TABLE OF CONTENTS

[INTRODUCTION] [Methods] [Results] [Discussion] [References] [Tables] [Figures]

Transactions of the American Fisheries Society: Vol. 127, No. 1, pp. 118–127.

Effect of Water Acceleration on Downstream Migratory Behavior and Passage of Atlantic Salmon Smolts and Juvenile American Shad at Surface Bypasses

Alex Haro, Mufeed Odeh, John Noreika, and Theodore Castro-Santos

S. O. Conte Anadromous Fish Research Center, U.S. Geological Survey, Biological Resources Division, Post Office Box 796, Turners Falls, Massachusetts 01376, USA

Received January 6, 1997; accepted June 17, 1997

Abstract.—Behavior and passage rate of smolts of Atlantic salmon *Salmo salar* and juvenile American shad *Alosa sapidissima* were compared between a standard (sharp-crested) and a modified surface bypass weir that employs uniform flow velocity increase (1 $m \cdot s^{-1} \cdot m^{-1}$ of linear distance). Within the first 30 min after release, significantly more smolts passed the modified weir than the standard weir, but no differences in passage rate between weir types were noted for juvenile American shad. More Atlantic salmon smolts and juvenile American shad were passed by the modified weir in groups of two or more than were passed by the standard weir. Mean lengths of passed and nonpassed smolts were not significantly different between weir types, but American shad passed by the sharp-crested weir were significantly smaller than nonpassed fish. Most individuals of both species that passed the modified weir maintained positive rheotaxis and strong swimming throughout the length of the weir. In addition to acceleration, visual cues may be an important factor in avoidance behaviors near bypass entrances. The observed reduction of delay time before passage and maintenance of school integrity may facilitate appropriate timing of emigration and enhance passage survival.

INTRODUCTION Return to TOC

Guidance and bypassing of downstream migrant fishes past low-head dams are commonly used to reduce turbine entrainment and associated fish mortality. Mechanical barriers, such as racks, louvers, and screens, and behavioral guidance systems, such as light and sound, have shown varying degrees of effectiveness in excluding fish from turbine intakes (EPRI 1986 , 1994 ; Ruggles 1992 ; OTA 1995). Most barrier or guidance systems use some type of bypass entrance structure that leads from a forebay to a chute or pipe that passes migrants downstream. However, fish are often reluctant to enter such structures from large forebay areas, presumably because of unnatural transition conditions of

accelerating water velocity, increasing darkness, or decreasing area. Various techniques have been used to overcome this avoidance behavior, including the attraction of fish into a bypass entrance by means of directional surface flow and lighting at night (Larinier and Boyer-Bernard 1991a ; RMC Environmental Services 1994) or repulsion of fish from turbine intakes with sound (Knudsen et al. 1992 ; Nestler et al. 1992) or strobe lights (Martin et al. 1991 ; Martin and Sullivan 1992). Overall bypass performance may also be related to the ability of downstream migrants to locate a bypass entrance that may occupy a very small area of the entire forebay area or pass a small fraction of forebay flow. Therefore, bypass efficiency may have a significant probabilistic component that is based on the rate at which fish encounter a bypass entrance and, once in the vicinity of a bypass, either pass or avoid the structure.

Early problems in guiding fish into bypass entrances were encountered by Andrew and Geen (1960) who noted that many juvenile sockeye salmon *Oncorhynchus nerka,* coho salmon *O. kisutch,* and chinook salmon *O. tshawytscha* were attracted to an inclined screen surface bypass on a 106-m-wide dam forebay but were reluctant to pass. An increase in bypass flows and manipulation of lighting enhanced the efficiency of the bypass, but it was still considered inefficient for the relatively small forebay. Similar results have been noted for smolts of Atlantic salmon *Salmo salar* by Larinier and Boyer-Bernard (1991a , 1991b). Brett and Alderdice (1958) tested passage of sockeye and coho salmon smolts through an experimental bypass entrance associated with a louver array sited on an open river. Their findings indicated that uniform acceleration of water velocities and minimization of visual and turbulence cues within the bypass entrance improved bypass efficiency. Ruggles and Ryan (1964) found that bypass width and the transition of water velocity influenced efficiency of experimental bypasses for coho, sockeye, and chinook salmon smolts. Following a series of experiments on a modified trash sluice used to pass Atlantic salmon smolts, Travade and Larinier (1992) also recommended uniform, low-turbulence water acceleration characteristics for bypass entrance designs. However, precise measures of improvement of bypass efficiency over a conventional bypass entrance (e.g., unmodified trash sluice or sharp-crested weir) have not been determined for this species.

Juvenile anadromous clupeids also migrate downstream in large numbers (Marcy 1976 ; O'Leary and Kynard 1986) and present similar problems in bypass siting and design. However, much of the work on methods for bypassing juvenile anadromous clupeids has focused on use of behavioral barriers, such as sound (Haymes and Patrick 1986 ; Nestler et al. 1992), light (Haymes et al. 1984 ; Martin and Sullivan 1992), and bubbles (Patrick et al. 1985), rather than the structure or hydraulics of bypass entrances.

We performed a controlled comparison between a conventional sharp-crested weir and a new bypass entrance design (the NU–Alden weir,[2] U.S. patent pending) that employs a uniform spatial flow velocity increase (1 $m \cdot s^{-1} \cdot m^{-1}$ of linear distance) with minimal hydraulic separation and turbulence. The new bypass design was developed by Alden Research Laboratory, Inc. (Holden, Massachusetts) (Johnson et al. 1995) for Northeast Utilities (NU), Berlin, Connecticut. The NU-Alden weir was designed to entrain downstream migrants into high-velocity (>3 m/s) bypass flow with minimal reaction to increased water velocity and minimal avoidance of the bypass entrance. We performed direct comparisons of characteristics of passage of Atlantic salmon smolts through both weir types with equal flow. We also conducted similar tests with juvenile American shad *Alosa sapidissima,* which emigrate from rivers in eastern North America in the late summer and fall and require similar bypass structures. The objectives of our study were to (1) quantify relative passage efficiency of full-scale prototype NU–Alden and sharp-crested weirs for juvenile American shad and Atlantic salmon smolts and (2) define quantitative and qualitative behavioral responses of migrants to both weir types.

Methods Return to TOC

Test facility and hydraulic measurements.—Experiments were performed in an enclosed flume (3 m wide, 6 m deep, and 38 m in length; Figure 1) supplied with river water from a hydropower canal adjacent to the Connecticut River at Turners Falls, Massachusetts. Two surface weir designs (NU–Alden and sharp-crested) were constructed from steel plate and beams that were painted flat gray. The weirs were interchangeable within the single flume (i.e., each weir was tested independently) and were alternated throughout the experimental season. The entire flume was illuminated with artificial light (eight 1,000-W sodium vapor lamps) and light intensities were approximately 1,000 lx at the water surface.

Uniform water depth (5.2 m) upstream of the test weir was achieved in the flume by opening two sluice gates, which provided 2.83 m^3/s of flow over each weir. Approach velocities of water in the flume upstream of the weir were approximately 0.25 m/s. Water velocities within the NU–Alden and sharp-crested weirs were measured with a Marsh McBirney two-directional electromagnetic velocity meter (model 511) with a 3.8-cm-diameter spherical probe. Average velocity contours along the centerline of both weir types are shown in Figure 2.

Test protocol.—Tests were performed during the periods of downstream migration for both species: from 11 May to 18 May 1995 for Atlantic salmon smolts (155–240 mm in fork length, FL; mean, 189.6) and from 26 September to 19 October 1994 for juvenile American shad (65–108 mm FL; mean, 82.1). Although passage rates at existing downstream bypasses are usually higher at night than during the day for both Atlantic salmon smolts (Larinier and Boyer-Bernard 1991b) and juvenile American shad (O'Leary and Kynard 1986), we chose to perform tests during the day (0700 to 1800 hours) because (1) visual avoidance behaviors would be maximized in daylight (minimizing differences in passage performance between the weir types and establishing a more conservative test) and (2) our video observation technique required significant amounts of light to resolve fish images.

Atlantic salmon smolts (age 1+) were obtained from White River National Fish Hatchery (Bethel, Vermont) and transferred to outdoor Burrows ponds (supplied with flowing river water) next to the flume facility for temporary holding before testing. Smolts were fed pelletized commercial trout feed daily. Groups of 50 smolts were transferred to 1-m^3 portable floating net-pens and held outdoors in a channel adjacent to the flume to recover from handling. Smolts that died in net-pens (0–5% of groups) were removed daily and the remaining number of fish was calculated. On the day of testing, a net-pen was floated into a secondary fixed staging pen located 5 m upstream of the weir. Smolts were released from the net pen and allowed to acclimate to flow conditions in the staging pen for 30 min before release into the chamber upstream of the weir (Figure 1).

Juvenile American shad were collected from a bypass sampler at a hydroelectric station (Cabot Station) 0.5 km from the flume facility. American shad were trucked to the flume in a 1,000-L tank within 3 h of capture and transferred directly to the net-pens (100/pen). American shad were tested within 1 week of capture with a release protocol identical to that used for Atlantic salmon smolts. Because American shad were reluctant to exit the staging pen upon release, the upstream chamber was covered with black plastic sheeting, which inhibited attraction of juveniles to the upstream end of the staging pen. Both weirs were uncovered for all tests with both species. Water temperature (nearest 0.1° C; VWR NIST digital thermometer) and transmissivity (α units; Martek model XMS transmissometer) were also measured at the beginning of each test run.

Release of fish from the staging pen marked the start (time 0) of each test run. Fish were allowed to swim freely in the chamber upstream of the weir and volitionally encounter the weir entrance and accelerating flow field. Passage of fish through the weirs was recorded by underwater video cameras mounted either directly upstream of the weir (sharp-crested weir) or behind an acrylic plastic window

(NU–Alden weir). Images were recorded on videotape at 30 frames/s. Fish passing the weir were retained in a downstream plunge pool. After a 180 min run period, the flume was drained, and fish were removed from the upstream chamber and downstream plunge pool, counted, and measured (nearest 0.5 cm FL for smolts, nearest mm FL for juvenile American shad).

Additional experiments with hatchery smolts were repeated in 1995 with the NU–Alden weir to investigate the effect of reduced visual cues. Runs were conducted with the entire flume and weir covered with black plastic (light intensities <0.1 lx at the water surface). Smolts within the weir were observed with an image-intensified video camera (Benthos model 4209). Although supplemental illumination from an array of five 150-mW red light-emitting diodes was necessary to provide usable video images, we noted no avoidance reaction of smolts to the additional light source.

Data analysis.—Videotapes were played back, and the time at which each fish passed the center of each weir was recorded to the nearest second. Times of fish passing the center of the weir but swimming back upstream (i.e., not passed) were not recorded. Fish orientation (facing upstream or downstream) and general behavior (swimming or drifting) was also recorded. Cumulative passage curves (percent of introduced fish passed per unit time) for each test run were generated, and distributions of data pooled for each weir type were compared. To evaluate passage rate at discrete time intervals, cumulative passage was determined for eighteen 10-min time intervals, and mean percent passage was compared between weir types for each interval.

If one fish passed within 1.5 s of another fish, both were classified as belonging to the same group. A grouping interval of $\leq$1.5 s was chosen because two or more fish passing within this time interval were usually no greater than approximately 1 m from each other when approaching either weir. Frequency distributions of percent of fish in each size-group were generated from data pooled from all runs and compared. Proportion of fish passing the weir singly or in groups of two or more were also calculated.

Horizontal and vertical focal positions of fish (measured at the tip of the snout) entering and passing the NU–Alden weir were digitized from video images at 0.1-s intervals. Localized water velocities within the field of view of the video image were measured with the velocity probe, and a resulting two-dimensional velocity map for the two-dimensional video image was calculated. Variability in velocity measurements incurred by averaging velocities laterally across the weir (third dimension) was less than 20% of mean velocity at each longitudinal position. By overlaying digitized fish positions on the velocity map, instantaneous water velocities could then be calculated for each fish position, and tracks of instantaneous focal water velocity versus time were generated for each individual. Tracked fish were classified as either passed (swept over the weir) or not passed (returning to the upstream chamber). Precise time–velocity tracks of fish passing the sharp-crested weir could not be generated because of the higher variability of velocities incurred by reducing the three-dimensional flow field to two dimensions.

Results Return to TOC

Passage Data

Cumulative passage curves of both Atlantic salmon smolts and American shad were asymptotic with time for both weir types, and final percent passage at 180 min was variable between trials (Figure 3; Tables 1, 2). Distributions of passage times between the NU–Alden and sharp-crested weirs were significantly different for both Atlantic salmon smolts (Kolmogorov–Smirnov test, $P < 0.001$) and American shad ($P < 0.01$). Significantly more smolts were passed by the NU–Alden weir than by the sharp-crested weir within the first 10-, 20-, and 30-min time intervals (Mann–Whitney U-test, $P < 0.05$),

but there was no significant difference in percent of smolts passed after 30 min ($P > 0.05$). No significant differences in percent of American shad passed between weir types were found for any time interval ($P > 0.05$). Mean lengths of passed and nonpassed smolts were not significantly different for both the NU–Alden and sharp-crested weirs (analysis of variance, ANOVA; $P > 0.05$). Mean lengths of passed and nonpassed juvenile American shad were not significantly different for the NU–Alden weir (ANOVA; $P > 0.05$), but American shad passed by the sharp-crested weir were significantly smaller (mean FL = 80.6 mm, SE = 0.29) than nonpassed fish (mean FL = 82.9 mm, SE = 0.62; $P < 0.001$). Neither temperature or transmissivity was significantly correlated with percent of fish passed per run (Spearman's ρ, $P > 0.05$).

Behavior

Most Atlantic salmon smolts and juvenile American shad were positively rheotactic (facing upstream) upon entering the accelerating flow field, but became negatively rheotactic (facing downstream) when they could no longer maintain position within high velocity regions. Few smolts entered the weirs headfirst from low-velocity zones. Mean percent of smolts passing the NU–Alden weir headfirst (0.35%; SE = 0.35) was not significantly different than for the sharp-crested weir (0%; SE = 0; Mann–Whitney *U*-test, $P > 0.05$). Mean percent of juvenile American shad passing the NU–Alden weir headfirst (34.6%; SE = 2.97) was significantly greater than for the sharp-crested weir (6.98%; SE = 3.65; Mann–Whitney *U*-test, $P = 0.003$).

Atlantic salmon smolts and juvenile American shad passing in groups were usually oriented in a similar direction. Smolts in groups attempted to maintain cohesion within the accelerating flow field, but some individuals were often swept over the weir and separated from groups. As defined by the 1.5-s grouping criterion, a significantly greater proportion of smolts passed the NU–Alden weir in groups of two or more (mean = 56.6%; SE = 0.12) than passed the sharp-crested weir (mean = 11.6%; SE = 0.04; Mann–Whitney *U*-test, $P = 0.018$; Figure 4). A significantly greater proportion of juvenile American shad also passed the NU–Alden weir in groups of two or more (mean = 59.5%; SE = 0.10) than passed the sharp-crested weir (mean = 18.1%; SE = 0.06; Mann–Whitney *U*-test, $P = 0.012$; Figure 4). Frequency distributions of group size for both Atlantic salmon smolts and American shad were significantly different between weir types (Kolmogorov–Smirnov test, $P < 0.01$).

Burst swimming against the flow was frequently used by both species to attempt escape from high (>1 m/s) water velocities. Instantaneous velocity tracks indicated that most smolts were able to escape from velocities less than approximately 2 m/s, and few fish escaped from higher velocities (Figure 5). Many smolts that passed the NU–Alden weir maintained positive rheotaxis and strong swimming throughout the length of the weir. Tracks of both species indicated they passed at a rate slower than that of passive particles (Figure 5). Virtually all juvenile American shad observed from the window camera of the NU–Alden weir were passed (Figure 5), and few juvenile American shad were observed to be successful in escaping upstream from velocities greater than 1.5 m/s in the NU–Alden weir.

Overall (180-min) passage rates of hatchery Atlantic salmon smolts in 1995 tests with the darkened NU–Alden weir were lower than the 1994 rates in the undarkened weir. However, smolts that were not passed in 1995 tests were significantly smaller than passed fish (ANOVA; $P < 0.001$). To determine the physiological smolting status of 1995 fish, a posttest analysis of gill Na^+,K^+-ATPase activity was performed on passed and nonpassed fish. The Na^+,K^+-ATPase activity of smaller fish was significantly lower than that of larger fish (S. McCormick, S. O. Conte Anadromous Fish Research Center, unpublished data), which indicated that smaller, nonpassed Atlantic salmon had not reached physiological smolt stage. We attribute the observed lower passage rates to a higher proportion of

juvenile Atlantic salmon in the 1995 tests that were neither physiologically nor behaviorally smoltified. As a result, we did not quantitatively evaluate cumulative passage data for 1995 tests. However, few smolts that entered the darkened weir swam upstream to escape, and most were swept over the weir with little or no hesitation. Virtually all smolts tested under darkened conditions were positively rheotactic and entered and passed the weir tail-first.

Discussion Return to TOC

The NU–Alden weir passed Atlantic salmon smolts sooner after release than the sharp-crested weir, and overall numbers of smolts passed at the end of each run were greater for the NU–Alden weir. Conversely, there was no discernable difference in either initial passage rate or overall passage between the NU–Alden and sharp-crested weirs for juvenile American shad. The low overall passage rate of American shad for both weir types (compared with that for salmon smolts) could be explained by either (1) strong avoidance of both weirs, or (2) low motivation to swim downstream and encounter either weir. Observations of juvenile American shad within the staging pen support the latter explanation; many American shad remained within the pen after release (even when the staging pen was darkened), whereas Atlantic salmon smolts usually exited the pen within several minutes of release. Because none of the external physical variables measured during testing (temperature, transmissivity) were significantly correlated with passage rate, motivation to swim downstream may have been responsible for a large portion of the variability in passage rate between Atlantic salmon and American shad.

Fish passing the NU–Alden weir maintained greater school integrity than those passing the sharp-crested weir. A larger proportion of juvenile American shad and Atlantic salmon smolts passed the NU–Alden weir in groups of two or more than passed the sharp-crested weir. Both smolts (Bakshtansky et al. 1987) and American shad (Marcy 1976) migrate downstream in schools that are occasionally large. Downstream progress of smolts can be inhibited by obstacles that do not allow most fish in a school to pass together (Bakshtansky et al. 1993), and the same avoidance behavior may hold for schooling juvenile American shad, which are highly gregarious. A bypass entrance design that accommodates the entry of large schools of fish without breaking up the school may therefore be more effective, especially if schools can be attracted to and retained near the bypass by flow conditions that the fish find acceptable.

An expectation of the NU–Alden weir design was that fish would enter the weir and become entrained into high water velocities with minimal reaction to (and avoidance of) the bypass entrance. Most Atlantic salmon smolts and juvenile American shad did not exhibit this expected behavior in the NU–Alden weir; instead, they exhibited strong positive rheotaxis and behavioral response to the accelerating flow field. When smolts reached a critical reaction point within the weir (corresponding to a water velocity of about 2.25 m/s), they either continued to pass or burst upstream to avoid entrainment. It is unknown whether smolts that were not passed were reacting to water velocity, spatial acceleration, or visual cues when they reached this point. Because few juvenile American shad could escape from water velocities within the field of view of the NU–Alden weir window camera, the critical reaction point for this species is unknown but may have existed at lower velocities located upstream of the field of view of the camera.

At very low light levels (<0.1 lx), passing salmon smolts still swam against the flow through the weir, but rarely swam back upstream. Pavlov (1994) found that when illumation fell below threshold values for optomotor reaction, juvenile riverine fishes would drift with a current rather than maintain position within a flow. Under darkened conditions, smolts entering the NU–Alden weir still maintained positive rheotaxis, rather than drifting passively. This behavior indicates the persistence of visual cues under the low light conditions, detection of the flow field, or displacement by another sensory system. Increased

passage rates for smolts have been noted when lights illuminating bypass entrances were turned off (Larinier and Boyer-Bernard 1991b), but passage rates of juvenile American shad have been observed to increase when bypasses are illuminated (RMC Environmental Services 1994). Visual cues therefore are probably an important (but not exclusive) component to avoidance behavior of fish entering bypasses.

These results indicate a significant improvement of the NU–Alden weir design over a standard sharp-crested weir for passing Atlantic salmon smolts and a minor improvement for passing juvenile American shad. It appears that expansion of the flow transition zone at a bypass entrance has positive effects that result in more fish entering the bypass sooner, and in larger groups. These positive traits are particularly important because in the field, (1) they increase the probability that a fish will enter a bypass within the first several encounters, reducing the delay incurred by searching for, but repeatedly avoiding, a bypass entrance and (2) school integrity will be maintained during and after passage, reducing stress and predation risk. Further modifications of this design and advances in methodologies to attract and retain fish near bypass entrances should enhance the performance of surface bypass designs in the future.

Acknowledgments

We thank George Hecker of Alden Research Laboratory and David Robinson of Northeast Utilities for providing engineering design and modeling data and for construction and modification of prototype weirs. Paul Ruggles derived the conceptual design for the NU–Alden weir. Steve McCormick facilitated physiological tests on smolts. Steve Walk, Philip Rocasah, and Martha Rullman provided valuable assistance with construction, instrumentation, fish collection, experimental assistance, and data analysis.

References Return to TOC

Andrew, F. J., and G. H. Geen. 1960. Sockeye and pink salmon production in relation to proposed dams in the Fraser River system. International Pacific Salmon Fisheries Commission Bulletin 11.

Bakshtansky, E. L., V. D. Nesterov, and A. Haro. 1993. Some aspects of juvenile anadromous salmonid behavior and behavioral studies, and their application to development of fish passage systems.205–209. *in* K. M. Bates, compiler. Fish passage policy and technology. American Fisheries Society, Bioengineering Section, Bethesda, Maryland.

Bakshtansky, E. L., V. D. Nesterov, and M. N. Nekludov. 1987. Development of schooling behavior in juvenile Atlantic salmon, *Salmo salar,* during seaward migration. Journal of Ichthyology. 27:1000–1009.

Brett, J. R., and D. F. Alderdice. 1958. Research on guiding young salmon at two British Columbia field stations. Fisheries Research Board of Canada Bulletin 117.

EPRI (Electric Power Research Institute). 1986. Assessment of downstream migrant fish protection technologies for hydroelectric application. EPRI, Report AP-4711, Palo Alto, California.

EPRI (Electric Power Research Institute). 1994. Fish protection/passage technologies evaluated by EPRI and guidelines for their application. EPRI, Report TR-104120, Palo Alto, California.

Haymes, G. T., and P. H. Patrick. 1986. Exclusion of adult alewife *Alosa pseudoharengus,* using low frequency sound for application at water intakes. Canadian Journal of Fisheries and Aquatic Sciences. 43:855–862.

Haymes, G. T., P. H. Patrick, and L. J. Onisto. 1984. Attraction of fish to mercury vapour light and its application in a generating station forebay. Internationale Revue der gesampten Hydrobiologie. 69:867–876.

Johnson, A., M. Padmanabhan, and G. E. Hecker. 1995. Development of a downstream fish passage weir hydraulic study. Alden Research Laboratory, Report 67-95/M295F, Holden, Massachusetts.

Knudsen, F. R., P. S. Enger, and O. Sand. 1992. Awareness and avoidance responses to sound in juvenile Atlantic salmon, *Salmo salar* L. Journal of Fish Biology. 40:523–534.

Larinier, M., and S. Boyer-Bernard. 1991a. La dévalaison des smolt de saumon atlantique au barrage de Poutès sur l'Allier: utilisation de lampes à vapeur de mercure en vue d'optimiser l'éfficacité de dévalaison. Bulletin Français de la Pêche et de la Pisciculture. 323:129–148.

Larinier, M., and S. Boyer-Bernard. 1991b. Dévalaison des smolts et efficacité d'un exutoire de dévalaison à l'usine hydroélectrique d'Halsou sur la Nive. Bulletin Français de la Pêche et de la Pisciculture. 321:72–92.

Marcy, B. C. 1976. Early life history studies of American shad in the lower Connecticut River and the effects of the Connecticut Yankee Plant.141–168. *in* D. Merriman and L. M. Thorpe, editors. The Connecticut River ecologial study: the impact of a nuclear power plant. American Fisheries Society, Monograph 1, Bethesda, Maryland.

Martin, P., J. Downing, N. Taft, and C. Sullivan. 1991. A demonstration of strobe lights to repel fish.103–112. *in* Waterpower '91. American Society of Civil Engineers, Denver.

Martin, P., and C. Sullivan. 1992. Guiding American shad with strobe lights. Hydro Review. 11:52–58.

Nestler, J. M., G. R. Ploskey, J. Pickens, J. Menzies, and C. Schilt. 1992. Responses of blueback herring to high frequency sound and implications for reducing entrainment at hydropower dams. North American Journal of Fisheries Management. 12:667–683.

O'Leary, J. A., and B. Kynard. 1986. Behavior, length and sex ratio of seaward-migrating juvenile American shad and blueback herring in the Connecticut River. Transactions of the American Fisheries Society. 115:529–536.

OTA (Office of Technology Assessment). 1995. Fish passage technologies: protection at hydropower facilities. U.S. Government Printing Office, OTA-ENV-641, Washington, D.C.

Patrick, P. H., A. E. Christie, D. Sager, C. Hocutt, and J. Stauffer. 1985. Responses of fish to a strobe light/air-bubble barrier. Fisheries Research. 3:157–172.

Pavlov, D. S. 1994. The downstream migration of young fishes in rivers: mechanisms and distribution. Folia Zoologica. 43:193–208.

RMC Environmental Services. 1994. Emigration of juvenile clupeids and their responses to light conditions at the Cabot Station, fall 1993. RMC Environmental Services, Drumore, Pennsylvania.

Ruggles, C. P. 1992. What's new in downstream fish passage?:402–416. *in* D. Mills, editor. Salmon in the sea and new enhancement strategies; 4th international Atlantic salmon symposium. Blackwell

Scientific, Oxford, UK.

Ruggles, C. P., and P. Ryan. 1964. An investigation of louvers as a method of guiding juvenile Pacific salmon. Canadian Fish Culturist. 33:3–67.

Travade, F., and M. Larinier. 1992. La migration de dévalaison: problèmes et dispositifs. Bulletin Français de la Pêche et de la Pisciculture. 326–327:165–176.

Tables Return to TOC

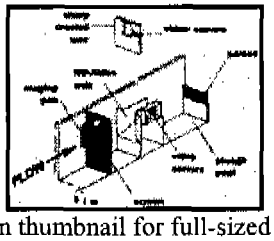
Table 1.—Water characteristics, fish fork length (FL), and cumulative percent of fish passed for single runs of Atlantic salmon smolts for the NU–Alden and sharp-crested weirs; ND = no data.

Date	Temperature (°C)	*N*	Mean (SE) FL, mm	Trans-missivity (α)	Percent passed in: 10 min	20 min	30 min
				NU–Alden weir			
May 11	11.4	50	186 (1.4)	40.0	66.0	86.0	86.0
May 12	12.3	50	184 (1.7)	38.0	58.0	68.0	88.0
May 13	11.9	50	189 (1.5)	46.0	70.0	70.0	78.0
May 14	11.6	50	189 (1.4)	47.5	6.0	6.0	14.0
May 16	12.3	50	190 (1.4)	45.6	40.0	92.0	94.0
May 17	11.6	50	190 (1.5)	44.4	26.0	60.0	82.0
May 18	10.9	50	195 (1.4)	ND	4.0	6.0	8.0
Overall mean (SE)					38.3 (10.3)	55.4 (21.0)	64.3 (24.3)
				Sharp-crested weir			
May 11	11.8	50	185 (1.8)	34.8	0.0	4.0	12.0
May 12	12.2	50	189 (2.0)	42.2	2.0	10.0	28.0
May 13	11.6	50	185 (1.5)	43.0	0.0	0.0	10.0
May 14	11.6	50	189 (1.5)	44.3	0.0	0.0	10.0
May 16	12.3	50	190 (1.5)	38.4	2.0	16.0	38.0
May 18	11.9	50	189 (1.5)	39.0	0.0	2.0	2.0
Overall mean (SE)					0.7 (0.4)	5.3 (2.6)	16.7 (5.5)

Table 2.—Water characteristics, fish fork length (FL), and cumulative percent of fish passed for single runs of juvenile American shad for the NU–Alden and sharp-crested weirs.

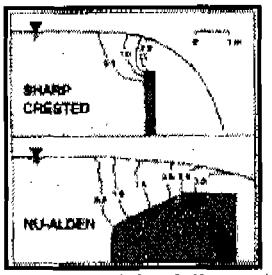
Date	Temperature (°C)	*N*	Mean (SE) FL, mm	Trans-missivity (α)	Percent passed in: 10 min	20 min	30 min
				NU–Alden weir			
Sep 26	18.5	59	80 (0.9)	53.6	8.5	8.5	10.2
Sep 27	18.4	73	83 (0.8)	56.6	9.6	11.0	12.3
Sep 28	18.0	94	81 (0.6)	54.4	7.5	17.0	20.2
Oct 11	14.2	50	84 (0.8)	49.6	4.0	8.0	8.0
Oct 12	13.8	56	87 (0.8)	50.8	5.4	5.4	8.9
Oct 13	13.6	52	87 (1.2)	50.0	5.8	5.8	5.8
Oct 14	13.5	77	86 (0.7)	47.4	0.0	5.2	27.3
Overall mean (SE)					5.8 (1.2)	8.7 (1.6)	13.2 (2.9)
				Sharp-crested weir			
Oct 3	15.5	78	80 (0.7)	54.1	7.7	14.1	28.2
Oct 5	15.1	77	78 (0.6)	54.7	3.9	5.2	6.5
Oct 6	14.7	76	81 (0.5)	55.5	10.5	22.4	26.3
Oct 7	14.9	63	81 (0.5)	56.5	6.4	14.3	15.9
Oct 19	12.8	69	85 (0.6)	49.2	1.5	1.5	1.5
Overall mean (SE)					6.0 (1.6)	11.5 (3.7)	15.7 (5.3)

Figures Return to TOC



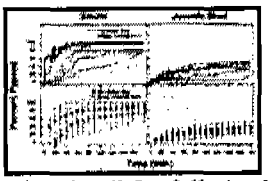
Click on thumbnail for full-sized image.

Figure 1.—Isometric view of installation of removable, exchangeable NU–Alden and sharp-crested weirs within the flume (one flume wall omitted, NU–Alden weir in testing position, sharp-crested weir removed). Arrow indicates direction of water flow. The sharp-crested weir was exchanged for the NU–Alden weir in alternating tests.



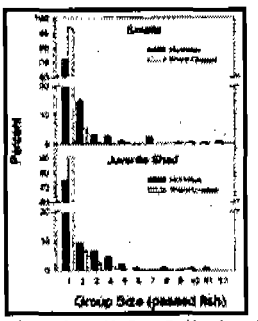
Click on thumbnail for full-sized image.

Figure 2.—Centerline velocity contours (m/s) for the sharp-crested and NU–Alden weirs.



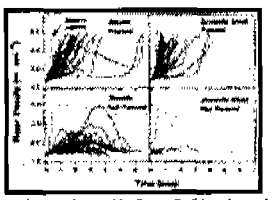
Click on thumbnail for full-sized image.

Figure 3.—Cumulative passage data (180 min) for NU–Alden and sharp-crested weirs for Atlantic salmon smolts and juvenile American shad. Upper panels show percent of the total number of introduced fish passed (as quantified by the video record) per unit time. Lower panels show means (points) ± 95% confidence intervals (vertical bars) of cumulative passage of each weir type at 10-min intervals.



Click on thumbnail for full-sized image.

Figure 4.—Percent of Atlantic salmon smolts and juvenile American shad passed in each group size as determined by the 1.5-s grouping criterion (all runs pooled).



Click on thumbnail for full-sized image.

Figure 5.—Focal water velocity–time tracks for individual Atlantic salmon smolts and juvenile American shad entering the viewing area of the NU–Alden weir. Upper panels represent data for fish entering and passing the weir; lower panels represent data for fish entering but not passing the weir. Dotted line is mean velocity–time track for passive particles.

[1] Corresponding author: E-mail: haro@forwild.umass.edu

[2] Use of trade names does not imply endorsement by the authors or the U.S. Geological Survey, Biological Resources Division.

© Copyright by The American Fisheries Society 1998