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Effectiveness of a High-Frequency-Sound Fish Diversion System at the Annapolis Tidal Hydroelectric Generating Station, Nova Scotia

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Abstract.—We describe an experiment to assess the effectiveness of a fish diversion system that utilizes high-frequency sound at the Annapolis Tidal Generating Station, Nova Scotia, Canada, during the fall of 1999. A band-limited, random-noise signal, with most of the energy focused between 122 and 128 kHz, was projected into the turbine forebay during randomly selected generating cycles. The effectiveness of the diversion system was assessed by monitoring fish passage through the turbine and two adjacent fishways. During the study, fish representing 27 taxa were captured. For the 11 species with sufficient data, we modeled the rate of passage as a function of the sampling site and the on/off status of the diversion system and compared models with and without a set of environmental variables. The environmental component of the model was highly significant for all 11 species. When the environmental variables were removed from the models, the standard errors of the diversion coefficients increased, and between-site comparisons showed that factors other than the on/off status of the diversion system were affecting the effectiveness estimates. Model coefficients were estimated using maximum likelihood, assuming Poisson or extra-Poisson error distributions. The catches of all 11 species were overdispersed, and the statistical significance of the effectiveness estimates was overestimated when a Poisson error distribution was assumed. We conclude that the diversion system reduced passage through the turbines for members of the genus *Alosa* but that it was not effective for the other eight species. With the diversion system activated, the rates of passage of American shad *A. sapidissima* and alewife *A. pseudoharengus* through the turbine tube decreased by 42% and 48%, respectively. For blueback herring *A. aestivalis*, no diversion effect was detected when all catches were included in the analysis. However, a 49% decrease in the rate of passage was detected after the tidal cycles when the three largest catches were trimmed from the data.

During the last decade, behavioral guidance systems have come to the forefront of fish passage research (Popper and Carlson 1998). Stimuli such as light, sound, and electric shock have been used to elicit avoidance responses from fish in an attempt to repel them from structures such as the intake pipes at cooling water plants or the turbine intakes at hydroelectric generating stations. Of these technologies, high-frequency sound (or ultrasound) has been demonstrated to elicit avoidance responses in alewife *Alosa pseudoharengus* (e.g., Dunning et al. 1992), blueback herring *A. aestivalis* (e.g., Nestler et al. 1992), and American shad *A. sapidissima* (e.g., Mann et al. 1997) in tanks and enclosures. The results of these experiments have led to the development of fish deterrent and guidance systems that have subsequently been tested at several electric generating stations with varying degrees of success (e.g., Nestler et al. 1992; Ross et al. 1993, 1996; Popper 1999; Ross 1999).

Fish abundance, behavior, and rates of passage at hydroelectric stations vary considerably in response to environmental variables (O'Leary and Kynard 1986; Stokesbury and Dadswell 1989; Jessop 1990; Gibson 1996), and the failure to incorporate important covariates into the analysis may have confounded some previous assessments of fish guidance systems (Ross et al. 1993). Changes in the rate of fish passage in response to environmental conditions have the potential to lead to under- or overestimation of the effectiveness of a diversion system if these variables are not included in the analysis.

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In this paper, we describe an experiment to test the feasibility of using ultrasound to deter fish from passing through the turbine at the Annapolis Tidal Generating Station in Nova Scotia. Age-0 fish of three species of anadromous *Alosa* that utilize the Annapolis River and Estuary as spawning and nursery habitat (American shad, blueback herring, and alewife) were the target species for this study. The sound barrier was designed specifically for these species. Due to the uncertainty of the range of hearing of many species of fish, we did not know if any of the other species present in the Annapolis Estuary would respond to this signal. The diversity of the Annapolis Estuary fish community provided the opportunity to test whether the selected signal would produce a measurable response in several other species, albeit without the anticipation of success for some of these.

Our objectives were to evaluate the extent to which the diversion system reduced fish passage through the turbine and to determine whether deterred fish then moved seaward through the fishways. We also wanted to determine how environmental variability affected the precision and accuracy of the effectiveness estimates. Specifically, we wanted to evaluate whether a model of the process that determines the rate of fish passage (including the environmental conditions and diversion system status) would result in diversion effectiveness estimates that were more accurate and had smaller standard errors if the confounding effects of the environmental variables were removed.

Methods

Study area.—The Annapolis River estuary is a macrotidal estuary in southwestern Nova Scotia. In 1960, a tidal dam was built across the estuary near Annapolis Royal. This dam transformed the estuary upriver of the dam from a vertically homogenous estuary with a tidal range of about 10 m, to a highly stratified, salt wedge estuary with a tidal range of approximately 0.5 m (Daborn et al. 1979). The Annapolis Tidal Generating Station was constructed at this dam and has been in operation since 1984 (Dadswell et al. 1986) . The operation of the generating station increased the flow of tidal water past the dam, thereby increasing the tidal range on the upstream side of the dam to between 0.5 and 1.0 m. At least 35 species of fish are present in the vicinity of the tidal generating station at some time during the year.

The Annapolis Tidal Generating Station was designed as a prototype to test the StraFlo turbine for proposed, large-scale hydroelectric development in the upper Bay of Fundy. This unit is a low-head, propeller turbine (7.6-m runner diameter) that rotates at 50 revolutions/min and generates only on the ebb tide (normal operating head range: 1.4–6.8 m). The output at a head of 5.5 m is 17.8 MW, with a corresponding discharge of 408 m^3/s. During an average tidal cycle the unit generates for 5.5 h. During low neap tides it may spin freely when the turbine tube is opened to allow the headpond to fill more quickly, but otherwise it is at a standstill for the remainder of the 12.5-h tidal cycle. During most tidal cycles the headpond is filled only through the three sluice gates located within the dam just south of the turbine (Figure 1). Two fishways have been constructed to augment fish passage at the dam. The ‘‘old fishway’’ is a 4-m-wide open slot located beside the sluice gates about 300 m from the turbine forebay; the ‘‘new fishway’’ runs between the turbine forebay and the tailrace, is 3 m wide, and is located about 12 m from the turbine intake. The water depth in both fishways varies between 1.5 and 3 m depending on the stage of the tide. The discharges through the fishways are 42.7 and 10.1 m^3/s for the old and new fishways, respectively, for a 0.3-m head (Stokesbury and Dadswell 1991). The intake to the turbine is 40 m wide and 15.1 m in height, and the water velocity at the entrance to this tube is 0.68 m/s at a flow of 408 m^3/s.

The fish diversion system.—The fish diversion system tested during this assessment was a band-limited, random-noise signal projected into the turbine forebay by 4 International Transducer Corporation model 3406 transducers mounted across the top of the turbine intake (Figure 2). Transducers were angled downward at 15° and sideways at 30° of the centerline. The signal pulse was presented at a 33% duty cycle (0.5 s on followed by 1 s off), with most energy focused between 122 and 128 kHz (Figure 3). The sound pressure level 1 m from the transducers was 181 dB re 1 μPa (Birmann 1999).

Hydrophone measurements were made across the intake canal at depths of 1.6, 3.2, and 4.8 m to verify the acoustic output of the transducer array (Figure 2). The measurements show a variation in sound pressure level of between 155 and 160 dB (Table 1). Based on these measurements, the sound pressure levels dropped below the 160-dB threshold (above which avoidance responses by *Alosa* spp. are known to occur) at a distance of about 10–12 m from the intake face (Birmann 1999).

Experimental design.—Migratory species de-

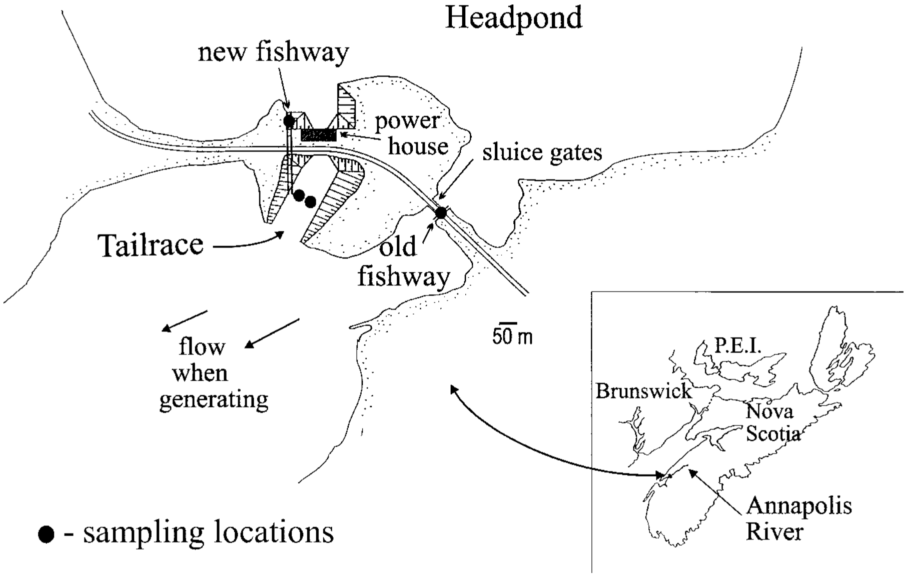

FIGURE 1.—A map of the Annapolis Tidal Generating Station, Nova Scotia, showing the location of the fishways, sluice gates, and sampling locations used during an assessment of an ultrasound fish diversion study during September and October 1999.

terred from passing through the turbine have the option of moving seaward through either of the two fishways. Resident species also have the option of remaining on the landward side of the dam. The requirements for fish diversion therefore differ among species: deterrence from turbine passage is sufficient for resident species, whereas redirection (diversion) to the fishways is a necessary requirement for migratory species. We designed our experiment to evaluate the effectiveness of the system for both deterrence and diversion.

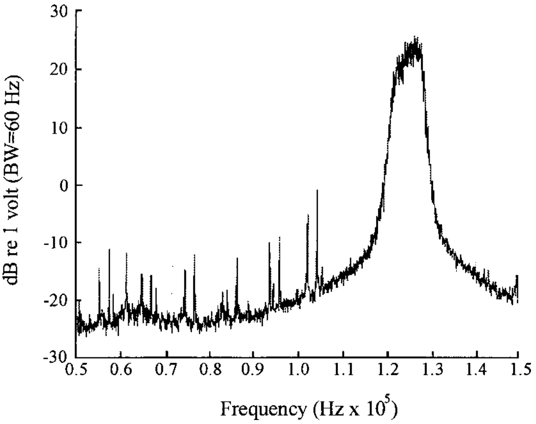

FIGURE 2.—Voltage spectrum of the signal applied to the transducers at the Annapolis Tidal Generating Station during September and October 1999, measured at a bandwidth of 60 Hz (adapted from Birmann 1999).

We conducted the evaluation by monitoring fish passage with nets deployed in the two fishways and at two locations in the tailrace below the turbine (Figure 1). We designed an experiment in which the diversion system was turned either on or off for the full generating period. While this decision limited the sample size, the alternative—to activate and deactivate the diversion system a number of times during a generation cycle—was rejected due to uncertainty about the independence of the samples and the difficulty of interpreting this type of experiment in the context of the actual operation of the plant. Additionally, migratory species tend to move past the turbine at the beginning of the generating cycle (Gibson 1996), so choosing this alternative would have substantially increased the complexity of the statistical model. We chose the catch of each species at each sampling location per generating cycle as our experimental unit. We did not weight our data by the volume of water filtered by a net or discharged through the turbine, because this standardization would only be applicable if the rate of passage was proportional to the volume of water. This assumption would not be suitable for species that stage between generation periods and then migrate early in the generation cycle. Additionally, the duration

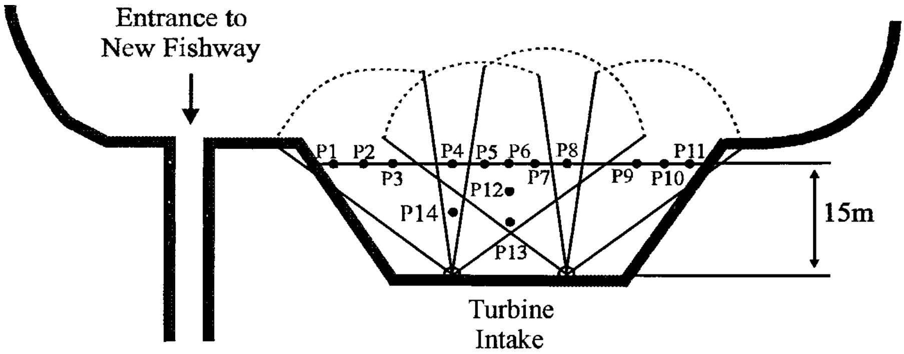

FIGURE 3.—A map of the turbine intake at the Annapolis Tidal Generating Station showing the location of the sound field, the location of the new fishway relative to the turbine intake, and the location of the sound pressure level measurements (P1−P14) taken on September 8, 1999 (adapted from Birmann 1999).

of generation and the discharge volume during each tidal cycle are relatively consistent because the volume of water available for generation is controlled as the headpond is filled.

Fish passage was monitored between September 7 and October 22, 1999. We used a stratified, random sampling design to more or less evenly distribute the sampling effort throughout the study period while retaining randomization. We divided the generation cycles between these dates into consecutive pairs, and randomly chose one cycle from each pair to be sampled. We then took the series of generation cycles to be sampled, divided this series into consecutive pairs, and randomly chose to turn the diversion on during one cycle in each pair, and off during the other.

TABLE 1.—Sound pressure levels measured in the turbine forebay at the Annapolis Tidal Generating Station, Nova Scotia, on September 8, 1999 (from Birmann 1999). Measurement locations are shown in Figure 2.

Location	Hydrophone depth (m)	Sound pressure level (dB re 1 μPa)
P1	3.2	155.2
P2	1.6	158.1
P2	3.2	157.0
P2	4.8	155.3
P3	3.2	157.5
P4	3.2	155.8
P5	3.2	157.9
P6	3.2	159.5
P7	3.2	156.3
P8	3.2	155.0
P9	3.2	158.0
P10	3.2	156.0
P12	1.6	160.0
P12	3.2	160.7
P12	4.8	161.3
P13	1.6	155.1
P13	3.2	163.1
P13	4.8	164.7
P14	3.2	167.4

Based on previous studies of fish passage at the Annapolis causeway (Stokesbury and Dadswell 1989; Gibson 1996), we anticipated that environmental conditions (water temperature, salinity, tidal range, and the proportion of the generating period occurring at night) and seasonal migratory patterns would markedly influence the number of fish moving past the generating station during any given generation cycle. If our randomization procedure (through time) did not achieve complete randomization across the set of environmental variables that determine the rate of fish passage, the resulting estimates of the diversion effectiveness could be inaccurate. Our experimental design allowed the detection of such a bias by comparing the direction of the response between sampling locations. For example, with the diversion system activated, an increase in the rate of passage through a fishway that was accompanied by an increase in the rate of passage through the turbine would not be attributed to the diversion system, but rather to incomplete randomization across environmental variables that determine the rate of fish passage.

Field methods.—The nets used to monitor fish passage in the tailrace were 1.0 m in diameter and consisted of three sections: a 2.0-m-long section, cylindrical in shape, made of 1-cm-mesh nylon netting; a middle section made of 2-mm Nitex net 3 m in length and tapering from 1 to 0.18 m during the final meter; and the collector. The collectors were 1.75 m long and were constructed with Spandex cloth fitted over 0.5-m-diameter aluminum cylinders (0.75 m in length). The entrances to the collectors were funnel shaped to keep fish from escaping; the tail ends of the collectors were designed so that they could be opened and closed with drawstrings. Nets deployed in the fishways were of similar design but were 0.75 m in diameter. Nets in the tailrace were deployed for the full generation period (approximately 5.5 h), while the fishway nets were deployed for the period of seaward flow (approximately 8 h).

Temperature and salinity were measured at the start of each generating period using a YSI model 1000 salinity–conductivity–temperature meter. The proportion of darkness during each sampling period was calculated using the time of sunrise and sunset predicted using ASTRONOMY LAB 1.13. We predicted the tide range by employing the computer program TIDES 3.05, using harmonic constants for Digby, Nova Scotia, at the mouth of the Annapolis estuary.

Data analysis.—We defined the effectiveness of the sound barrier, E, for deterring fish from passing through the turbine as the mean proportion of fish deterred and used the number of fish captured at each site in the tailrace during each generation cycle as a measure of the rate of passage through the turbine during that cycle. The effectiveness of the sound barrier was therefore defined as

$$E = 1 - \frac{\bar{C}_{\mathrm{on}}}{\bar{C}_{\mathrm{off}}}$$

where $\bar{C}_{\mathrm{on}}$ is the mean number of fish of a given species captured in the turbine tailrace with the diversion activated, and $\bar{C}_{\mathrm{off}}$ is the mean number of fish of that species captured in the turbine tailrace with the diversion deactivated. This is the definition used by Popper (1999), although some other researchers have worked with totals rather than means.

To assess whether deterred fish then moved seaward through the fishways, we defined a ''fishway factor,'' F_p, as the ratio of the mean rate of fish passage through a fishway p with the diversion activated to the rate of fish passage with the diversion deactivated. This factor was defined as

$$F_p = \frac{\bar{C}_{p,\mathrm{on}}}{\bar{C}_{p,\mathrm{off}}}$$

where $\bar{C}_{p,\mathrm{on}}$ is the mean number of fish of a given species captured in passage p with the diversion activated, and $\bar{C}_{p,\mathrm{off}}$ is the mean number of fish of that species captured in passage p with the diversion deactivated.

For each species, the effectiveness of the diversion E and the fishway factor F_p are therefore transformations of similar quantities for each passage: the ratios of the mean number of fish captured in a passage with the diversion activated to the mean number captured with the diversion deactivated. We discuss two models that were used to estimate these ratios—one that includes environmental variables and a base model that does not.

For our base model, we assumed that the number of fish of each species captured in passage p during generation period t ($C_{p,t}$) was a random variable that is a function of (1) the passage p, and (2) the on/off status of the diversion system during generation period t (D_t). While we expected that the catches at the two tailrace sites would differ, we expected that the diversion effect would be the same at these sites. We accounted for the differences in catchability among sites by including site as a factor in the model. We assumed that the effects of the diversion system and other factors that influence the rate of fish passage would act multiplicatively and for this reason used log-linear models. In the base model, the expectation of the catch $E(C_{i,t,d})$ of each species at site i, on generation cycle t, given diversion status d was modeled as

$$E(C_{i,t,d}) = \exp(\mu + \beta_i + \beta_{p,d} D_t).$$

Here, μ is the grand mean of the natural logarithm of the catch of the given species, β_i is the coefficient for site i, and $\beta_{p,d}$ is the coefficient for the diversion status d at passage p.

To examine the influence of environmental variability on the resulting estimates, we developed a model to simultaneously estimate the effects of a set of environmental variables together with the effectiveness of the diversion system. This second model is an extension of the base model that includes the following environmental variables: temperature (X_t), salinity (S_t), tidal range (R_t), and the proportion of the sampling period occurring at night (L_t). We postulated that an optimal value for fish passage existed for each species for each environmental variable, and that the rate of passage would decrease as the value deviated from the optimal. We therefore included quadratic terms for each of these variables in the model. The fitted model was therefore

$$\begin{aligned} E(C_{i,t,d}) = \exp(&\mu + \beta_i + \beta_r R_t + \beta_{r2} R_t^2 + \beta_l L_t \\ &+ \beta_{l2} L_t^2 + \beta_{x1} X_t + \beta_{x2} X_t^2 \\ &+ \beta_{y1} S_t + \beta_{y2} S_t^2 + \beta_{p,d} D_t) \end{aligned}$$

where βs not included in the base model correspond to the matching environmental variables.

In both models, the quantity ($\beta_{t,\mathrm{on}} - \beta_{t,\mathrm{off}}$) is an estimate of the difference in the natural logarithms of the mean catch in the tailrace with the diversion activated and deactivated. From this quantity, the ratio of the number of fish captured with the diversion turned on to the number captured with the diversion turned off can be calculated directly and transformed to provide estimates of the effectiveness of the diversion system. Similarly, an estimate of the fishway factor for the new fishway follows directly from the quantity ($\beta_{n,\mathrm{on}} - \beta_{n,\mathrm{off}}$).

We fitted both models to the observed data using two methods within a generalized linear modeling framework (McCullagh and Nelder 1989). First, we assumed a Poisson error structure, which is often used for count data and is appropriate when the passage of individual fish is independent of the passage of other fish. If fish passage is not independent, the precision of the resulting estimates will be under or overestimated using this distribution. We therefore also fitted the models using quasi-likelihood, which allows estimation of a dispersion parameter, ϕ, simultaneously with the model coefficients. Overdispersion ($\phi > 1$) is a common characteristic of fish catches due to a number of factors that affect their distribution (e.g., schooling behavior, habitat preferences, or diel variability) and leads to an overestimation of statistical significance if a Poisson error structure is assumed. The dispersion parameter is used to rescale the variance of $C_{p,t}$ from the Poisson model. This quasilikelihood approach does not change the parameter estimates but results in more realistic estimates of their associated error than would be obtained under an assumption of a Poisson error distribution (which occurs if the estimate of $\phi = 1$). Here, we present standard errors estimated under the assumptions of Poisson and extra-Poisson errors to illustrate that the former can lead to substantial overestimates of statistical significance if the independence assumption is violated.

We tested the statistical significance of the model coefficients under the assumption of asymptotic normality of the response on the link scale (McCullagh and Nelder 1989). Model coefficients were considered statistically different from 0 if the interval $\beta \pm z_{1-\alpha/2}s_\beta$, where s_β is the standard error of the coefficient and $z_{1-\alpha/2}$ is the critical value of a standard normal distribution for a given confidence level, did not include 0. Significance tests for the diversion effectiveness and fishway factor were similarly carried out using one-sided t-tests.

We used likelihood ratio tests (Venables and Ripley 1999) to compare the fits of the base model and the model with the environmental variables. Here, the difference in the residual deviances of the base model D_{base} and the model with the environmental variables D_{env} is assumed to be approximately chi-square distributed. This difference is rescaled by the dispersion parameter to correct for overdispersion (Venables and Ripley 1999),

$$\frac{D_{\mathrm{base}} - D_{\mathrm{env}}}{\phi} \sim \chi^2_8$$

where 8 is the number of degrees of freedom associated with the environmental component of the model.

Alternative models.—To assess the robustness of our conclusions with respect to the models selected, several other models were fitted to both the data and subsets of the data. First, we compared the means of the ratio of the tailrace catch to the new fishway catch with the diversion activated to that with the diversion deactivated using a Mann–Whitney U-test. This approach standardizes the tailrace catch against the new fishway catch and can be used to test for the existence of a significant deterrent effect. The approach has the advantages of not requiring an environmental component of the model (the fishway catch is used as an index of the rate of fish passage) and of not assuming a statistical distribution. The disadvantages are that when the data are standardized in this way, the magnitude of the diversion effect cannot be estimated because the deterrent and diversion characteristics of the diversion system cannot be separated. Additionally, zeros in the new fishway data are problematic because division by 0 is not defined. We used a similar approach where we modeled the catch in the tailrace as a function of the catch in the new fishway and the status of the diversion system using log-linear models and quasilikelihood. This approach allows zeros in the new fishway data to be included in the analysis, but otherwise has the same advantages and disadvantages as the approach above.

Other models that were fitted to the data are modifications of the base model and the environmental models. We fitted both models to the data for each sampling site individually to determine whether the environmental effects at any one site substantially influenced the fit of the model. We also fitted both models to the data after removing periods at the beginning and end of the time series

TABLE 2.—The number of fish of each species captured at each sampling location at the Annapolis Tidal Generating Station, Nova Scotia, while evaluating the effectiveness of an ultrasound fish diversion system during September and October 1999. The two columns for each location present the number of fish captured with the diversion activated (on) and deactivated (off). The number of cycles is the number of generation cycles during which fish of each species were captured. Species for which the data are modeled are marked with an asterisk.

	Tailrace (north side)		Tailrace (south side)		New fishway		Old fishway			
Species	On	Off	On	Off	On	Off	On	Off	Total	Number of cycles
Atlantic silverside *Menidia menidia**	479	304	464	115	17214	18706	4183	6534	47999	47
Atlantic herring *Clupea harengus**	232	387	107	165	317	561	50	38	1857	42
Northern pipefish *Syngnathus fuscus**	55	75	27	55	89	343	57	346	1047	41
Blackspotted stickleback *Gasterosteus wheatlandi**	18	28	19	11	260	341	78	95	850	44
Blueback herring *Alosa aestivalis**	70	68	42	28	43	50	10	0	311	33
Mummichog *Fundulus heteroclitus*	2	0	2	2	22	75	12	54	169	14
Alewife *Alosa pseudoharengus**	8	12	3	11	85	39	2	0	160	23
Sea lamprey *Petromyzon marinus*	10	8	2	0	18	18	52	50	158	4
Hake *Urophycis* spp.*	19	38	14	24	7	16	2	3	123	24
American eel *Anguilla rostrata**	1	6	3	1	36	64	0	5	116	27
American shad *Alosa sapidissima**	9	15	3	13	44	18	0	0	102	23
Butterfish *Peprilus triacanthus**	12	18	0	4	8	39	2	5	88	26
Windowpane *Scophthalmus aquosus**	7	9	4	10	8	14	2	7	61	23
Winter flounder *Pleuronectes americanus*	11	9	5	12	1	2	0	2	42	16
Rainbow smelt *Osmerus mordax*	2	2	1	1	4	3	0	2	15	10
Atlantic mackerel *Scomber scombrus*	2	2	2	4	0	1	1	0	12	12
Lumpfish *Cyclopterus lumpus*	1	2	0	0	2	1	0	0	6	6
Cunner *Tautogolabrus adspersus*	3	0	0	0	0	2	1	0	6	5
White perch *Morone americana*	0	0	0	0	0	2	1	0	3	1
Pollock *Pollachius virens*	0	0	0	0	1	2	0	0	3	3
Smooth flounder *Pleuronectes putnami*	0	1	0	0	0	0	1	0	2	2
Bluefish *Pomatomus saltatrix*	0	0	0	0	2	0	0	0	2	1
Wrymouth *Cryptacanthodes maculatus*	0	0	0	0	0	0	0	1	1	1
Longhorn sculpin (*Myoxocephalus octodecemspinosus*	0	0	1	0	0	0	0	0	1	1
Meek's halfbeak *Hyporhamphus meeki*	0	0	0	0	0	1	0	0	1	1
Flying gurnard *Dactylopterus volitans*	0	0	0	0	0	1	0	0	1	1
Fourbeard rockling *Enchelyopus cimbrius*	1	0	0	0	0	0	0	0	1	1

if the species under investigation was not present throughout the study to determine if these zero catches were influencing the results. We also estimated the effectiveness of the diversion system after removing seasonal trends in abundance by including ‘‘generation cycle number’’ as a third-order polynomial in the model, again using both the full data set and subgroups based on sampling site. Finally, for species present in adequate abundance, we fitted the models after trimming subsets of the largest catches from the data to determine if the effectiveness of the diversion changed as abundance increased.

Results

Sampling was conducted at the four locations during 48 generation cycles. Net failures (typically due to fouling with seaweed or other debris) reduced the number of valid samples to 47 for the north side of the tailrace, 45 for the south side of the tailrace, 45 for the new fishway, and 44 for the old fishway. Storm conditions and a diversion equipment malfunction near the end of the project resulted in the diversion being turned off during more periods ($N = 28$) than it was on ($N = 20$).

Over 53,000 fish representing 27 taxa were captured during this study (Table 2). Of these, Atlantic silversides were by far the most abundant. We present the results for the 11 species that were captured during more than 20 generation cycles (Table 2). While some species (e.g., sea lamprey*)* were captured in greater abundance than some of the species for which results are presented, a preliminary analysis for these species produced results that were sensitive to the model formulation and had very wide standard errors, and therefore could not be considered reliable. We present a detailed analysis of the clupeid data and a summary of the results for the remaining 7 species.

The relative abundance of the clupeids varied throughout the study and among sampling sites. Blueback herring were captured most frequently in the tailrace (north side) and new fishway (Figure 4), and were most abundant at all four locations during the last week of September. Most alewives and American shad were captured in the new fish-

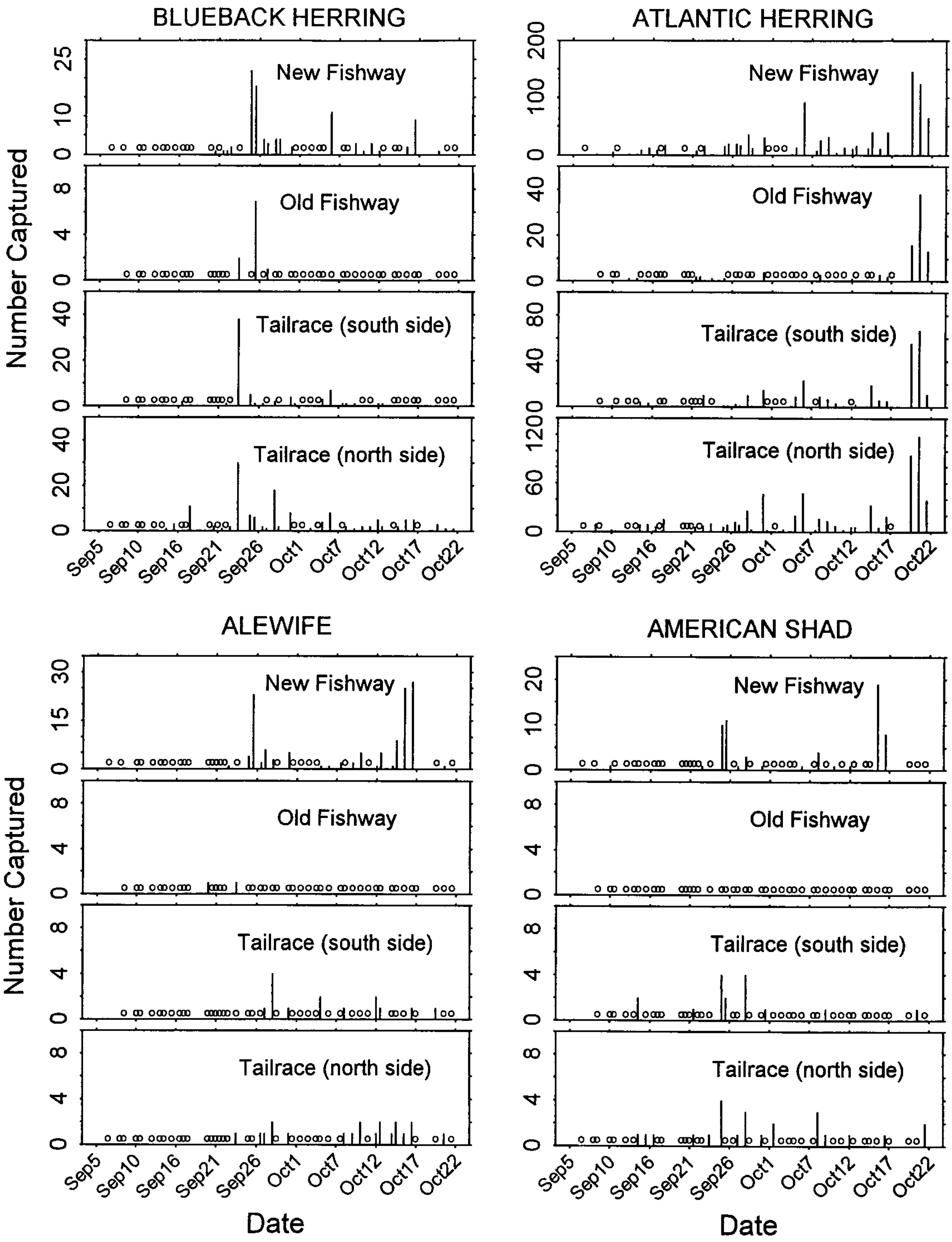

FIGURE 4.—The locations, times, and magnitudes of clupeid catches at the Annapolis Tidal Generating Station while evaluating the effectiveness of an ultrasound fish diversion system during September and October 1999. Generation periods sampled when fish were not captured are marked with small circles Note the scale differences between axes.

TABLE 3.—Model coefficients and standard errors (in parentheses) for clupeids captured at the Annapolis Tidal Generating Station, Nova Scotia, while evaluating the effectiveness of an ultrasound fish diversion system during September and October 1999. Standard errors are corrected for overdispersion. The site coefficients are scaled against the tailrace (south side) site. The diversion coefficients are defined as $\log_e N_{\text{off}} - \log_e N_{\text{on}}$, where N_{off} and N_{on} are the numbers of fish captured with the diversion system off and on, respectively. Statistical significance was assessed by means of two-tailed *t*-tests; $P < 0.10$*, $P < 0.05$**, and $P < 0.01$*** (residual degrees of freedom = 169).

Variable	American shad	Blueback herring	Blueback herring (trimmed)	Alewife	Atlantic herring
Dispersion parameter	2.24	3.37	2.35	1.39	8.58
Intercept	6.70 (12.06)	−26.37 (10.10)***	−5.53 (9.51)	5.56 (8.21)	25.88 (5.06)***
Site: new fishway	3.54 (5.61)	0.23 (0.27)	0.73 (0.25)***	2.27 (0.30)***	0.72 (0.18)***
Site: old fishway	−6.67 (16.84)	−1.16 (0.45)**	−0.73 (0.40)*	−1.51 (0.65)**	−1.20 (0.32)***
Site: tailrace (north side)	1.76 (5.62)	0.80 (0.21)***	0.61 (0.21)***	−0.15 (0.34)	0.63 (0.16)***
Proportion of darkness	4.43 (3.29)*	5.76 (2.30)**	7.58 (2.09)***	11.38 (2.75)***	1.78 (1.54)
Proportion of darkness squared	−2.50 (2.81)	−3.74 (1.97)*	−5.53 (1.78)***	−8.03 (2.27)***	0.66 (1.28)
Tidal range	−2.40 (2.20)	1.60 (1.64)	−3.30 (1.60)**	−6.89 (1.75)***	−4.17 (1.23)***
Tidal range squared	0.19 (0.16)	−0.11 (0.12)	0.23 (0.12)**	0.48 (0.13)***	0.33 (0.09)***
Salinity	0.03 (0.50)	0.57 (0.38)	−0.28 (0.35)	−0.39 (0.40)	−0.59 (0.29)**
Salinity squared	−0.01 (0.01)	−0.01 (0.01)*	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)**
Temperature	−0.23 (0.98)	1.98 (1.01)**	2.78 (0.92)***	3.42 (0.92)***	−0.53 (0.43)
Temperature squared	0.01 (0.03)	−0.06 (0.03)*	−0.09 (0.03)***	−0.12 (0.03)***	0.01 (0.02)
Diversion: new fishway	−1.20 (0.4)***	0.04 (0.39)	−0.45 (0.39)	−0.92 (0.27)***	0.31 (0.22)
Diversion: old fishway	−0.18 (30.8)	−7.52 (13.81)	−7.47 (12.22)	−6.71 (13.99)	−0.51 (0.63)
Diversion: tailrace	0.54 (0.54)	−0.22 (0.27)	0.68 (0.31)**	0.65 (0.48)	−0.01 (0.23)

way, with peak abundances during the last week of September and mid-October. Very few clupeids were caught in the old fishway, regardless of whether or not the diversion was activated (Figure 4). Additionally, no significant diversion effect was detected for any species at the old fishway (clupeids: Table 3), although standard errors for the parameters estimates were very large. Consequently, the data provide little indication about the effectiveness of the diversion at this site, other than it does not appear to be an important passage for most species with or without the diversion system. For this reason, we focus the remaining analysis on the rates of passage through the turbine and the new fishway.

When the catches in the tailrace were modeled as a function of the catches in the new fishway and the on/off status of the diversion system, significant deterrent effects were detected for American shad ($P = 0.03$; df = 40) and alewife ($P = 0.06$; df = 40), but not for the other species. No significant deterrent effects were detected using the Mann–Whitney *U*-test.

With one exception, the other alternative modeling approaches resulted in only minor differences in the coefficient estimates and did not change our interpretation of the effectiveness of the diversion system from that described below. For blueback herring, the estimates for both the diversion effectiveness and the fishway factor changed when the largest catches were trimmed from the data. We have included an analysis of the blueback herring data with the three largest catches removed under the label ‘‘blueback herring trimmed,’’ as well as the analysis for the full set of data for blueback herring.

Environmental variables affected the rate of fish passage at the Annapolis Tidal Generating Station. For *Alosa* spp., daylight (the proportion of darkness) had the greatest influence of the environmental variables (Table 3), with the largest catches occurring at night. Catches of all clupeid species except alewife increased with tidal range. Within the clupeids, salinity was a significant variable only for Atlantic herring (Table 3). Temperature was a significant variable for alewives and blueback herring. Comparison of the deviances for the base model with the model including environmental variables shows that the environmental component of the model was highly significant for all species (Table 4). The percentage of the null deviance explained by the base model ranged between 3.9% for windowpane to 44.6% for American eels, and was less than 30% for 8 of the 11 species. The percentage of the null deviance explained by the model with the environmental variables ranged from 36.6% for windowpane to 97.5% for Atlantic herring, and was greater than 50% for 8 of the 11 species.

Estimates of the effectiveness of the diversion system differed between the base model and the model including the environmental variables for

TABLE 4.—An analysis of the residual deviances for the base model and the model with environmental variables for 11 species of fish captured at the Annapolis Tidal Generating Station, Nova Scotia, during September and October 1999, while evaluating the effectiveness of an ultrasound fish diversion system. The mean dispersion parameter (ϕ) is the mean of the parameter estimates from the two models. The *P*-values are based on a likelihood ratio test after correcting the differences in the residual deviances for overdispersion. The residual degrees of freedom are 166 and 174 for the models with and without the environmental variables.

		Residual deviance				
Species	Null deviance	Base model	Environmental model	Difference	Mean ϕ	*P*-value
Atlantic silverside	182,871.9	111,997.8	56,370.6	55,627.2	899.8	<0.001
Atlantic herring	4,541.8	3,657.8	1,020.4	2,637.4	21.9	<0.001
Pipefish	2,428.1	1,766.9	706.5	1,060.4	9.2	<0.001
Blackspotted stickleback	2,290.0	1,352.8	1,007.3	345.5	8.7	<0.001
Blueback herring	1,003.8	848.1	459.2	388.6	6.6	<0.001
Blueback herring (trimmed)	628.3	487.4	281.2	206.2	3.2	<0.001
Alewife	688.4	430.6	184.7	245.9	2.3	<0.001
Hake spp.	409.1	353.7	150.2	203.5	2.4	<0.001
American eel	452.2	250.6	190.8	59.8	1.9	<0.001
American shad	436.2	317.5	237.6	79.9	2.6	<0.001
Butterfish	293.8	221.8	168.8	52.9	2.4	0.005
Windowpane	201.7	193.8	127.7	66.1	1.4	<0.001

all species (Figure 5). When estimated with the base model, a limited deterrent effect was detected for 8 of the 11 species (Figure 5). Fish passage in the new fishway increased with the diversion activated for all *Alosa* spp., Atlantic silversides, and blackspotted sticklebacks. However, for the latter two species, the rate of passage through the turbine also increased with the diversion activated (Figure 5), which suggests that some factor other than the on/off status of the diversion was influencing their rate of passage. Similarly, the decreased rates of passage through the turbine with the diversion activated was accompanied by decreased rates of passage through the new fishway for Atlantic her-

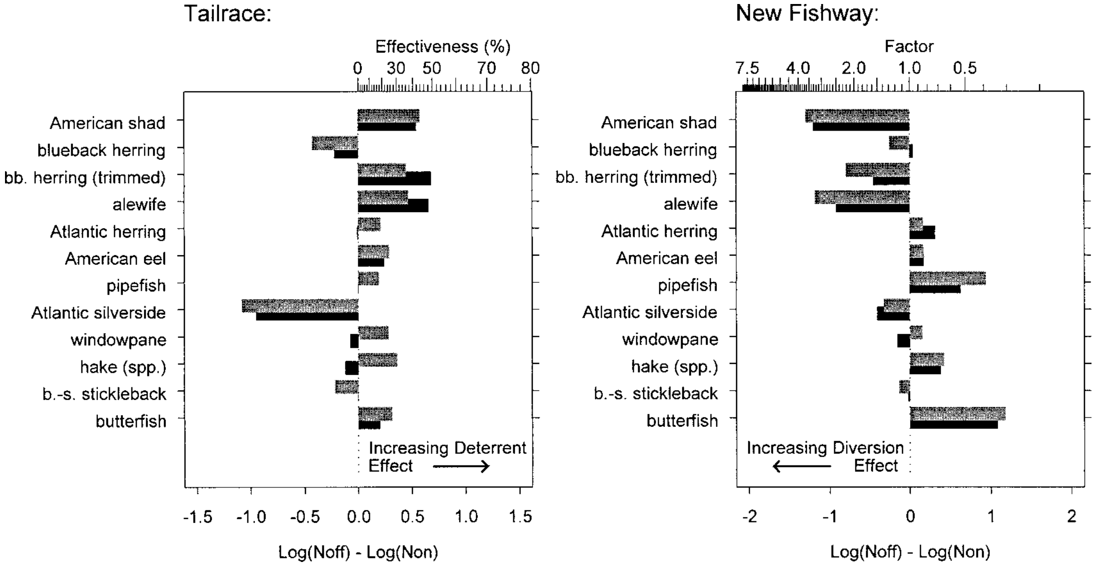

FIGURE 5.—A comparison of two estimates of the effectiveness of an ultrasound fish diversion system at the Annapolis Tidal Generating Station during September and October 1999. The dark bars show the estimates obtained from a model that includes environmental variables and the light bars the estimates from a model without the environmental variables. The left panel (tailrace) shows estimates of the deterrent effect based on changes in the rates of fish passage through the turbine tube, while the right panel (new fishway) shows the changes in the rates of passage of fish through a fishway that bypasses the turbine.

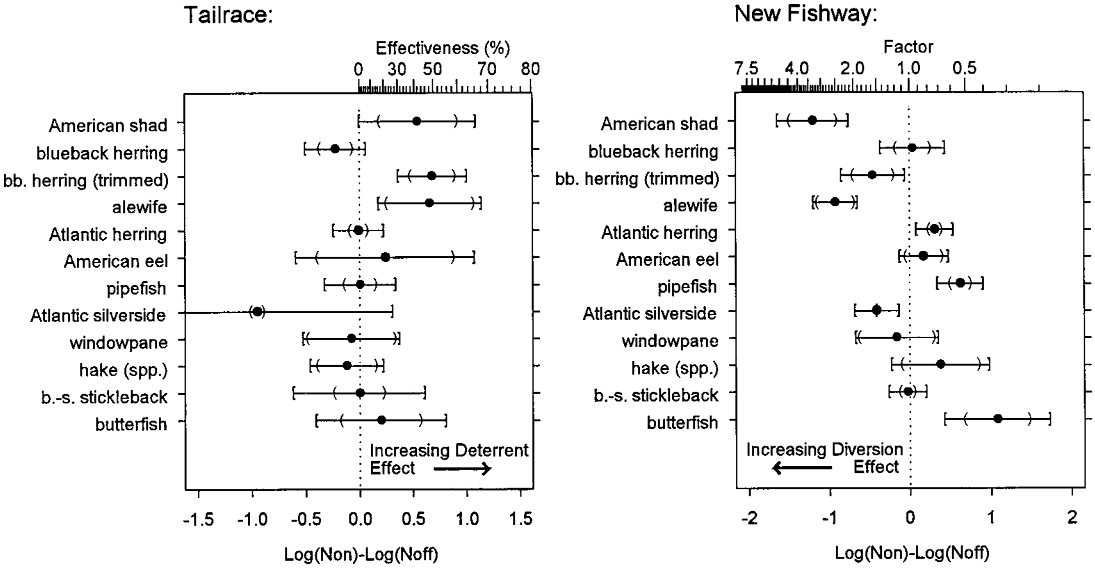

FIGURE 6.—Estimates of the effectiveness of an ultrasound fish diversion system and the increase in fish passage in the new fishway with the diversion activated at the Annapolis Tidal Generating Station during September and October 1999. Coefficients were estimated using the model with environmental variables. Error bars are one standard error; round brackets indicate standard errors estimated under the assumption of a Poisson error distribution, and square brackets indicate those estimated assuming a quasi-Poisson error distribution.

ring, American eels, northern pipefish, windowpane, hake, and butterfish (Figure 5). These results also indicate that some factor other than the on/off status fish diversion system was influencing the rate of fish passage for these species. Hence, the comparisons of the base model results for the tailrace and new fishway indicate that the limited effectiveness implied by the results from a single sampling location may be erroneous for all non-*Alosa* species.

When the environmental variables were included in the model, the diversion effectiveness estimates for non-*Alosa* species shifted closer to 0 (Figure 5), and the results for the new fishway and tailrace were more consistent. This improved consistency, together with the highly significant improvement in the model fit, indicate that the model with the environmental variables provided better estimates of the effectiveness of the diversion system.

Dispersion parameters were greater than 1 for all species except winter flounder (Table 4), indicating that, for a given species, the passage of fish at the generating station is not independent of that of other fish of the same species. As a result of this, the standard errors obtained from the quasilikelihood model were larger than those obtained from the Poisson model for all species (Figure 6). Atlantic silverside catches had the highest dispersion parameter, which was the result of 54.8% percent of their catch occurring during four generation periods (even though Atlantic silversides were captured during all generation periods). This migratory pattern results in very wide standard errors for the effectiveness coefficient for Atlantic silversides when estimated using quasilikelihood (Figure 6).

While the use of quasilikelihood increased the standard errors of the effectiveness coefficients, the inclusion of the environmental variables in the model decreased these standard errors for 10 of the 11 species. When estimated using quasilikelihood, the standard errors for the effectiveness coefficients for the environmental model ranged from 58.5% of the size of those from the base model for Atlantic silversides to 115.7% for butterfish.

Of our modeling approaches, the model with the environmental variables provided the best fit to the data, along with smaller standard errors for the effectiveness coefficients and the best consistency among sampling locations. This is sensible because factors other than the status of the diversion system likely contribute to the rates of fish passage at this generating station. From this model, the results for the tailrace suggest an effectiveness of

42% for American shad and 48% for alewife (Figure 6), although these estimates are not significantly different from zero when the standard errors are calculated using quasilikelihood (Table 3). However, the increases in the catch of these species in the new fishway with the diversion activated that are statistically significant (3.3 and 2.5 times for American shad and alewife, respectively) are consistent with these estimates and enhance their credibility. For blueback herring, the catch did not decrease with the diversion activated when the model was fitted to the full blueback herring data set. However, the system diverted about 49% for blueback herring after the generation cycles with the three largest catches were removed from the data (Figure 6). These findings are again consistent with the new fishway results: no increase in catch with the diversion activated using the full blueback herring data set, and an increase in catch of approximately 1.5 times when estimated using the trimmed blueback herring data set (Figure 6).

Discussion

In this paper, we have provided the first evaluation of an ultrasonic fish diversion system at a tidal hydroelectric generating station and have used a modeling approach that allows separation of the effects of environmental variables on the rate of fish passage from those of the diversion system. On the whole, our results indicate that the ultrasonic barrier was partially effective for the members of the genus *Alosa*, but not for the other species.

Comparisons of the results of the base model with those of the model that includes the environmental variables show that varying environmental conditions can affect both the accuracy and the precision of the diversion effectiveness estimates. This problem may have confounded some other studies (Ross et al. 1993). By monitoring fish passage at two locations where the response to an effective diversion stimulus should be in opposite directions (i.e., decreased rates of passage through the turbine accompanied by increased rates of passage through the fishways), we were able to detect such biases by comparing the consistency of the estimates at the two locations. When we included environmental variables in the model, the overall model fit was improved, the resulting effectiveness estimates had smaller standard errors, and the estimates were more consistent between the new fishway and tailrace sampling locations. This result shows that both the accuracy and the precision of the effectiveness estimates can be improved if the diversion effectiveness is evaluated within a model of the process that determines the rate of fish passage.

The influence of environmental variables on the rate of passage or impingement is consistent with studies at other generating stations. For example, Ross et al. (1993) found that wind direction, temperature, and time of day affected the rate of impingement at the James A. Fitzpatrick (JAF) Nuclear Power Plant (Lake Ontario) cooling water intake. Nestler et al. (1992) found that the response of blueback herring to ultrasound varied between day and night at the Richard B. Russell dam (Georgia–South Carolina). While not quantified during our study, environmental variables may also influence a fish's response to a stimulus and hence the effectiveness of a diversion system. Additionally, the ‘‘motivational state’’ of fish has been shown to vary throughout the year, as discussed by Popper and Carlson (1998). The timing of our study was appropriate for age-0 *Alosa* spp., the target species in this study, because they are only present at the Annapolis Tidal Generating Station during the fall. The response of other species that are present at this location at other times of the year and under different environmental conditions, as well as that of adult *Alosa* that are present in the late spring and summer, remain to be examined at this station.

When the movement of fish past generating stations is not independent of that of other fish (due to schooling behavior or some other reason), estimates with reasonable levels of precision may be difficult to obtain. This problem is well illustrated in our study, where the catches of all 11 species were overdispersed. As recognized by Popper (1999), the use of a Poisson error structure can lead to an overestimation of statistical significance if fish passage is not random. The quasilikelihood approach used herein corrects for this problem by rescaling the standard errors by the dispersion parameter. If fish catches are highly overdispersed, the resulting standard errors may be large relative to the parameter estimates and thereby greatly reduce statistical significance. In our study, the distribution of the catch (characterized by the dispersion parameter) had a greater effect on the precision of the diversion coefficient estimates than did the number of fish captured. While Atlantic silversides were by far the most abundant fish in this study, the species had the second largest standard errors for the diversion coefficients at the tailrace site when the effects of overdispersion were included in the model. The catches of some species for which we have not presented results were also clumped: sea lamprey were captured only during a 6-d period, a pattern similar to that observed during other studies at this station (Gibson 1996), and 86.7% of mummichog were captured on five tides. When fish migrations occur during relatively short time periods, obtaining reliable diversion estimates may be problematic.

Comparisons of the results when the blueback herring data are modeled as a whole and when the generation cycles with the three largest catches are trimmed from the data suggest that the effectiveness of the diversion system may be partially dependent on the abundance of target species. This pattern was observed at both the tailrace and the new fishway. While the reason for this observation at the Annapolis Tidal Generating Station is unknown, crowding may limit the ability of fish to respond to a signal. Alternatively, the increased abundance under favorable environmental conditions may be a result of an increased motivation to move seaward.

Our estimates of the diversion effectiveness at Annapolis are both similar to and lower than those reported by other authors. Popper (1999) reported the results of a comprehensive project to divert fish away from the cooling water intake at the Salem Nuclear Power Plant, New Jersey. As part of that project, a composite sound signal that included an ultrasound component was found to reduce the impingement of blueback herring (11.6–33.2%), alewife (9.2–14.7%), bay anchovy *Anchoa mitchilli* (33.1–35.7%), and Atlantic silversides (23.5–24.7%). Species estimates and statistical significance also varied depending on the modeling approach used. For *Alosa* spp., these estimates are similar to our results at the Annapolis station, as is the apparent increase in the impingement or turbine passage of some species when the diversion was activated. Both studies suggest that randomization of the on/off status of the diversion through time does not ensure randomization across the set of variables that determine either abundance or the rate of fish passage. In our study, the better model fit, smaller standard errors, and better compatibility between the tailrace and new fishway results when environmental variables were included in the model demonstrate that this problem can be at least partially alleviated by evaluating the diversion system effectiveness in a model of the process that determines the rate of fish passage.

Other authors have reported better success when attempting to divert fish with ultrasound. While Ross et al. (1993) reported that ultrasound reduced the impingement of alewives by as much as 87% at the JAF cooling water intake, they also found that environmental variables affected the rate of impingement and the effectiveness estimates. Ross et al. (1996) conducted a follow-up study that utilized an improved deterrent system, and concluded that the system should be 87% effective in most years. However, comparisons of the effectiveness of the ultrasound at Annapolis with the effectiveness at the JAF may not be appropriate given the differences between the locations. Diversion at a cooling water intake requires only that fish are deterred from the vicinity of the intake; fish do not need to be directed towards a fishway, as is the case with migratory species at the Annapolis generating station.

Ross (1999) reported good success when testing the use of ultrasound to divert blueback herring at the Vischer Ferry and Crescent hydroelectric stations in New York State. At the Vischer Ferry site, over 90% of blueback herring used the bypass. At the Crescent site, the system was effective for age-0 blueback herring but was ineffective for adults. Ross (1999) suggested that the effectiveness for adult blueback herring could be increased by moving the sound field. Hydrology, the time of day, and the condition of the fish were found to influence both the abundance of fish and the effectiveness of the ultrasonic barrier for part of his study.

Our investigation and those of others show that ultrasound can be used to reduce power plant impacts on *Alosa* populations, although the extent of the reduction varies among studies. Undoubtedly, the effectiveness of a diversion system depends on many site- and system-specific variables, and had we tested a different system (with a different range of frequencies, signal strength, and number and orientation of transducers), we probably would have obtained a different result. However, since the effectiveness of a behavioral guidance system also depends on the time of year, the time of day, fish age, flow field, environmental conditions, and the ‘‘motivational state’’ of the fish (see Popper and Carlson 1998), the signal we tested may simply have been less effective under the conditions present at the Annapolis station during the fall. The Annapolis Tidal Generating Station and the Salem Nuclear Generating Station cooling water intake are both estuarine facilities. Comparison of the results obtained at the Annapolis station with those obtained at the Salem plant may therefore be more valid than comparisons with results from riverine hydroelectric systems or cooling water intakes in the Great Lakes. However, the partial effectiveness of the diversion system for *Alosa* spp. at Annapolis does imply a response by these fish to the ultrasound signal under the conditions at Annapolis. Therefore, the effectiveness of the diversion could possibly be enhanced through the redeployment or the addition of transducers, or an increase in signal strength. Additionally, the system may be most effective when used in conjunction with other strategies. At Annapolis, migratory species tend to move just after the start of generation (Gibson 1996). Providing an alternate passage before the start of generation by keeping an extra sluice gate open prior to the onset of generation might reduce the number of fish upstream of the turbine at the start of generation, leading to an overall reduction of turbine passage.

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