariates were compared to reduced models and the top models were chosen by lowest AIC scores.

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 above at the uppermost antenna of a PIT antenna array and then detected in a downstream sequence at all of the antennas.

## I. 3. Results

### I. 3. 1. Town Brook

Hydraulic gradeline data for the Town Brook study site are shown in **Fig. I-3**. Water temperatures at the Town Brook site during the study period ranged from 10.0 to 24.6 °C, and showed a diel fluctuation of approximately 2°C to 4°C on most days (**Fig. I-4**). Water levels at the upstream datalogger ranged from 0.23 to 0.34 m relative depth (**Fig. I-4**).

Data were collected from 43% (175) of the 400 fish tagged. Fate of undetected fish is unknown; it is possible that they either stopped migrating once they reached the impoundment above Newfield Street Dam (from handling tagging effects or simply to spawn), lost their tags, or succumbed to handling/tagging mortality. However due to a monitoring system malfunction the movements of the first 100 fish tagged and released went unrecorded for 117 hours. One-way ANOVA 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 nature-like fishway, 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 4/26 through 5/15.

Lengths of the 103 fish included in analyses ranged from 212 mm to 263 mm, scale loss from 0 to 50% and the male to female ratio was 1:0.90. 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%.

Passage success through the Town Brook nature-like fishway was high (**Fig. I-5**); 94% (N=97, 95% CI 89.1% - 97.8%) of fish that entered successfully completed their ascent through it**.** Sixty-six percent of the fish (N=68) reached their maximum distance of ascent above the nature-like fishway at Antenna 6. Only seven fish reached their maximum distance of ascent within the nature-like fishway. Survival estimates for intervals between antennas remained high until the section between Antennas 6 and 7, indicating a passage problem at the upstream pool-and-weir fishway. Cox's proportional hazards regression indicated no significant relationship between sex, length, or proportion of scale loss on the maximum distance of ascent. Attraction efficiency could not be calculated for Town Brook because an antenna was not placed below the entrance of the nature-like fishway in order to detect the fish that were available to pass.

Of the 97 successful fish, 93.8% (91) completed the nature-like fishway section on their first attempt (**Fig. I-5**). Five fish completed the section 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 daylight hours.

Transit times of successful fish through the entire nature-like section ranged from 4.85 min to 44.08 min with a median time of 11.09 min (**Fig. I-6**). One-way ANOVA analysis found no significant difference in transit times between males and females (df=1, F=.29 p=.5903). The top multiple regression model (F=3.86, df=5 P=.0034) explained the variation in transit time as a function of standardized length, standardized scale loss, and temperature at the time the successful attempt was begun. Temperature and length were negatively correlated with transit time and scale loss was positively correlated with transit time. The model explained 13.84% of the variation and standardized partial regression coefficients indicate that length (b=-0.32) has the greatest effect and temperature (b=-0.21) and scale loss (b= 0.21) have equal effects.

Transit times between antenna pairs in the nature-like fishway section were variable (**Fig. I-7**). Fish took the longest to swim between Antennas 3 and 4 but assuming a constant rate of travel, traveled the fastest horizontally through the first 17 m of the nature-like fishway section between Antennas 1 and 2 (median 4.07 $m \cdot min^{-1}$) and Antennas 2 and 3 (median 4.04 $m \cdot min^{-1}$). Fish traveled the slowest through Antennas 3 to 4 with a median of 2.85 $m \cdot min^{-1}$. Vertically, the fish ascended the fastest through the section between Antennas 1 and 3, which is the steepest part of the nature-like fishway section.

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 of the pool-and-weir fishway, resulting in an attraction efficiency of 29.17% for the pool-and-weir fishway. Six fish successfully completed the pool-and-weir fishway giving it a passage efficiency of 21.43%. Transit time from Antenna 7 to 8 ranged from 11.9 to 30.5 sec. Fish were visually observed congregating below the spillway of the dam and attempting to swim through the spillway flow.

Downstream movement through the nature-like fishway was observed after two different events. If detections from the first release group of fish are included, ten fish were known to have passed upstream of the pool-and-weir fishway and then moved back downstream 8 to 27 d later. The downstream transit times of these fish through the nature-like fishway ranged from 17 to 96 sec. Downstream movements through the nature-like fishway 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 nature-like fishway ranged from 17.2 sec to 11.1 min with a median of 72.4 sec. Transit times from the last detection at Antenna 5 to the last detection at Antenna 4 ranged from 94 sec to 3.5 h with a median of 5.0 min.

### I. 3. 2. East River

Hydraulic gradeline data for the East River study site are shown in **Fig. I-3**. Water temperatures at the East River site ranged from 11.1 °C to 26.4°C throughout the monitoring period, and showed a diel fluctuation of approximately 1°C to 2°C on most days (**Fig. I-4**). Water levels at the downstream datalogger (located in a deep pool at the downstream end of the bypass channel) ranged from 0.13 to 0.54 m relative depth.

PIT data were collected from 59.5% (234) of the fish tagged. Their lengths ranged from 201 to 271 mm, scale loss ranged from 0 to 40% and the male to female ratio was 1:0.55. 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%.

The monitoring system did not operate for 60 h 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 30$^{th}$, no fish were detected at any antennas. The first detections of fish after this event occurred several h later and were in the lower portion of the antenna array at Antennas 1 or 2. 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 antenna array, 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 antenna array 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 lower nature-like fishway section at Antenna 3. Ninety-four percent of detected fish (221) were detected at the entrance to the overflow channel (Antenna 1) but only three of these fish were detected only at Antenna 1 and not in the passage channel.

Passage success through the entire passage channel was modest. Of the 212 fish that were detected at Antenna 3, 40.6% (N=86, 95% CI 34.4% - 47.5%) completed the nature-like and steeppass sections and reached Lower Guilford Lake **(Fig. I-5).** Seventy-eight percent (67) of successful fish were male and 22% (19) were female. For 25% (54) of fish that entered the passage channel, Antenna 3 was the maximum antenna ascended to. These fish successfully found the entrance to the lower nature-like fishway section but were either unable, or chose not to ascend further. Twenty-four percent (51) of fish reached their maximum antenna near the top of the upper nature-like fishway at Antenna 8.

On the first attempt 64.62% (137) of fish ascended no further than the lower nature-like fishway section at Antenna 3 and only 8.96% (19) successfully ascended the entire passage channel. Of the 86 fish that successfully ascended to Lower Guilford Lake, 22.09% (19) of fish completed the passage channel on their first attempt, 36.04% (31) on their second, and 15.12% (13) on their third. The remaining 13 fish made between four and eight attempts to complete the passage channel. Seventy-two percent (153) of fish approached the passage channel during daylight hours.

Transit times of successful fish (86) through the entire passage channel (both nature-like and steeppass sections) ranged from 19.6 min to over 3 d (**Fig. I-6**). The median passage time was 75 min and 90% of the successful fish passed in 7 h. A one-way ANOVA analysis found no significant difference in transit times between males and females (df=1, F=0.0 p=.9611). Model 1 (F=6.5 df=2 p=.0025) best explained the variation in transit time and included the time elapsed between release and detection and the positive interaction between scale loss and length. Release to detection time (p=.0009) and the interaction of scale loss and length (p=.0657) were positively correlated with transit times. The model explained 12.8% of the variation and standard partial regression coefficients indicated that release to detection time (b=0.39) is approximately twice as important as the length scale loss (b=0.21) interaction.

Median transit times between individual pairs of antennas through the nature-like section ranged from 44 sec between Antennas 7 and 8 to 19 min between Antennas 8 to 9 (**Fig. I-7**). Fish travelled the fastest horizontally between Antennas 7 to 8 (median=7.94 $m \cdot min^{-1}$) and the slowest from Antennas 8 to 9 (median=0.099 $m \cdot min^{-1}$; **Fig. I-7**). Median times of elevation gain ranged from 0.328 $m \cdot min^{-1}$ between Antennas 7 to 8 to 0.003 $m \cdot min^{-1}$ at Antennas 3 to 4 (**Fig. I-7**). Median transit times through the steeppass sections were 1.7 sec for the downstream steeppass and 3.02 sec for the upstream steeppass.

Sixty-six percent (57) of the 86 fish that successfully ascended to Lower Guilford Lake were detected moving downstream through the passage channel. Time spent in the lake ranged from 1 to 41 d with a median residence time of 16.5 d. Downstream transit times through the passage channel ranged from 1.7 min to 23.2 min with a median of 8.4 min. Downstream transit times through the two steeppass sections were 2.28 sec and 1.74 sec. Transit times for the nature-like sections ranged from 7.29 sec (Antennas 9 to 8) to 295.03 sec (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 initially detected at Antenna 10 (exit of upper steeppass fishway) but was later detected descending through the overflow channel 8 d later. This fish likely explored the steeppass fishway as an exit route from the lake, but ultimately did not enter the fishway and searched for other downstream passage routes from the lake before descending over the east spillway. Twenty-eight percent (24) of successful fish were not detected again after the last upstream presence at Antenna 10.

### I. 3. 3. Effect of Fishway Slope on Passage

Linear regression analysis found a significant ($p=0.0041$) effect of inter-antenna slope on hazard rate for nature-like fishway sections pooled from both sites (**Fig. I-8**). However, this relationship was based on only 6 data points and was not significant when the data point from the highest slope section (East River, Antennas 3-4) was omitted from the dataset.

**Figure I-1.** Upper panel: location of Town Brook study site, Plymouth, Massachusetts. Lower photos: left - Billington Street Dam and defunct structural (pool-and-weir) fishway prior to removal; right - nature-like fishway installation after removal of Billington Street Dam, at moderate spring flows. Note antennas (Antenna 3 and Antenna 4) spanning the fishway.

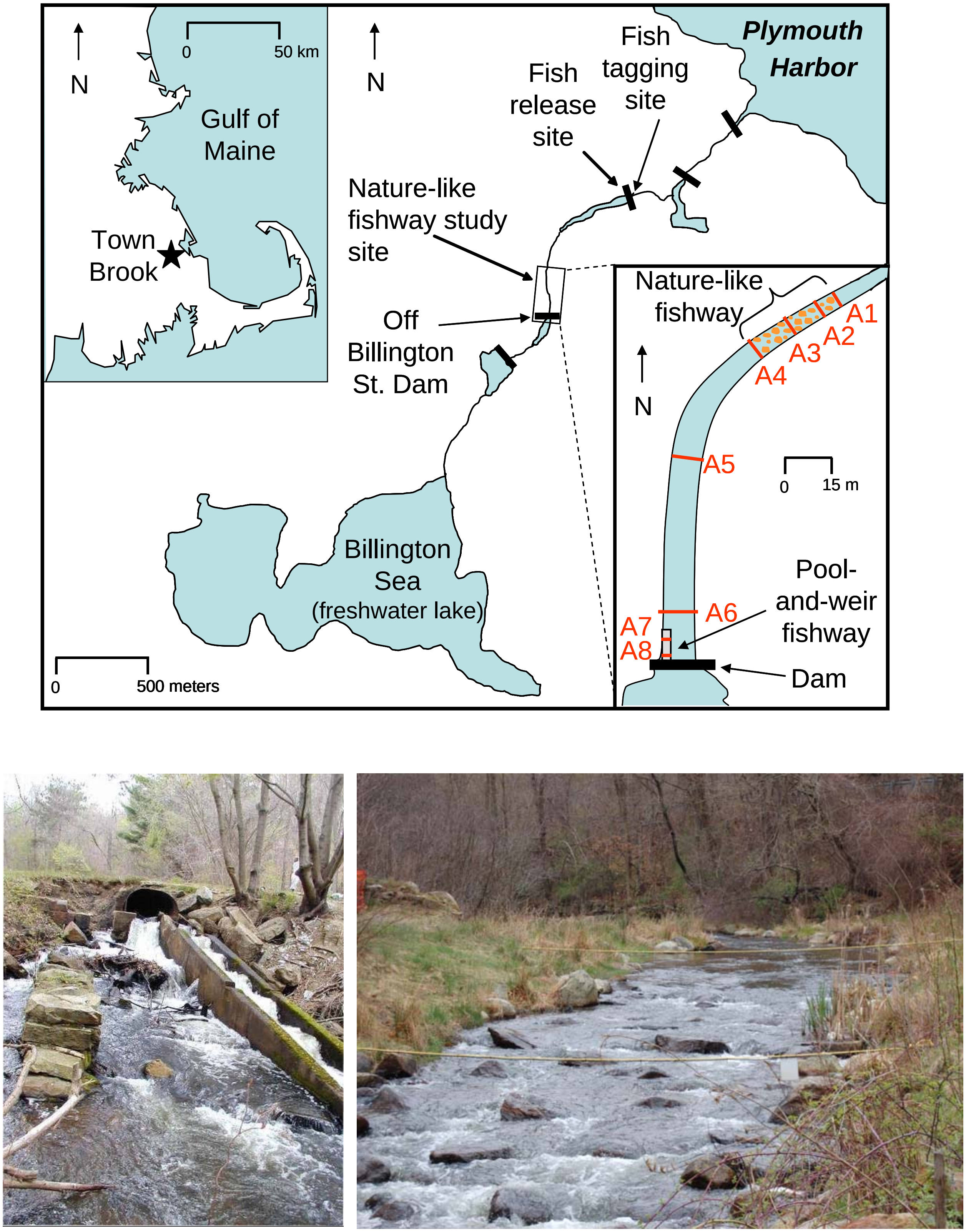


**Figure I-2.** Upper panels: location and PIT antenna layout of East River study site, Guilford Lakes, Connecticut (not to exact scale). Lower photos: left photo - East River looking upstream towards at junction of overflow and passage channels; note locations of Antennas 1 and 2 (yellow ropes spanning channels with safety signage); right photo: bypass channel looking upstream from lower steeppass fishway.

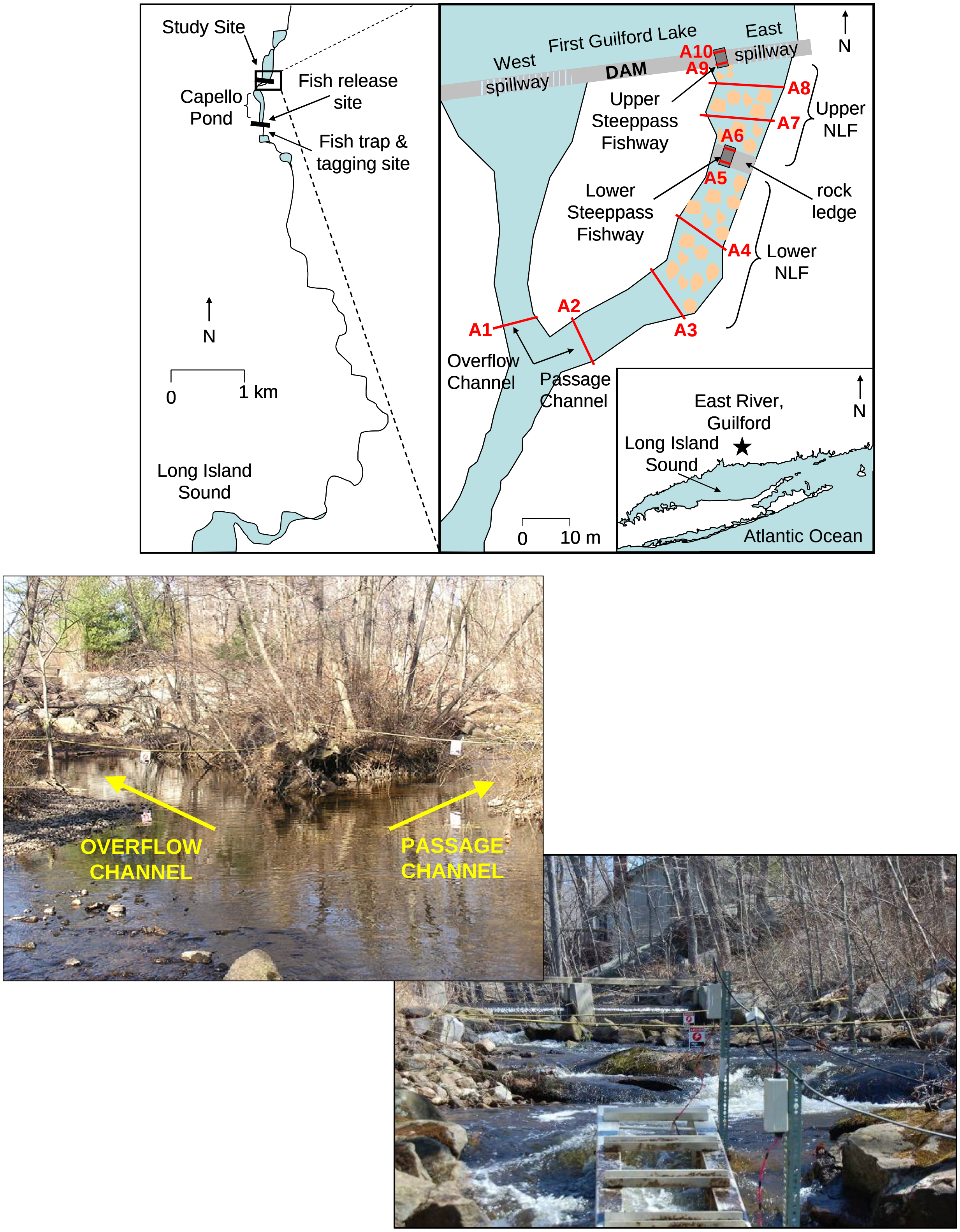
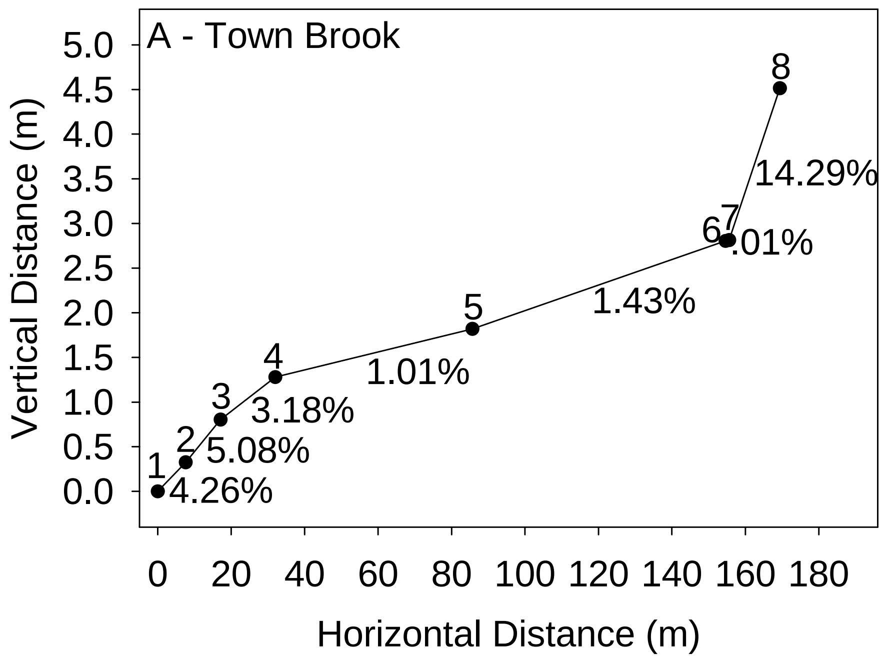


**Figure I-3**. Hydraulic gradelines between antennas (numbers) and resultant slopes (%) for Town Brook and East River study sites.



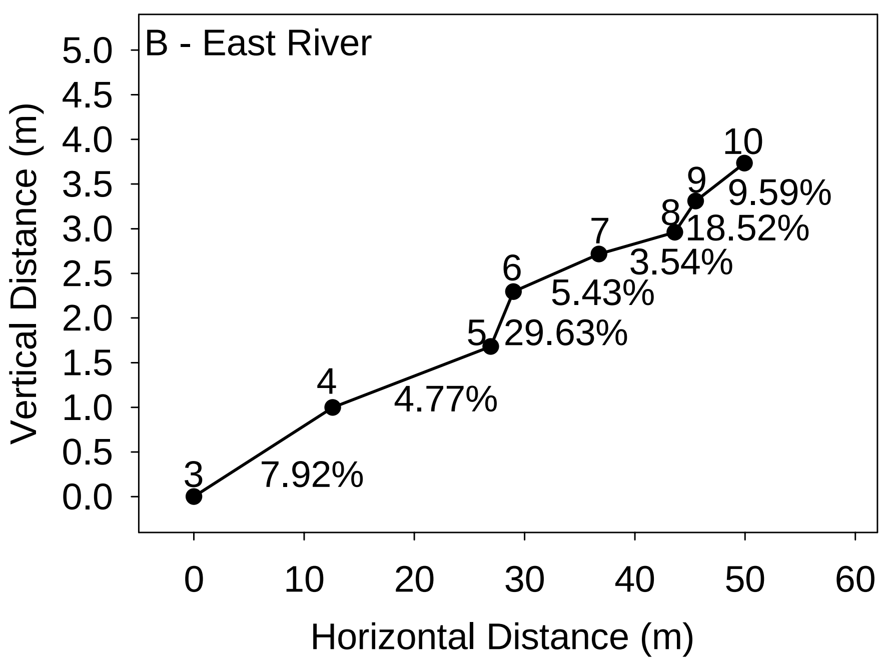



**Figure I-4.** Time series of water temperature and level recorded at the Town Brook site and water temperature and flow estimated from level data from the East River site.

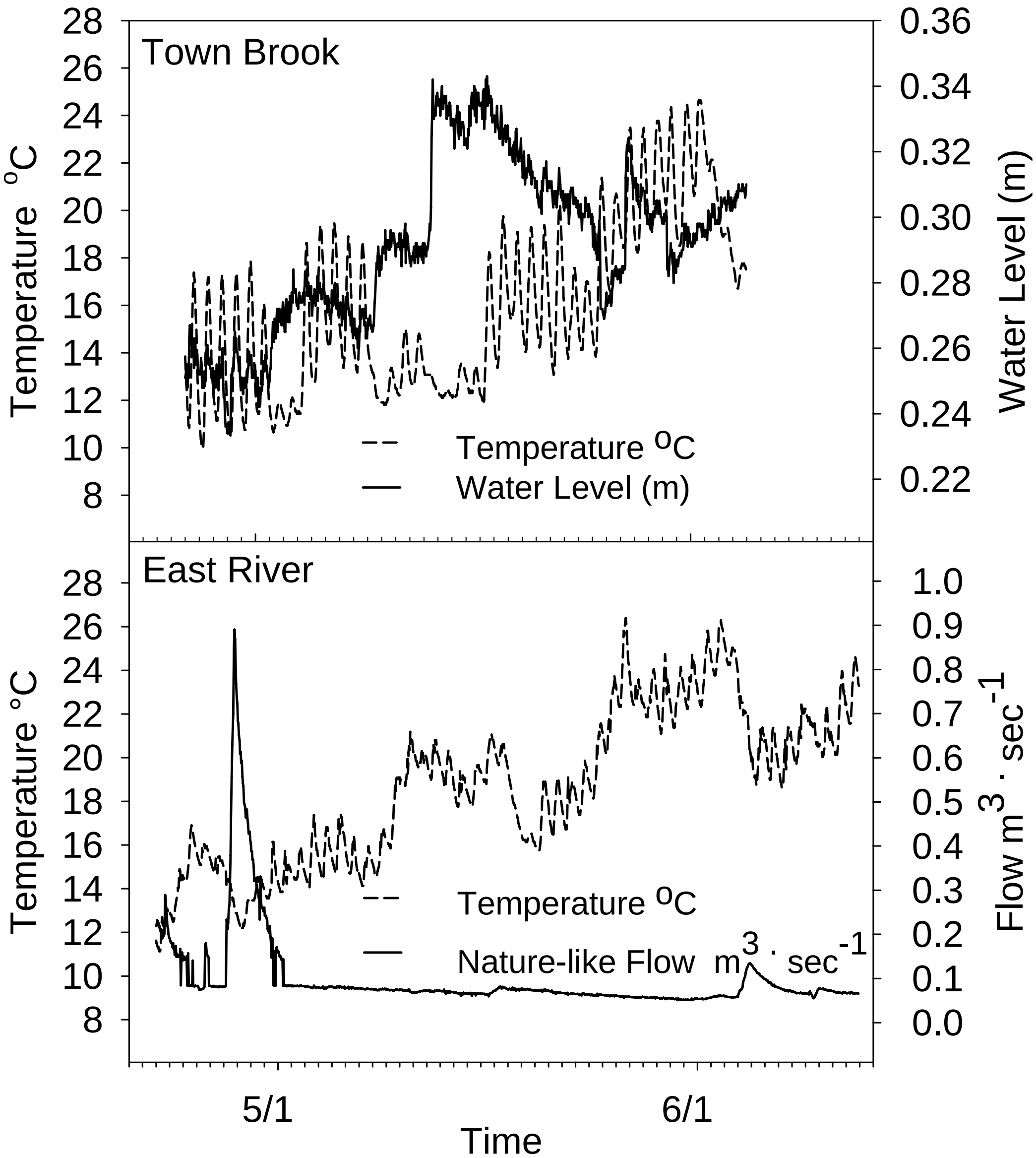


**Figure I-5.** Proportion of detected fish passing each antenna for Town Brook (left panels) and East River (right panels) sites. Upper panels: proportion of fish reaching each antenna on their first attempt. Lower panel: proportion of fish reaching each antenna over all attempts. Vertical bars indicate 95% confidence intervals. Areas shaded in green are nature-like fishway (NLF) sections of the study reaches; blue shaded areas are pool-and-weir (P&W) fishway sections (Town Brook) and yellow shaded areas are steeppass (SP) fishway sections (East River).

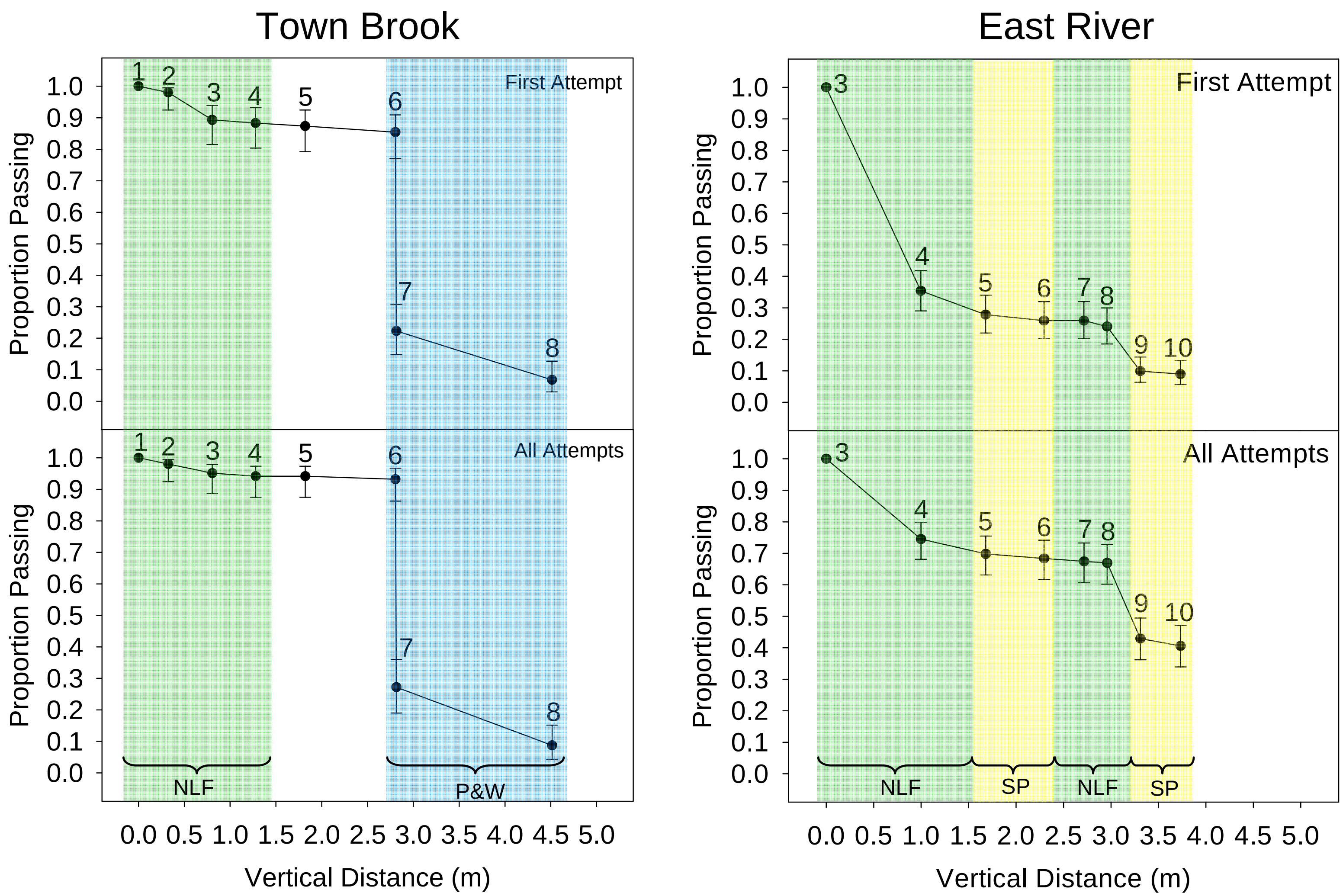


**Figure I-6**. Distributions of transit times through nature-like fishway sections at Town Brook and East River sites. East River transit times include time to pass both steeppass sections. Note difference in scales of x-axes.

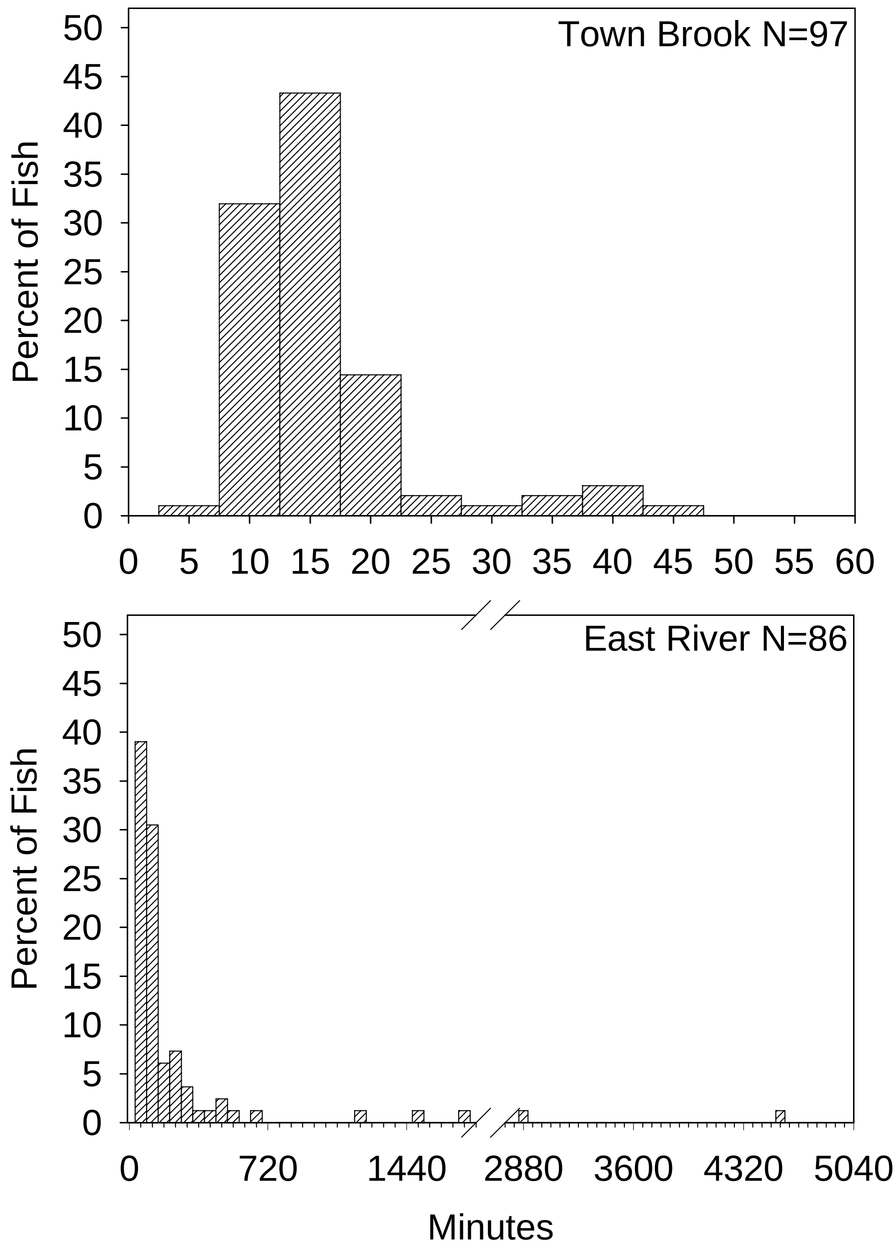


**Figure I-7.** Distribution of overall inter-antenna transit times for the nature-like fishway sections at the Town Brook (left panel) and East River (right panel) sites and resultant horizontal and vertical (elevation gain) rates of travel. Horizontal line within box = median; box = 25th and 75th percentiles; whiskers = 5th and 95th percentiles; dots = data points from individual fish (range). Note variation in y-axis scales.

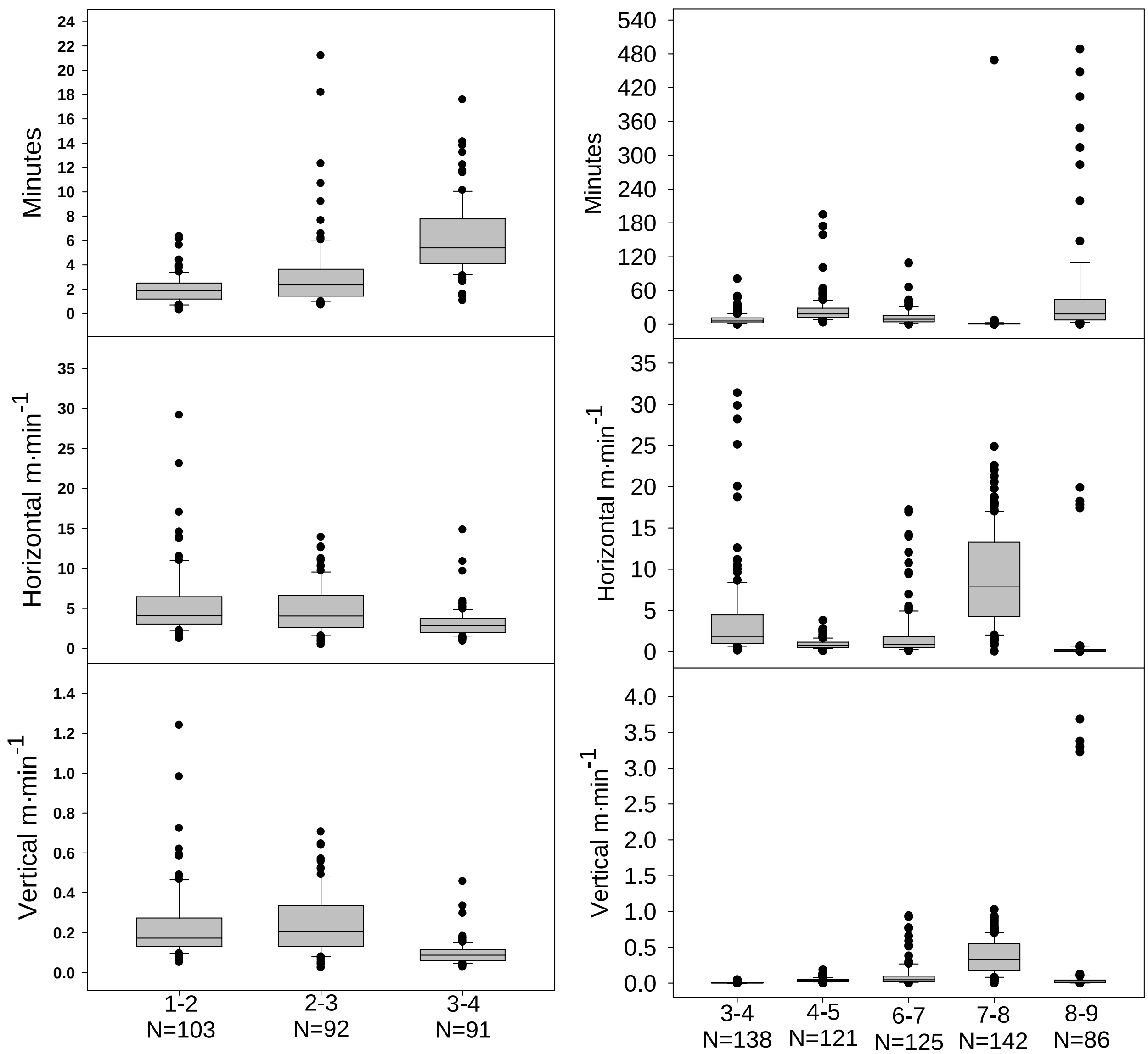
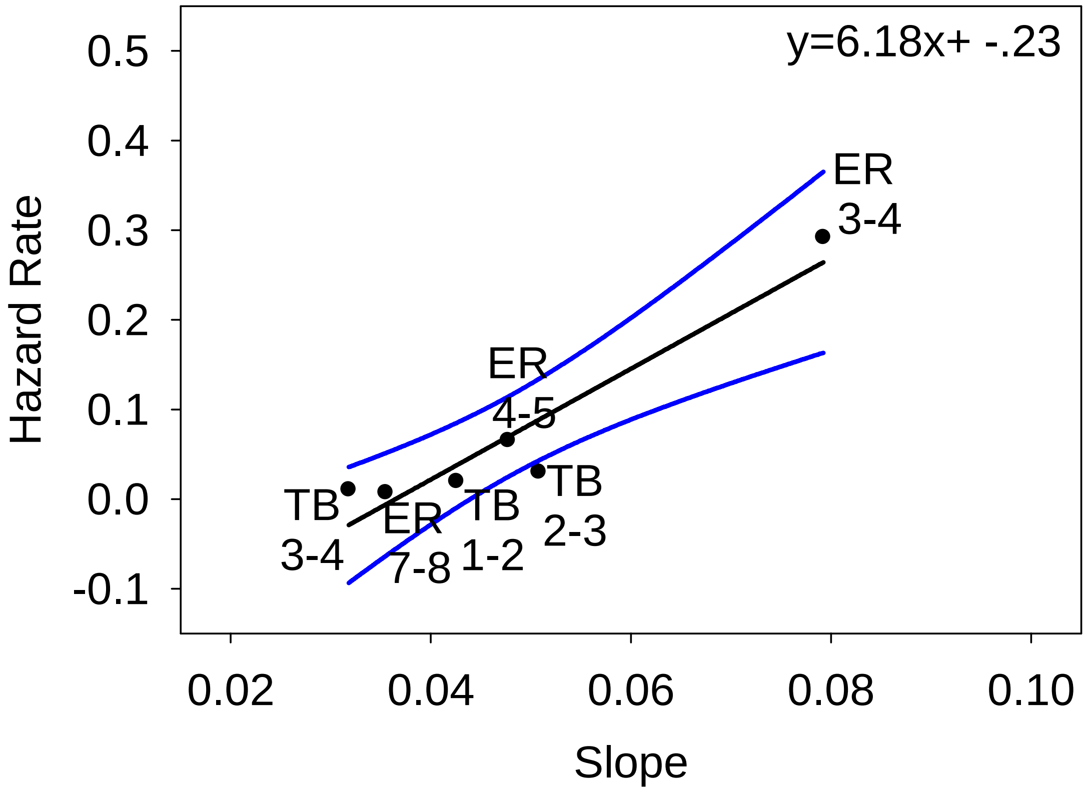


**Figure I-8.** Regression of fishway slope on hazard rate. Data are combined from inter-antenna sections from Town Brook (TB) and East River (ER) nature-like fish passes.



# PART II. Laboratory Studies

**II. 1. Experimental Design and Facility**
Two side-by-side nature-like fishway designs were tested in the 6.10 m (20 ft) width flume of the CAFRL flume complex; one in a rock weir design and the other in a perturbation boulder (randomized boulder placement) design (**Figs. II-1, II-2**). Each fishway was 3.05 m (10 ft) in width and 33.5 m (110 ft) in length, with a 1:20 slope. Design of the side-by-side fishways allowed us to evaluate two designs simultaneously, ensuring true replication of comparative tests and reducing down-time between tests required by repositioning of rock structures (larger boulders were fabricated from fiberglass, facilitating repositioning by hand). In 2006 tests, two rock placement designs were tested: for the perturbation boulder design, uniformly spaced rocks and rocks spaced to create a meandering central channel; for the rock weir design, low rocks in each weir were positioned to create a meandering channel (Configuration A) or an in-line channel (Configuration B). In 2007, only rock Configuration A was tested. Test flow depths were 0.42 m (16 in), 0.51 m (20 in), 0.61 m (24 in), and 0.76 m (30 in) (invert of base of rocks to water surface upstream of rocks; mean pool depths were slightly less).

**II. 2. Methods**

**II. 2. 1. Hydraulic Measurement**
Point velocity measurements were taken over an 8 by 8 horizontal grid (0.38 to 0.46 m between points) in representative pools with total approximate dimensions of 3.05 m (10 ft) by 3.7 m (12 ft) with developed flow. Measurements were taken at each point at four vertical depths distributed evenly over the total depth. A Marsh McBirney two dimensional electromagnetic velocity meter with a 3.8 cm diameter spherical probe was used for point velocity measurements. Flow ratings of the fishways at all test conditions were also measured using a sharp-crested rating weir at the downstream end of each fishway. Total flow (Q) and energy dissipation factor (EDF) were also calculated for each flow condition.

**II. 2. 2. Fish Collection and Passage Monitoring**
For both test years, American shad were collected and transported to the CAFRL facility from the Holyoke Dam fishlift; all other species (except alewife in 2006) were collected and transported from the lower Connecticut River mainstem and tributaries (Farmington River, Windsor Locks) by boat electrofishing. Alewife tested in 2006 were collected and transported from Town Brook (Plymouth, Massachusetts) at the Jenny Grist Mill Dam tailwater. Passage of fish through the fishways was monitored by passive integrated transponder (PIT) telemetry, with PIT tags attached externally to fish and eight antennas placed at regular intervals along the length of each fishway, using the method of Castro-Santos et al. 1996. Fish were allowed to select either fishway from a central tailwater pool. Trials were run for 3 to 6 h periods in 2006, and for 24 h periods in 2007.

**II. 2. 3. Data Analysis**
PIT detection data were imported into a Microsoft Access database and condensed into presences by reducing consecutive reads at individual antennas of less than a second into single presences of individual fish at an antenna. Passage data were evaluated to determine fishway selection,

passage attempts (detection by at least one PIT antenna), and maximum distance ascended in each fishway ($D_{max}$) over all attempts. Data were pooled for individuals of each species to derive $D_{max}$ curves under each test (flow) condition. Data from species with low sample sizes and/or few detections (<5 per trial) were not analyzed with respect to $D_{max}$.

## II. 3. Results

### II. 3. 1. Hydraulic Evaluation

Summaries of hydraulic data from both fishway designs (two rock configurations at the three nominal flow depths) are given in **Table II-1**. No hydraulic data were collected from the fishways subject to the 0.41 m depth condition or Configuration B at the 0.51 m depth condition. Three-dimensional flow field plots from the two fishways under both configurations and 0.61 and 0.76 flow depths are given in **Appendix 1**.

Increasing flows increased maximum velocities within both fishway designs (with velocities highest at slots between rocks in the perturbation boulder design, or over low rocks in the rock weir design). Under the highest flow depths, these slot/weir velocities approached 3 m $\cdot sec^{-1}$, exceeding maximum velocities permissible in some structural fishway designs. Reconfiguration of rocks to create a meandering central channel in the perturbation boulder fishway or an in-line configuration of low rocks in the rock weir fishway modestly increased maximum velocities.

Energy dissipation factors in both fishways were high (range 166-319 watts $\cdot$ $m^{-3}$ [3.5-6.7 ft-lbs $\cdot$ $sec^{-1} \cdot (ft^3)^{-1}$ ]); in all cases exceeding the 150 watts $\cdot$ $m^{-3}$ (3.2 ft-lbs $\cdot$ $sec^{-1} \cdot (ft^3)^{-1}$) maximum for shad pool-and-weir fishways recommended by Larinier and Travade (2002).

### II. 3. 2. Biological Evaluation

Numbers of tagged test fish detected at PIT antennas for the two fishways under different flow depths are given in **Table II-2**; note that sample sizes for some species are very low, largely due to limited numbers of fish collected. Not all species were tested at all depths; only American shad and blueback herring were tested at the 0.41 m depth. Graphical results of 2006 $D_{max}$ curves (Configurations A and B) with American shad and alewife are given in **Fig. II-3**; comparative 2007 data (Configuration A only) for shad, alewife and other species are given in **Fig. II-4**.

Both years of testing yielded percent passage of American shad generally over 50% throughout the total length of the experimental fishway under most conditions. There appeared to be no consistent preference of fishway type by shad, and upstream passage performance of shad was similar for both designs, regardless of flow depth or rock configuration. We noted that in the rock weir design, shad appeared to seek the deepest portion of pools as resting areas, especially under low flow conditions.

Due to poor attempt and passage performance of alewives in 2006, we elected to test blueback herring in 2007 collected via electrofishing from the more local lower Connecticut River or its tributaries to minimize potential transport and interbasin transfer effects on migratory motivation. However, performance of 2007 blueback herring was roughly equivalent that of 2006 alewives, with less than 50% of fish ascending to the top of the fishways. The cause of limited motivation in both species of river herring continues to be unknown, but collection method (including electrofishing) and handling/transport stress may be dominant factors. Effects of decrease in water temperature over ambient temperatures upon introduction into the CAFRL facility or other reaction to novel water seem to be less important based on 2007 results.

No consistent trends in effect of fishway design, configuration, or flow depth were noted for alewife or blueback herring. However, the lowest test depth of 0.41 m (one trial in 2007) resulted in the best overall passage performance of blueback herring (~40%) recorded for this species or alewife under any condition. Effect of flow depth in passage performance of fish with larger sample sizes (American shad, blueback herring, white sucker, white perch) appeared to be relatively minor; slightly better performance was noted at the higher depths, but this trend was not consistent among species or fishway types. Observations in 2007 of shad behavior in the two fishways (fishway selection, reaction to shallow pool depth, general transit time) appeared to be similar to 2006.

Passage performance of other species (smallmouth bass, yellow perch, black crappie, channel catfish, common carp, fallfish) tested was variable (a few individuals of some of these other species were able to ascend the entire fishway, while others did not even make attempts). However, low sample sizes of these other species that were tested make these results statistically inconclusive.

# PART III - Discussion and Summary

Based on results from the field study, alewives appear to be able to pass nature-like fishways of the Town Brook design with little difficulty. Some questions remain about effects of fishway length; for most applications these fishway designs are best suited to low-head barriers, so typically nature-like fishways will be relatively short in total length. The East River fishway appeared to possess some specific bottlenecks possibly associated with its more pool-and-weir like design; overall gradient was higher (1:15) at East River than at Town Brook (1:20) and alewives may have had difficulty negotiating drops and/or high velocity zones between pools. Overall performance of the East River fishway is more difficult to interpret due to the integrated steeppass fishways, but the basic design may be appropriate for some sites as long as pool drops and plunging flows can be minimized and kept relatively uniform. Data pooled from both fishways indicated an overall relationship between slope and passage performance, but the correlation was based on minimal data and may not necessarily be linear. From this study, the East River design might be viewed as representative of the upper limit for design criteria (slope, length, number of and drop per pool) for nature-like fishways constructed for alewife passage. The Town Brook nature-like fishway offers more conservative design criteria: 1:20 slope, minimal drop per pool, and uniform slope. Both fishway designs appear to allow effective and rapid downstream passage of postspawning adult alewives.

The bypass design of the East River introduced some delay in passage as arriving fish explored both the passage and overflow channels. Full-stream-width passage structures such as Town Brook may therefore some advantage over bypass designs in that there are no competing flow attraction delays associated with full-stream-width designs.

The laboratory experiments permitted more extensive evaluation of fishway design, flow, and rock configuration effects. Results with American shad and white sucker indicated that these two species can negotiate the fishway designs/lengths relatively well, generally with over 50% passing under most of the test conditions. No specific trends in the effects of fishway flow and configuration were noted for these species, at least under the range of flows and configurations tested. Performance of both species would probably be limited under more extreme (higher and lower) test flow conditions. As with the field studies, effects of fishway length for these designs remain unknown. Given that overall passage success for both species rarely exceeded 80% to 90%, there may be limits to overall total length of these fishway designs at this design slope, if failure rates throughout the fishway are cumulative. However, it should be remembered that the 1:20 test slope is still relatively high for this fishway design; passage of these and other species may be even higher if slopes were reduced to the more nominal 1:30 to 1:40 slopes (but fishway length would also be proportionally longer).

No species exhibited an obvious trend in preference for one type of fishway over another. However, these analyses are still pending, and there may be some interaction between fishway flow depth, rock configuration, and fishway selection. It should be noted that most individuals made more than one attempt to ascend a fishway, and many made attempts to ascend both fishways. Entry of fish into a particular fishway design probably is related to attraction to entrance configuration and hydraulics, which deserves further study. It is unclear whether EDF *per se* affects passage in nature-like fishways; EDF values in the experimental fishways were significantly higher than values recommended for structural fishways for American shad (Larinier and Travade 2002), yet shad appeared to negotiate the nature-like fishways well. If EDF is a factor, it can be effectively reduced by either increasing pool volume (length, width, or depth) or decreasing water velocity entering the pool (i.e., reducing drop-per-pool, or effectively, slope).

Passage of other species in the laboratory studies was less efficient. Results from the Town Brook and East River field studies, which evaluated nature-like fishways of similar design and slope to the flume prototypes, indicated that alewives (and possibly morphologically and behaviorally similar blueback herring) should have had little difficulty ascending the prototype fishway structures in the flume facility. Although a transport-handling effect may be the cause of this difference, and attempt rate was low for both species, we noted increased performance of blueback herring under the lowest (0.41 m depth) flow condition, suggesting that passage of this species (and possibly alewives as well) may be higher under flow depths lower than were tested. Passage of striped bass and white perch was also modest in both designs and configurations, and both species appeared to have better passage performance under low flow depths. Although these species are known to use structural fishways, little is known about their passage performance and relative migratory motivation when ascending fish passage structures, so it is difficult to gauge these results against a structural fishway standard. It is possible that these two species again require shallower depths and lower velocities to ascend these and other fishway designs.

**Figure II-1.** Perturbation boulder and rock-weir nature-like passes evaluated at the CAFRL flume facility, showing two rock configurations (A and B) for each pass type (flow direction from top to bottom). Low rocks in rock weir pass are white. Red lines and numerals indicate approximate position and number of PIT tag antennas. 2007 biological evaluations tested configuration A of both fishway types only.

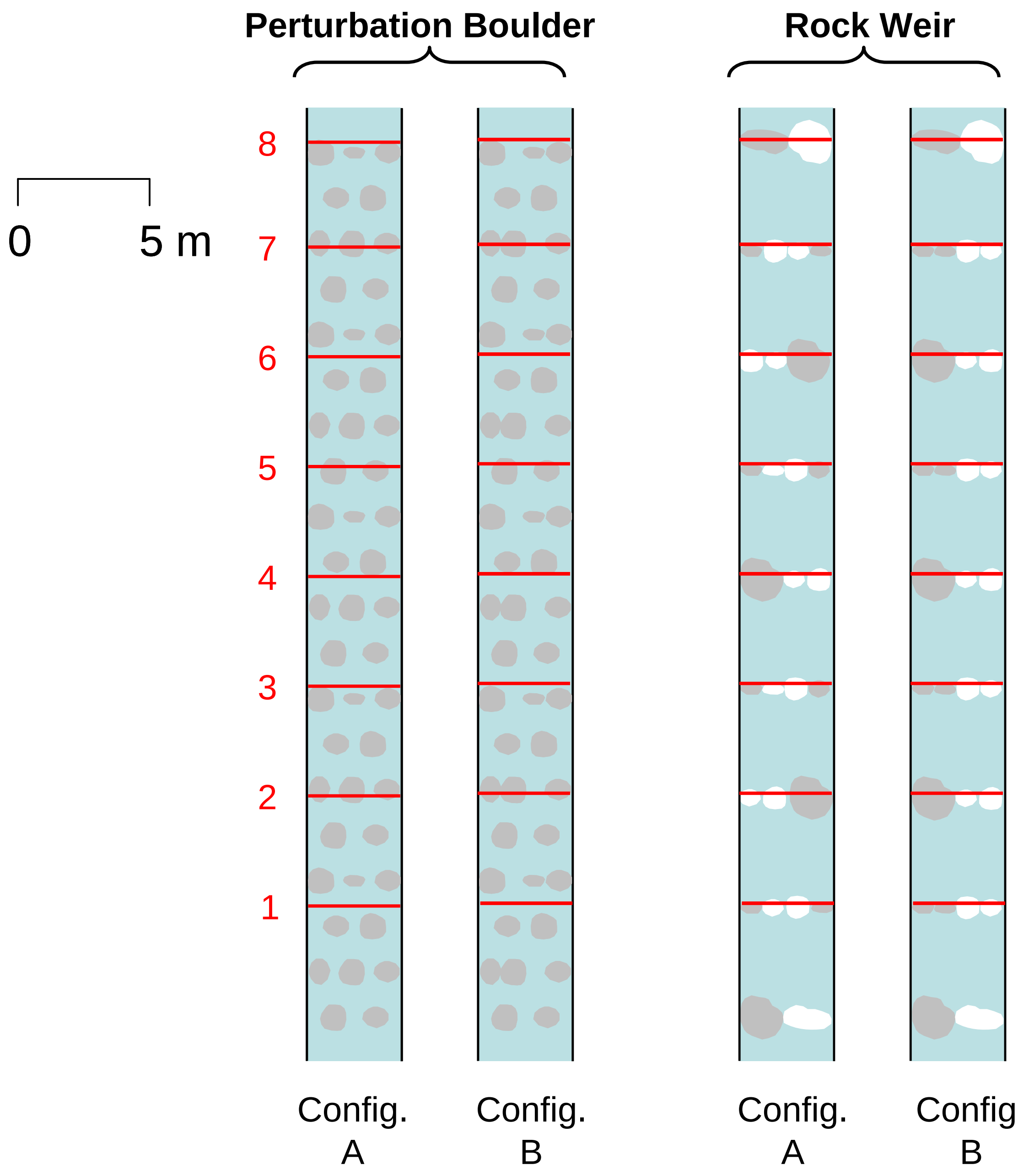


**Figure II-2**. Left: installation of nature-like fishways in the CAFRL flume facility (dewatered). Right: nature-like fishways in operation at 0.76 m flow depth.

**Table II-1**. Hydraulic data for Rock Weir and Perturbation Boulder fishways under two rock configurations (2006 tests) and three test depths. 2007 biological evaluations tested configuration A of both fishway types only

| | | | Rock Weir | | | | Perturbation Boulder |
|---|---|---|---|---|---|---|---|
| **Rock Configuration** | **Test (Headpond) Depth, m (in)** | **Q, $m^3$/sec ($ft^3$/sec)** | **Pool Depth, m (in)** | **Pool Volume, $m^3$ ($ft^3$)** | **EDF watts/$m^3$ ((ft-lbs/sec)/$ft^3$)** | **Maximum velocity, m/sec (ft/sec)** | **Maximum velocity, m/sec (ft/sec)** |
| A | 0.51 (20) | 0.44 (15.4) | 0.43 (16.8) | 4.53 (160) | 172.4 (3.6) | 2.26 (7.4) | 1.98 (6.5) |
| A | 0.61 (24) | 0.68 (24.1) | 0.51 (19.9) | 5.35 (189) | 228.4 (4.8) | 2.68 (8.8) | 2.19 (7.2) |
| A | 0.76 (30) | 1.26 (44.5) | 0.67 (26.4) | 7.08 (250) | 318.9 (6.7) | 2.74 (9.0) | 2.25 (7.4) |
| B | 0.51 (20) | 0.40 (14.3) | 0.41 (16.3) | 4.36 (154) | 166.1 (3.5) | *no data* | *no data* |
| B | 0.61 (24) | 0.63 (22.2) | 0.50 (19.6) | 5.27 (186) | 214.0 (4.5) | 2.74 (9.0) | 2.37 (7.8) |
| B | 0.76 (30) | 1.16 (40.8) | 0.64 (25.3) | 6.80 (240) | 304.5 (6.4) | 2.80 (9.2) | 2.37 (7.8) |

**Table II-2.** Numbers (N) of trials and fish of each species tested in 2006 and 2007, by test flow depths and fishway configurations. N Trials = total number of trials; N Avail = total number of fish available to pass (introduced into flume); N Attempting = number of fish attempting to ascend a fishway (PIT tag detected on at least one antenna); PB = Perturbation Boulder; RW = Rock Weir. Because introduced fish can ascend either fishway, and some individual fish attempt to ascend both fishways during a trial, the total species N for both PB and RW columns under a given flow depth may exceed N Avail. Empty cells indicate no trials run, no data collected.

| | Flow Depth 0.41 m (16") | | | | Flow Depth 0.51 m (20") | | | | Flow Depth 0.61 m (24") | | | | Flow Depth 0.76 m (30") | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | N Attempting | | | | N Attempting | | | | N Attempting | | | | N Attempting | |
| **Year, Configuration, Species** | **N Trials** | **N Avail** | **PB** | **RW** | **N Trials** | **N Avail** | **PB** | **RW** | **N Trials** | **N Avail** | **PB** | **RW** | **N Trials** | **N Avail** | **PB** | **RW** |
| **2006** | | | | | | | | | | | | | | | | |
| Configuration A | | | | | | | | | | | | | | | | |
| American shad | | | | | 3 | 44 | 7 | 27 | 3 | 120 | 47 | 45 | 3 | 118 | 68 | 61 |
| Alewife | | | | | 6 | 437 | 7 | 121 | 3 | 220 | 0 | 55 | 3 | 220 | 22 | 9 |
| Smallmouth bass | | | | | 1 | 5 | 2 | 2 | 1 | 2 | 0 | 2 | | | | |
| Configuration B | | | | | | | | | | | | | | | | |
| American shad | | | | | | | | | 3 | 126 | 19 | 86 | 3 | 134 | 20 | 97 |
| Alewife | | | | | 1 | 57 | 0 | 13 | | | | | 1 | 57 | 20 | 0 |
| **2007** | | | | | | | | | | | | | | | | |
| Configuration A | | | | | | | | | | | | | | | | |
| American shad | 1 | 33 | 31 | 32 | 2 | 125 | 102 | 120 | 4 | 186 | 100 | 101 | 2 | 70 | 57 | 51 |
| Alewife | | | | | 2 | 9 | 3 | 1 | 2 | 17 | 8 | 2 | | | | |
| Blueback herring | 1 | 44 | 37 | 16 | 4 | 215 | 51 | 30 | 3 | 146 | 54 | 30 | 1 | 9 | 7 | 2 |
| Black crappie | | | | | 1 | 1 | 1 | 1 | | | | | | | | |
| Channel catfish | | | | | 1 | 1 | 1 | 0 | 1 | 4 | 2 | 4 | | | | |
| Common carp | | | | | | | | | 1 | 1 | 1 | 1 | | | | |
| Fallfish | | | | | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 3 | 1 | 1 |
| Smallmouth bass | | | | | 1 | 1 | 1 | 1 | 1 | 4 | 4 | 3 | 1 | 2 | 2 | 2 |
| Striped bass | | | | | 1 | 9 | 8 | 7 | 2 | 20 | 17 | 15 | 1 | 7 | 5 | 5 |
| White sucker | | | | | 1 | 33 | 26 | 23 | 2 | 79 | 66 | 64 | 1 | 16 | 12 | 13 |
| White perch | | | | | 1 | 33 | 27 | 28 | 2 | 22 | 20 | 20 | 1 | 24 | 21 | 20 |
| Yellow perch | | | | | 2 | 3 | 2 | 2 | 2 | 5 | 0 | 0 | 1 | 10 | 9 | 9 |

**Figure II-3**. Proportion of fish (American shad and alewife only) passing each antenna position in 2006 tests in Perturbation Boulder and Rock Weir fishways, under three flow depths and two rock configurations.

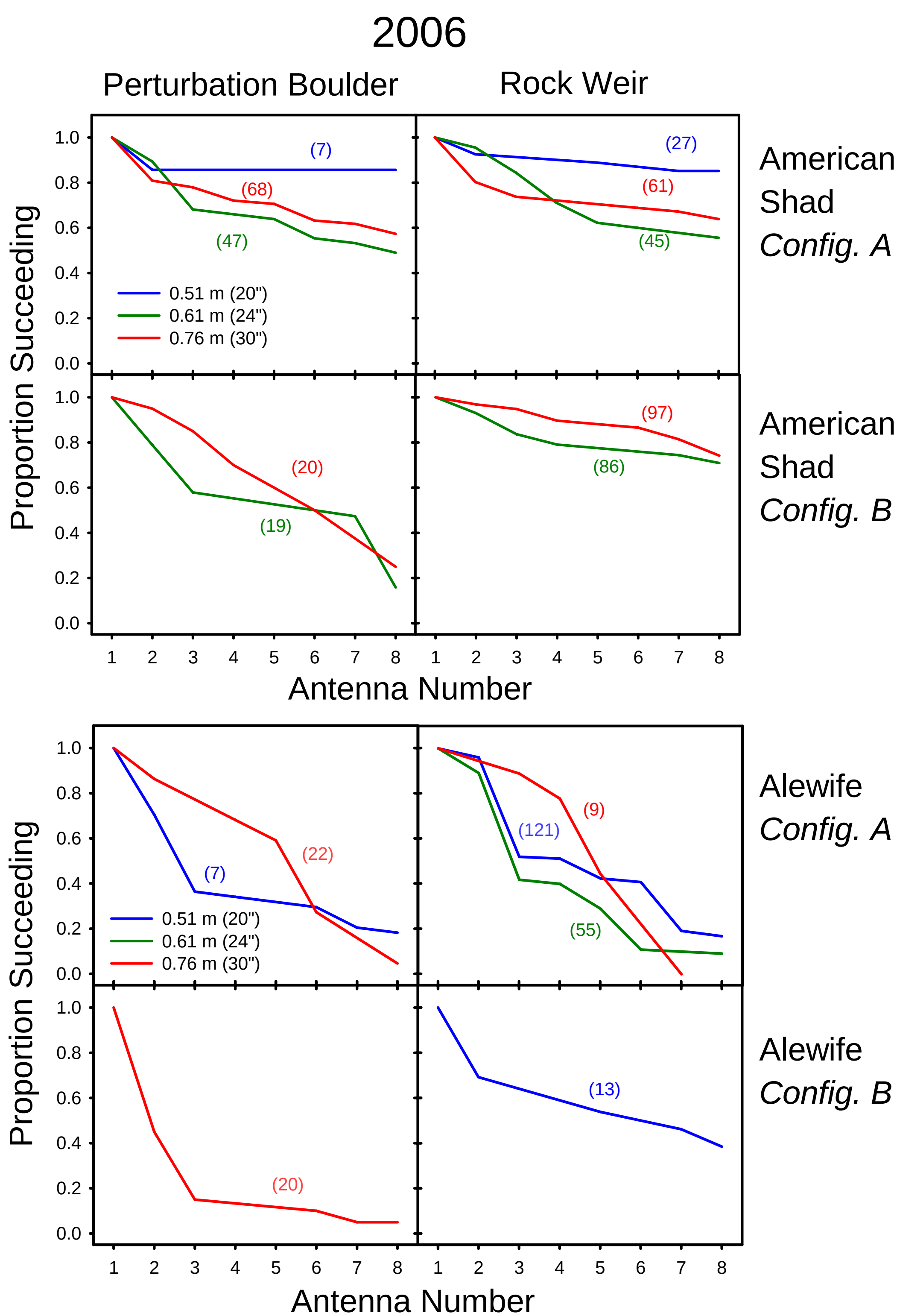
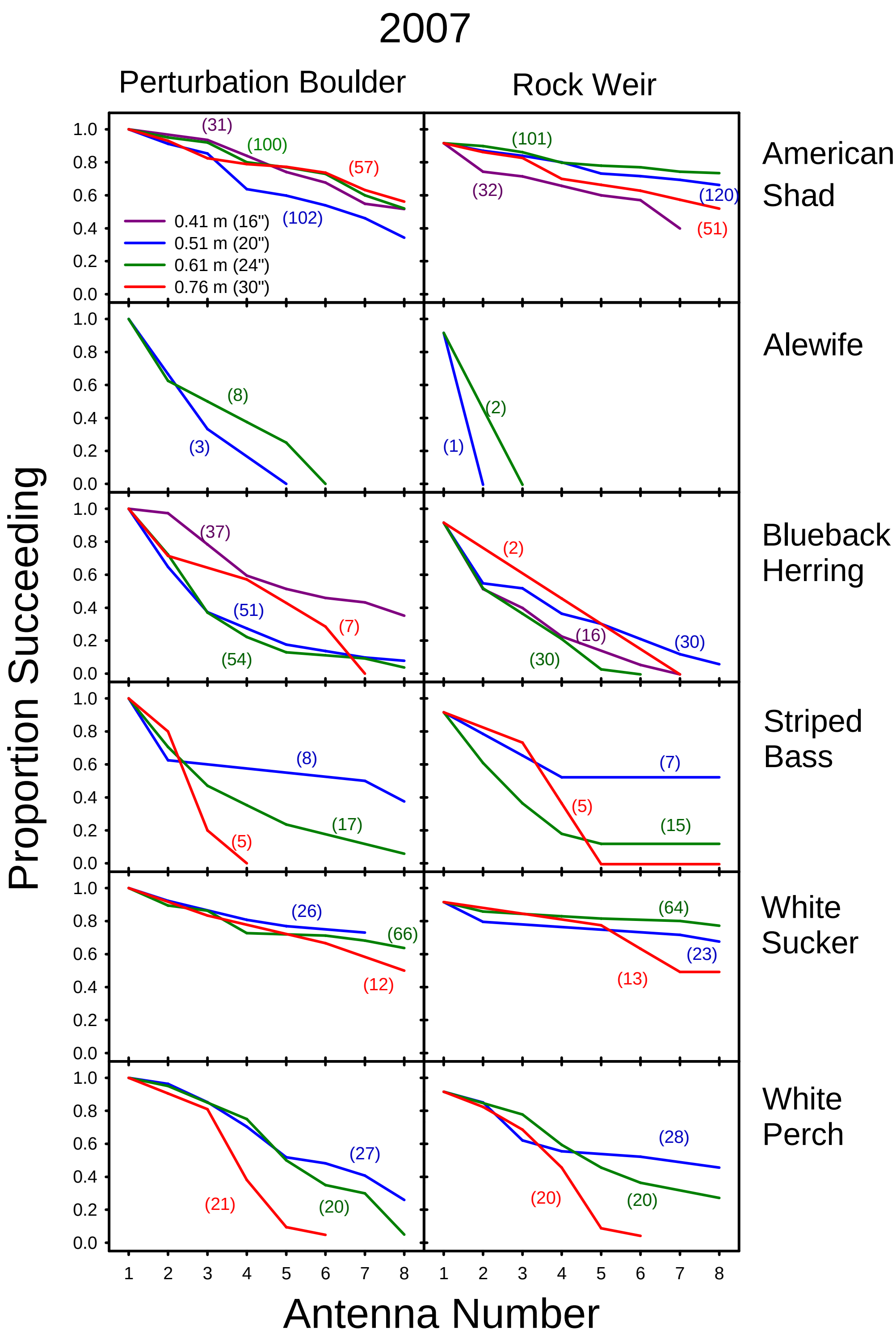


**Figure II-4**. Proportion of fish passing each antenna position in 2007 tests in Perturbation Boulder and Rock Weir fishways, under varying flow depths. Total number of fish detected under each test condition in parentheses. Some passage performance curves may be based only on very few fish, and thus not accurately reflect true passage performance.



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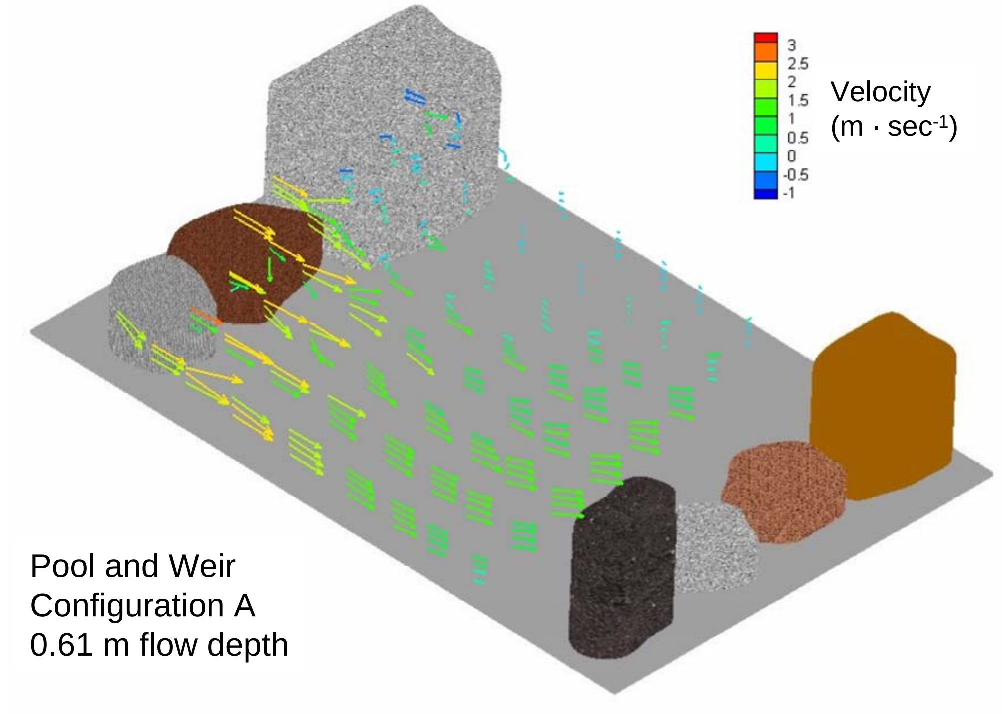
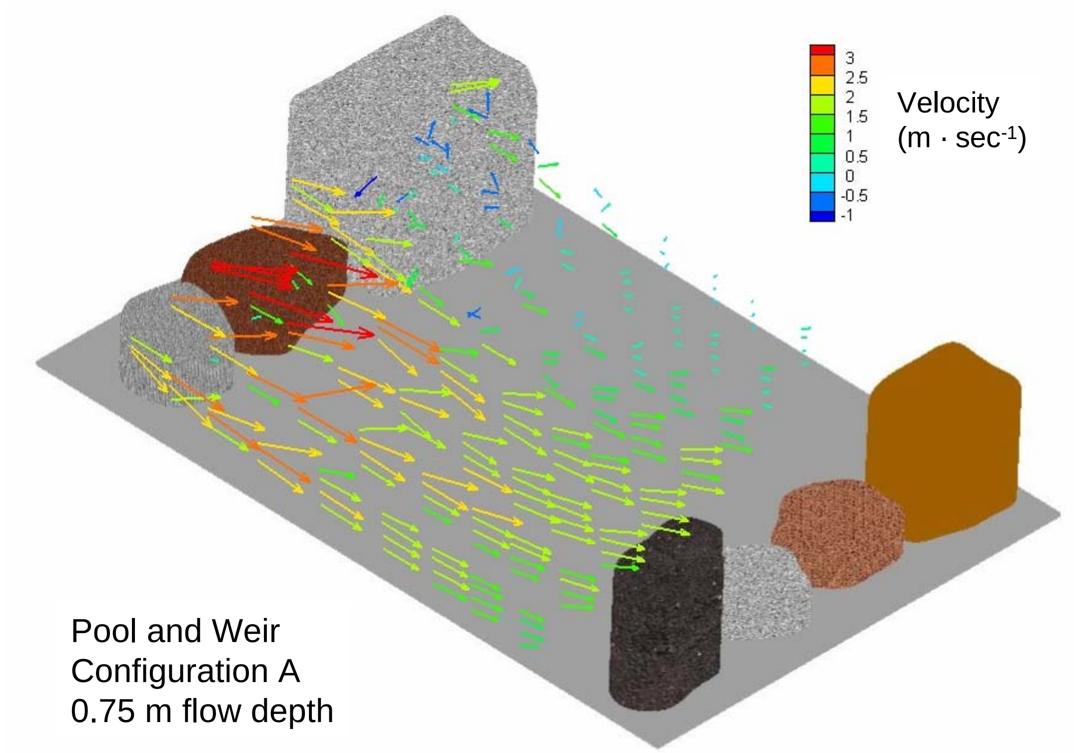
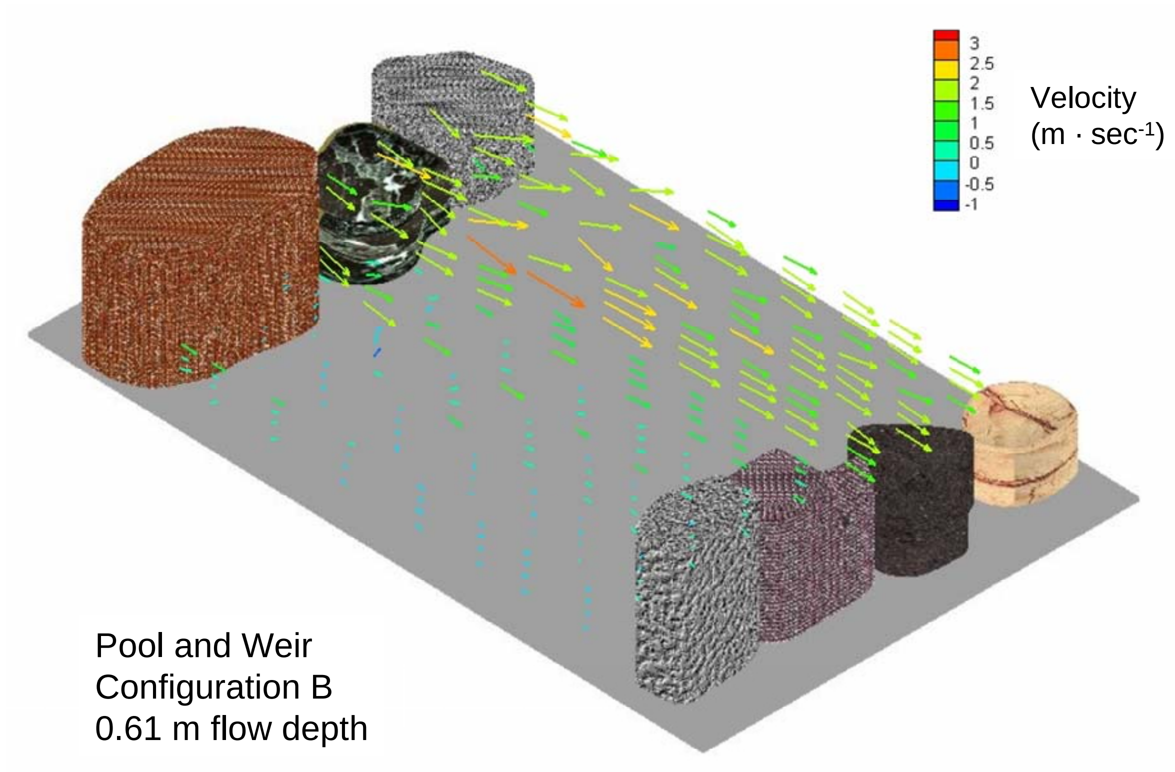
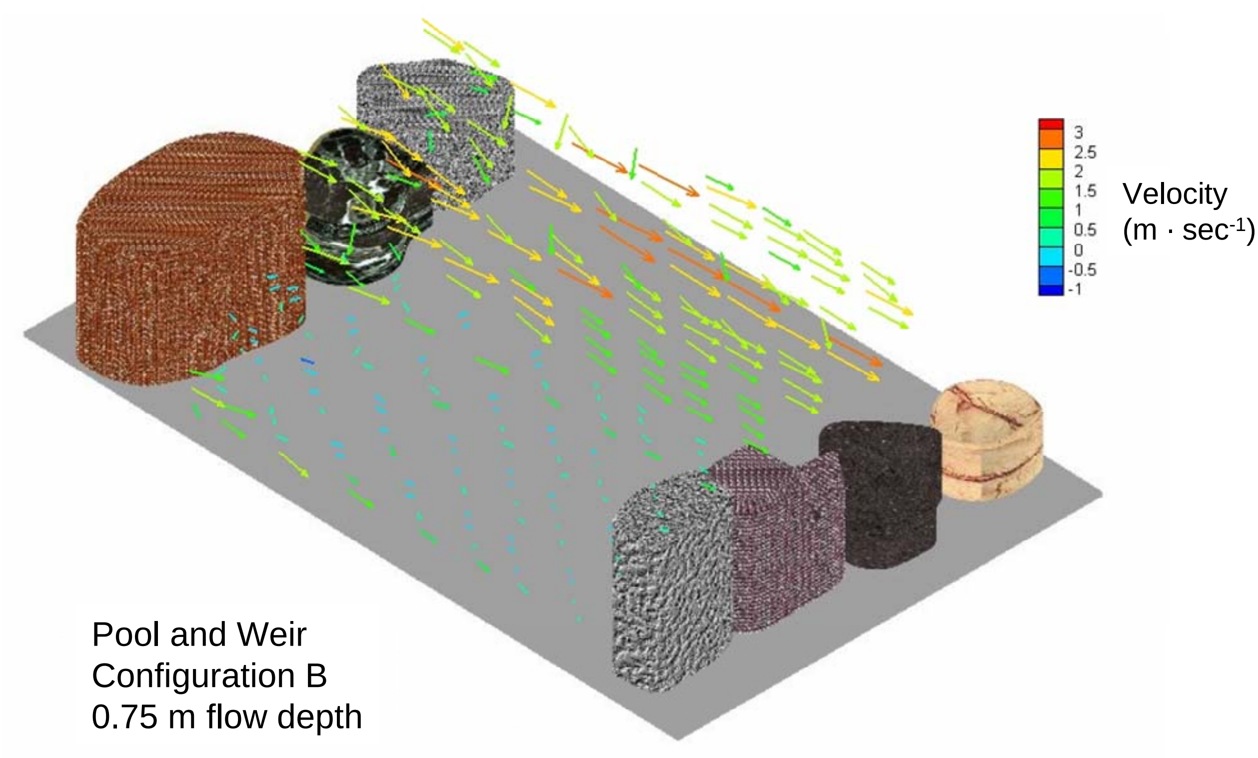
# APPENDIX 1 – Flow Field Data

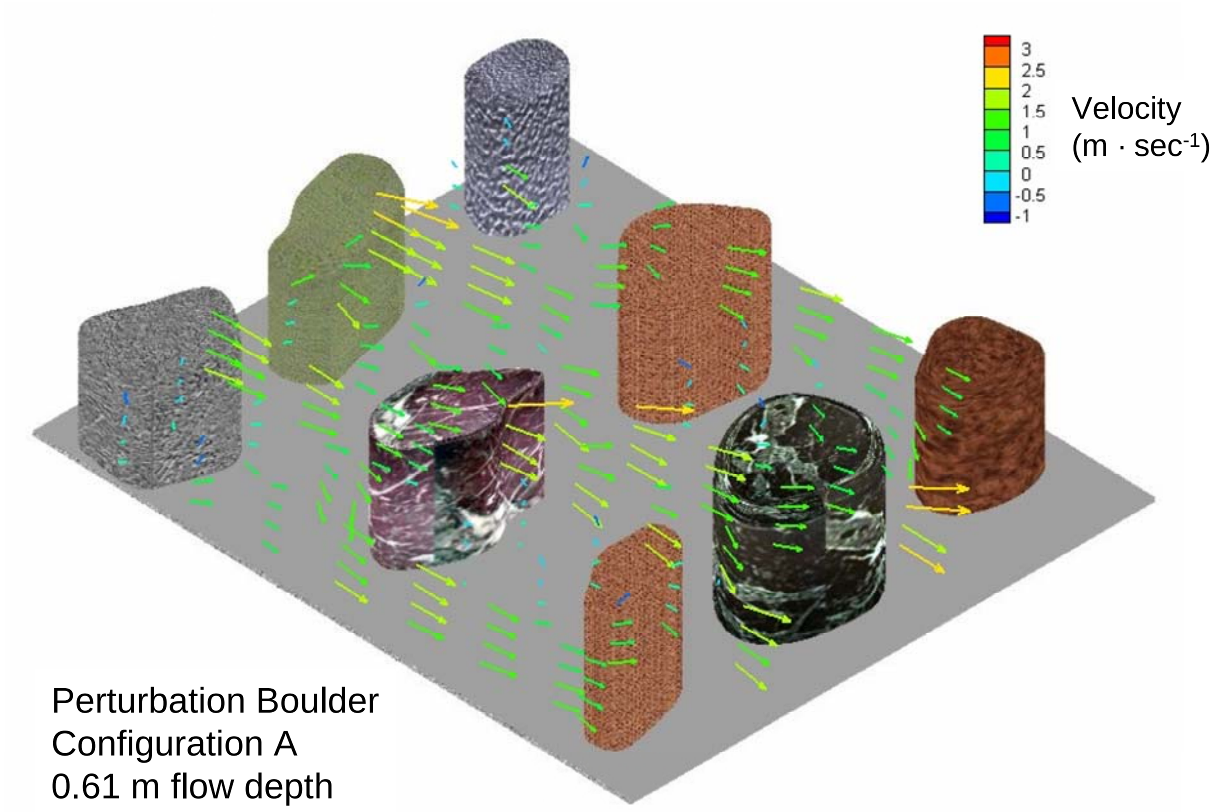
The figures below illustrate measured three-dimensional flow fields for the perturbation boulder and rock weir fishways in Configurations A and B, under flow depths of 0.61 and 0.76 m (24 and 30 inches). Vectors indicate the direction and magnitude (coded by both color and vector length) of mean velocity at each depth point. See **Section II.2.1.** for methods of data collection.

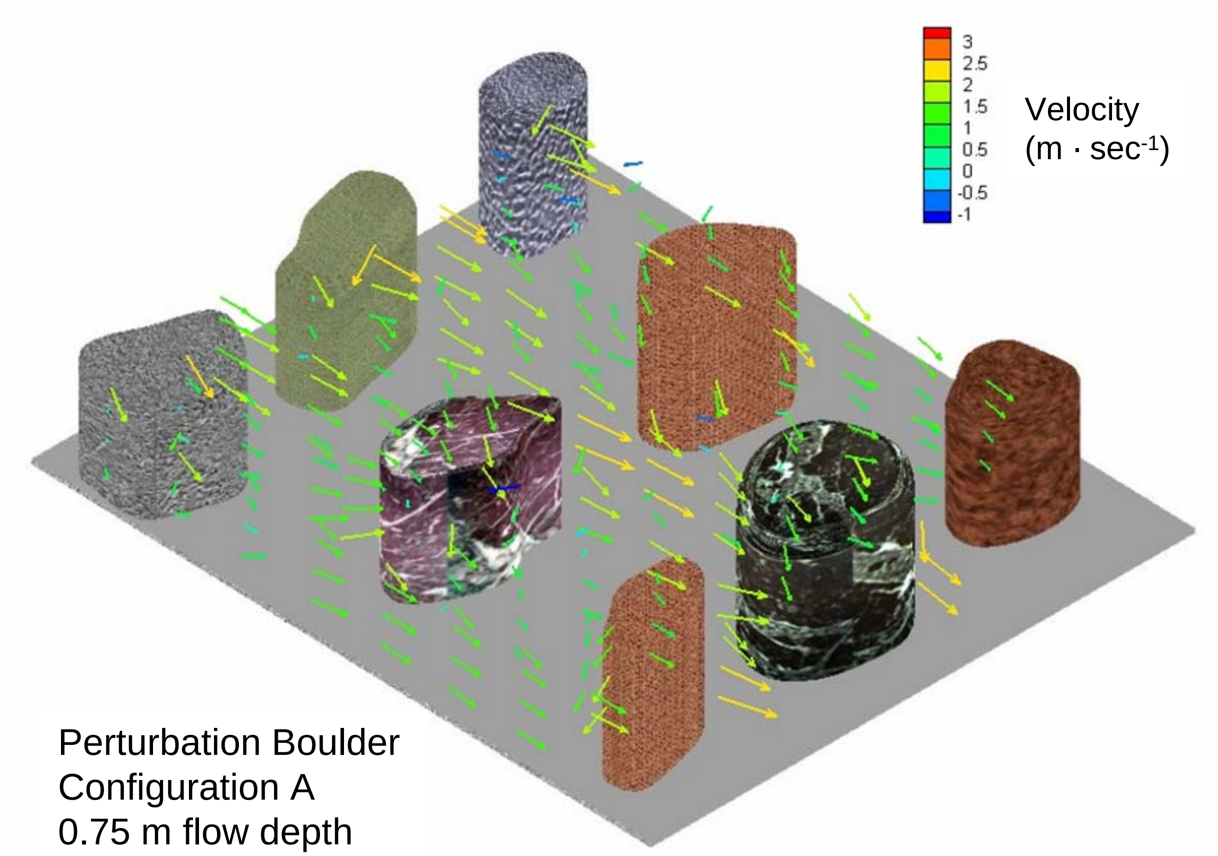


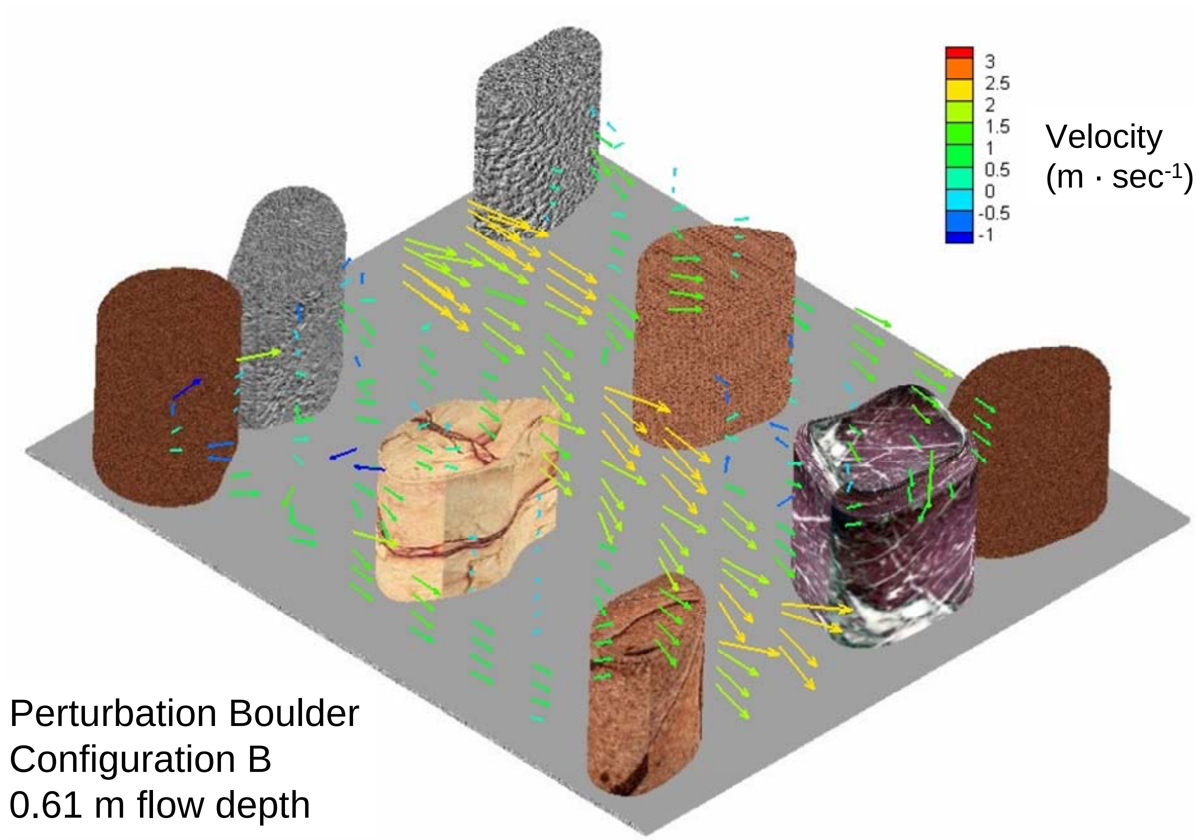



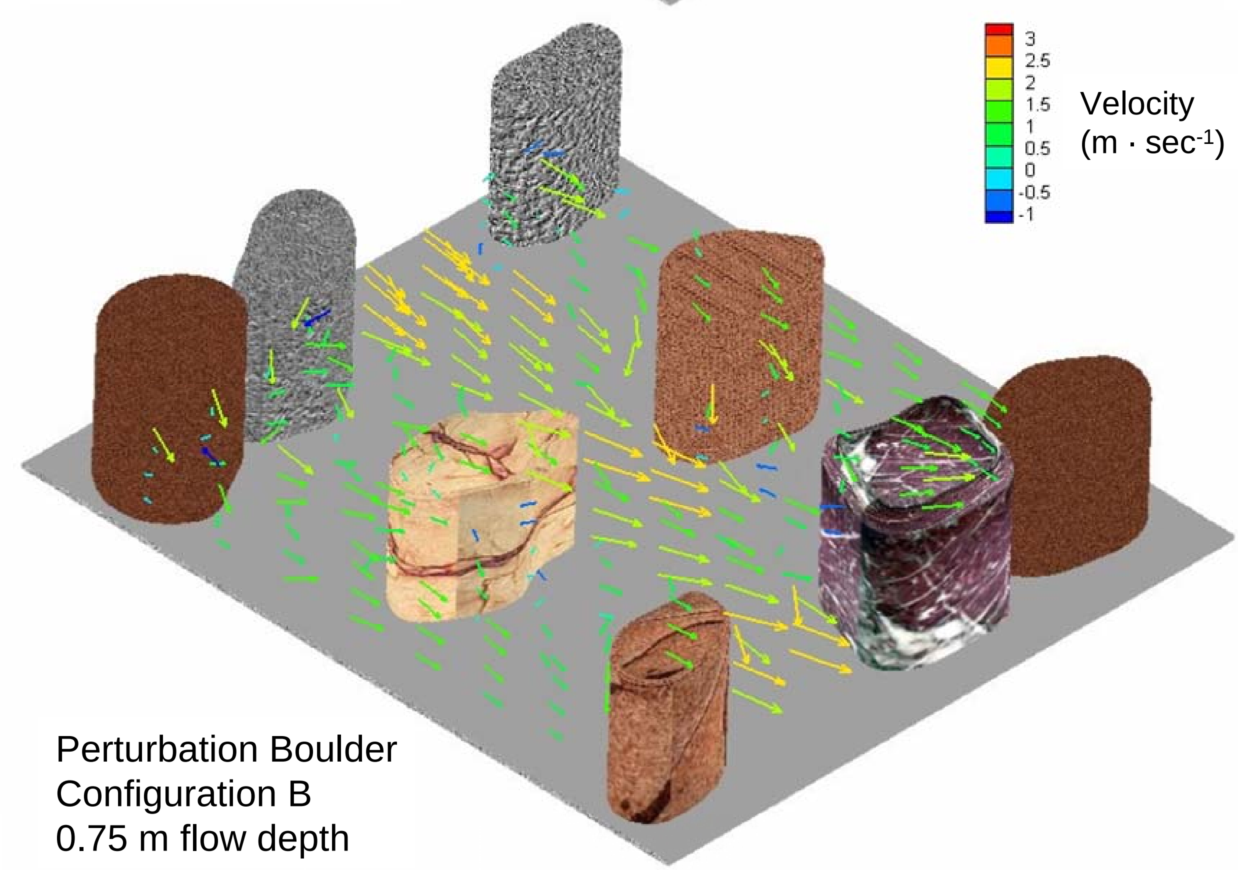

3
2.5
2
1.5
1
0.5
0
-0.5
-1
Velocity
(m · sec-1)
Pool and Weir
Configuration B
0.61 m flow depth


3
2.5
2
1.5
1
0.5
0
-0.5
-1
Velocity
(m · sec-1)
Pool and Weir
Configuration B
0.75 m flow depth


3
2.5
2
1.5
1
0.5
0
-0.5
-1
Velocity
(m · sec-1)
Perturbation Boulder
Configuration A
0.61 m flow depth


3
2.5
2
1.5
1
0.5
0
-0.5
-1
Velocity
(m · sec-1)
Perturbation Boulder
Configuration A
0.75 m flow depth


3
2.5
2
1.5
1
0.5
0
-0.5
-1
Velocity
(m · sec-1)
Perturbation Boulder
Configuration B
0.61 m flow depth


3
2.5
2
1.5
1
0.5
0
-0.5
-1
Velocity
(m · sec-1)
Perturbation Boulder
Configuration B
0.75 m flow depth