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ARTICLE

Multibeam sonar (DIDSON) assessment of American shad (*Alosa sapidissima*) approaching a hydroelectric dam

Ann B. Grote, Michael M. Bailey, Joseph D. Zydlewski, and Joseph E. Hightower

Abstract: We investigated the fish community approaching the Veazie Dam on the Penobscot River, Maine, prior to implementation of a major dam removal and river restoration project. Multibeam sonar (dual-frequency identification sonar, DIDSON) surveys were conducted continuously at the fishway entrance from May to July in 2011. A 5% subsample of DIDSON data contained 43 793 fish targets, the majority of which were of Excellent (15.7%) or Good (73.01%) observation quality. Excellent quality DIDSON targets (n = 6876) were apportioned by species using a Bayesian mixture model based on four known fork length distributions (river herring (alewife, *Alosa psuedoharengus*, and blueback herring, *Alosa aestivalis*), American shad, *Alosa sapidissima*) and two size classes (one sea-winter and multi-sea-winter) of Atlantic salmon (*Salmo salar*). 76.2% of targets were assigned to the American shad distribution; Atlantic salmon accounted for 15.64%, and river herring 8.16% of observed targets. Shad-sized (99.0%) and salmon-sized (99.3%) targets approached the fishway almost exclusively during the day, whereas river herring-sized targets were observed both during the day (51.1%) and at night (48.9%). This approach demonstrates how multibeam sonar imaging can be used to evaluate community composition and species-specific movement patterns in systems where there is little overlap in the length distributions of target species.

Résumé : Nous avons étudié la communauté de poissons s'approchant du barrage Veazie, sur le fleuve Penobscot (Maine, États-Unis), avant la mise en œuvre d'un important projet de démantèlement du barrage et de remise en état du fleuve. Des relevés au sonar multifaisceaux (DIDSON) ont été menés en continu à l'entrée de la passe migratoire, de mai à juillet 2011. Un sous-échantillon de 5 % des données DIDSON contenait 43 793 cibles de poissons, la majeure partie de ces observations étant d'excellente (15,7 %) ou de bonne (73,01 %) qualité. Les cibles DIDSON d'excellente qualité (n = 6876) ont été réparties par espèce à l'aide d'un modèle de mélange bayésien basé sur quatre distributions connues de longueurs à la fourche, soit celles des aloses de rivière (gaspareau, *Alosa psuedoharengus*, et alose d'été, *Alosa aestivalis*), de l'alose savoureuse (*Alosa sapidissima*) et de deux catégories de tailles (un hiver en mer et plus d'un hiver en mer) de saumon atlantique (*Salmo salar*). Des cibles observées, 76,2 % ont été affectées à la distribution de l'alose savoureuse, alors que les saumons atlantiques et les aloses de rivière représentaient 15,64 % et 8,16 %, respectivement, des cibles observées. Les cibles de tailles de l'alose savoureuse et du saumon s'approchaient de la passe migratoire presque exclusivement durant le jour (99,0 % et 99,3 %, respectivement), alors que les cibles de tailles des aloses de rivière étaient observées tant durant le jour (51,1 %) que durant la nuit (48,9 %). Cette approche démontre l'utilité de l'imagerie par sonar multifaisceaux pour l'évaluation de la composition de communautés et des habitudes de déplacement d'espèces données dans des systèmes dans lesquels les distributions des longueurs de différentes espèces cibles se chevauchent peu. [Traduit par la Rédaction]

Introduction

Dam removal is an increasingly used management option for the restoration of impounded and impaired aquatic systems (Pohl 2002; Stanley and Doyle 2003). The ecological benefits of dam removal may include re-establishing the natural hydrograph, thermal regime, sediment dynamics, nutrient cycling, and migratory fish connectivity (Gregory et al. 2002). One of the major challenges associated with dam removal is the assessment of system response with respect to those potential benefits, and to date there is a dearth of well-designed studies evaluating the ecological outcomes of river restoration efforts (Babbitt 2002; Hart et al. 2002; Palmer et al. 2005).

Baseline data collection is a critical, but often neglected, step in restoration assessment (Bernhardt et al. 2007). Baseline data are necessary as they allow managers and researchers to compare conditions before and after dam removal and thereby evaluate system response (Kibler et al. 2011). In spite of their importance, pretreatment data can be challenging to collect, especially for ecological restoration projects. The presence of Threatened or Endangered aquatic species may limit not only the types of sampling (netting, angling, electrofishing, piscicide application) that are utilized, but also the seasonality and duration of sampling episodes. Thus, a major question facing many dam removal and river restoration projects is how to evaluate baseline fish behavior and species composition without adversely affecting protected fish.

The Penobscot River is currently the subject of an intensive river restoration effort. Under the Penobscot River Restoration

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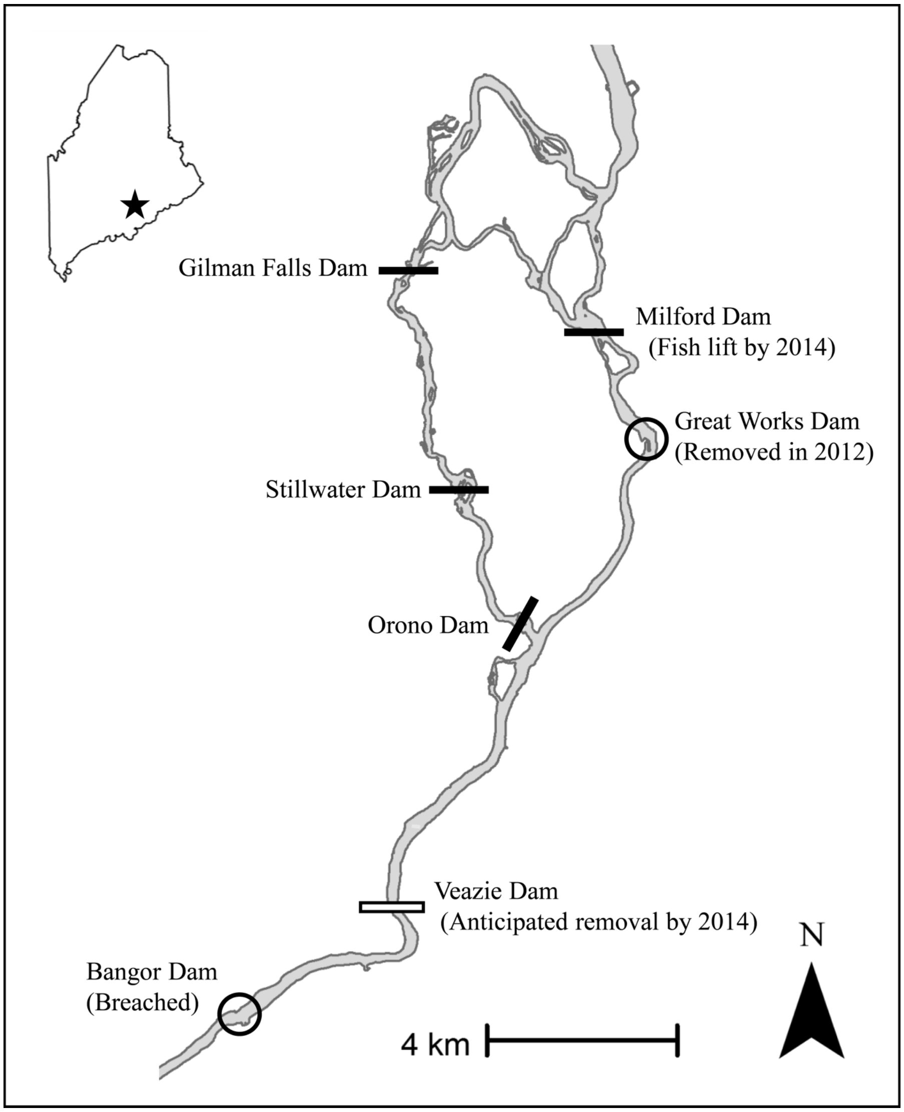
Fig. 1. Map of the Penobscot River, Maine, including dams that will be removed (Veazie Dam, Great Works Dam) and retrofitted for improved fish passage (Milford Dam) under the Penobscot River Restoration Project (PRRP).



Project (PRRP), the two lowest dams in the system, Veazie Dam at river kilometer (rkm) 48 and Great Works Dam at rkm 60, will be removed (Fig. 1). Great Works Dam was dismantled in the summer of 2012, and Veazie Dam is scheduled for demolition by 2014. Additional PRRP restoration measures include the construction of a new fish passage system at Howland Dam (rkm 100) and the installation of a fish elevator at Milford Dam (rkm 62).

Re-establishing migratory connectivity for the suite of diadromous fish species that historically inhabited the Penobscot River is a central objective of the PRRP. Today the river supports diminished runs of federally listed Atlantic salmon (*Salmo salar*: Endangered), shortnose sturgeon (*Acipenser brevirostrum*: Endangered), and Atlantic sturgeon (*Acipenser oxyrinchus*: Threatened), along with alewife (*Alosa psuedoharengus*), American eel (*Anguilla rostrata*), American shad (*Alosa sapidissima*), Atlantic tomcod (*Microgadus tomcod*), blueback herring (*Alosa aestivalis*), rainbow smelt (*Osmerus mordax*), sea lamprey (*Petromyzon marinus*), and striped bass (*Morone saxatilis*). While much of the previous work in this system has concentrated on Atlantic salmon, there is growing recognition that the recovery of Penobscot River species may be best accomplished through the restoration of an intact diadromous fish community (Saunders et al. 2006).

Although American shad were targeted for recovery under the PRRP, range-wide declines in shad stocks (Limburg et al. 2003), coupled with a documented lack of shad passage at the Veazie Dam (Oliver Cox, Maine Department of Marine Resources (MEDMR), personal communication), fueled concerns that shad were largely absent from the current day Penobscot River fish assemblage. American shad were historically abundant in this system, with annual landings of over 2 million adults reported in the 1860s (Foster and Atkins 1869). The current population is of unknown size, but had been surmised to be 1000 or fewer fish (MEDMR 2009); however, this estimate was based on the size of other "remnant" populations in the region and was not derived from Penobscot River-specific information.

This study used dual-frequency identification sonar (DIDSON) to collect baseline data on migration dynamics and species composition of the fish community at the base of the Veazie Dam during spring 2011. The DIDSON records near-video quality sonar images (Moursund et al. 2003) and can be used for a wide range of fisheries applications, including generating escapement (Holmes et al. 2005) or abundance (Han and Uye 2009) estimates and monitoring fish presence (Crossman et al. 2011), behavior (Boswell et al. 2008), and community dynamics (Becker et al. 2011). DIDSON surveys are noninvasive and do not require capturing, handling, or disturbing study subjects. These characteristics make the DIDSON well-suited for use in systems like the lower Penobscot River, where multiple threatened and endangered fish species are present, and adverse effects associated with traditional physical sampling (Ellender et al. 2012) must be minimized.

A second advantage of the DIDSON is that that the images are constructed from sound and not light information; therefore, data can be collected at night and in turbid waters (Maxwell and Gove 2007). As a result, DIDSON sampling can be conducted continuously, 24 h a day, and in weather and flow conditions where physical surveys would not be feasible. The resulting data are appropriate for systematically investigating diurnal effects (Tiffan et al. 2005; Kimball et al. 2010; Becker et al. 2011), which is an important consideration for spawning and migrating fishes.

The overall goal of this study was to describe baseline conditions (species proportions, migration dynamics) of the Penobscot River fish assemblage prior to dam removal using DIDSON. Our hypothesis was that American shad were present in the lower river and that they would be discernible based on fork length (FL) data. The specific objectives of the study were to (*i*) apportion DIDSON observations by species based on FL data, (*ii*) assess whether American shad were approaching the Veazie Dam fishway, and (*iii*) characterize the behavior of fish approaching Veazie Dam.

Methods

Study area

Fish passage in the Penobscot River has long been impeded by an extensive network of dams. From 1877 to 1977, the head-of-tide dam was located in the city of Bangor at rkm 44. The Old Bangor Dam breached naturally in 1997, and today the river is tidal through Eddington Bend to Veazie Dam. Both Veazie Dam and Great Works Dam will be removed by 2014, and following full implementation of the PRRP, Milford Dam will be the lowest dam on the mainstem Penobscot River (Fig. 1).

The Veazie Hydroelectric Project is a 7.6 m high concrete dam with an installed hydroelectric capacity of 8.4 megawatts. Fish passage structures at this facility include a vertical slot fishway located mid-channel between the forebay and spillway and a derelict, nonoperable pool–weir ladder on the eastern shore. MEDMR maintains a wire and fyke fish trap at the exit of the operable fish ladder. The trap is operated annually from May through October and is tended on a daily basis. Although the main purpose of this operation is to collect and enumerate Atlantic salmon, other large-bodied fish are also trapped and counted. Smaller fish, such as river herring, are sometimes retained in the trap, but gaps in the trap wall are big enough to allow many smaller fish to escape. Nontarget fish are released into the Veazie Dam headpond. While some migratory species, including Atlantic salmon, successfully navigate the fish ladder to the trap, American shad typically do not. Only 16 American shad have been collected from the trap from 1978 to 2012 (Oliver Cox, MEDMR, personal communication).

Known length frequency distributions

The lower Penobscot River is occupied by a diminished migratory and resident fish community (Saunders et al. 2006). Recent data from both electrofishing surveys (Kiraly et al. 2012) and the Veazie Dam trap (Oliver Cox, MEDMR, unpublished data) were used to identify fish species expected to migrate to and attempt to pass the Veazie Dam. Based on those data, four species (alewife, blueback herring, American shad, and Atlantic salmon) were assumed as those most likely to be schooling at the base of the dam.

Fish images obtained using DIDSON typically cannot be identified to species, but DIDSON length data can be used to estimate species proportions. This is done using a mixture modeling approach (see below), along with auxiliary information on Penobscot River-specific FL distributions for the four species of interest.

Table 1. Mixture model prior parameters (fork length (FL) mean, standard error (SE), and precision) derived from the known length frequencies of Penobscot River river herring, American shad, and one sea-winter (1SW) and multi-sea-winter (MSW) Atlantic salmon.

Component distribution	Mean	SE	Precision	*n*
River herring*	22.5	0.12	65.35	234
American shad†	43.1	0.39	6.71	93
1SW salmon‡	53.5	0.08	149.13	702
MSW salmon‡	73.6	0.07	234.46	2275

*Oyster River 2012. Kevin Sullivan, unpublished data.
†Penobscot River 2010–2011.
‡Penobscot River 2011. Oliver Cox, unpublished data.

Data from the spring 2011 Veazie Dam trapping season were used to describe Atlantic salmon FL distributions (Table 1; Oliver Cox, MEDMR, unpublished data). Atlantic salmon spawn after either one sea-winter (1SW) or multiple sea winters (i.e., multi-sea-winter, MSW), and MSW fish are substantially larger. As a result, the Atlantic salmon length frequency data were bimodal and were modeled as separate length distributions.

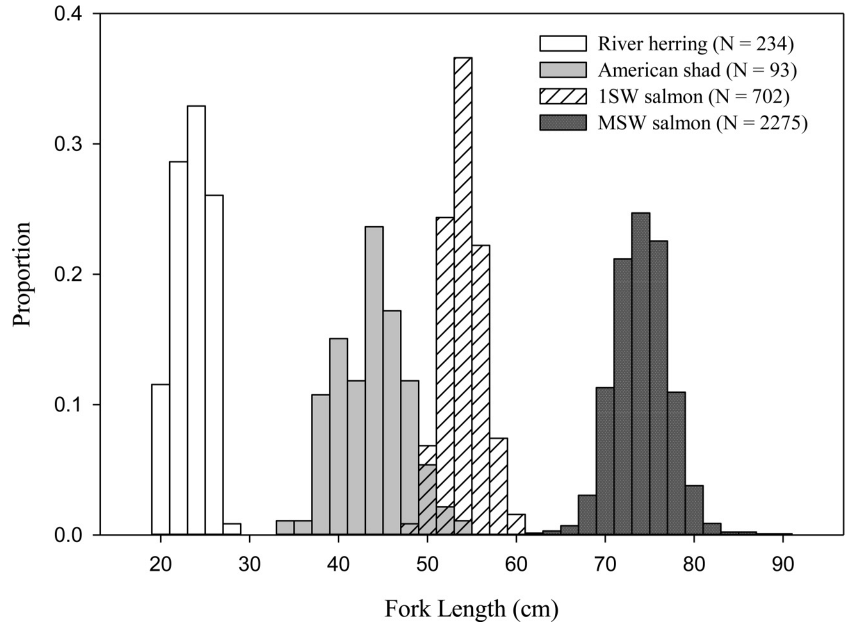
Length data for alewives and blueback herring were collected in 2010 and 2011 from below the Veazie Dam (Kiraly et al. 2012), but only total lengths (TLs) were recorded. To standardize length metrics across species, linear regression was used to relate FLs and TLs for alewife and blueback herring data from the Oyster River in New Hampshire (Kevin Sullivan, New Hampshire Fish and Game, unpublished data). Data from the Oyster River were used because it was the closest system with available length data for both alewife and blueback herring runs. The resulting model met all regression assumptions and was applied to Penobscot River TL data to estimate FLs. These two herrings are very similar in size and appearance, and adults migrating in the same system may be difficult to identify to species. To avoid any issues with misidentification in the Oyster River, Penobscot River, or DIDSON data sets, all length data for alewife and blueback herring were combined into a single “river herring” distribution for our analysis. River herring FL was positively and significantly related to TL ($FL = 0.406 + 0.868TL$, $R^2 = 0.977$, $P < 0.001$), and this relationship was used to estimate FLs for river herring from the Penobscot system.

Finally, American shad FL data were collected in 2010 and 2011 in a companion telemetry study (Grote et al. in press) that focused on the behavior of adult Penobscot River shad. The range of observed (and, in the case of river herring, modeled) FLs were as follows: river herring 18.0–26.0 cm, American shad 34.0–53.5 cm, 1SW Atlantic salmon 48–60 cm, and MSW Atlantic salmon 62–90 cm (Fig. 2).

Hydroacoustic sampling

Fixed DIDSON surveys were conducted at the base of the Veazie Dam from 24 May to 21 July 2011. Water flows in this area of the tailrace are turbulent, with spill from the headpond and flows from the fish ladder mixing with the water at the base of the dam. Data were collected using a standard (short-range) DIDSON, operating in high-frequency identification mode (1.8 MHz). The window length was set to 2.5 m (starting at 1.67 m and ending at 4.17 m), and the focus was set at 2.91 m. This short window was selected to improve the image quality of smaller targets. The recording frame rate varied between 9 and 11 frames per second, and data files were saved to external drives every 10 min. Data were collected continuously 24 h per day, except when the data drives were swapped, the unit was cleaned, or power outages affected operations. The longest interruptions to data collection occurred on 19 June – 20 June and 9 July – 11 July. Despite these interruptions, the DIDSON was operational for 1301 of 1389 possible sample hours (93.7%) over the course of the entire survey period.

Fig. 2. Known fork length distributions for captured river herring (Oyster River, 2012), American shad (Penobscot River, 2010 and 2011), and one sea-winter (1SW) and multi-sea-winter (MSW) Atlantic salmon (Penobscot River, 2011).



The DIDSON was attached to the downstream side of the dam using a vertical track and trolley mount. The DIDSON housing was oriented 28 degrees horizontally from the lower dam wall and was positioned to ensonify the area just outside the fish ladder. The trolley vertical position was adjustable, so that the DIDSON could be raised or lowered in response to water level fluctuations at the base of the dam. Throughout the field season, the unit was maintained at a depth of 1.5 to 2.5 m below the water surface, with the shallower deployments occurring in July at reduced flows. The unit was deployed in a side-looking position approximately 2.5 m downstream of the fishway entrance.

Data processing

Data were processed using Sound Metrics Control and Display software (version 5.25.25, Bellevue, Washington). Turbulence, image occlusion due to overlapping fish, and the lack of a static background made automated data processing infeasible. Instead, a team of 11 readers reviewed the DIDSON footage manually. Readers reviewed a 5% subsample of 2011 data, processing a fixed 30 s interval from every 10 min data file. This subsampling routine was implemented to (*i*) reduce the volume of footage requiring manual processing and (*ii*) reduce the likelihood of the same individual or school of fish swimming in front of the camera repeatedly. Display threshold and intensity settings were adjusted by individual readers, and the files were reviewed without the smoothing control feature.

Individual fish targets were defined as the same fish imaged repeatedly in consecutive frames, although occasionally targets did occur in only a single frame. For a given target, all fish images were classified according to image quality (Fig. 3). "Excellent" quality images were defined as those where (*i*) the fish was centered in the frame, (*ii*) both the head and tail were visible, (*iii*) there was no transducer feedback, and (*iv*) the images were distinct and did not overlap. "Good" images were those failing to meet all the criteria listed above, but where the general size of the fish was still evident — such as when fish were swimming in an arched position or when the majority of the image was on the screen with only a small percentage (end of head or tail) cut off. "Poor" images were those where "glimpses" of fish were detected based on movement, but size information was lacking. The best image quality observed in individual frames was assigned as the overall image quality for each target.

All Excellent images were measured by hand using the box measurement tool, and the diagonal length metric in metres was recorded as the DIDSON fork length (DFL). If the same fish target produced more than one Excellent image, the lengths were averaged to produce an overall DFL for the target. Precise length measurements could not be obtained from Good quality images; however, length information was still contained in these data. Good quality images were therefore also measured using the box tool and assigned into size classes as follows: Small (18–31 cm), Medium (32–54 cm), and Large (55–92). For Good quality targets, the largest size classification observed in individual frames was assigned as the overall target size.

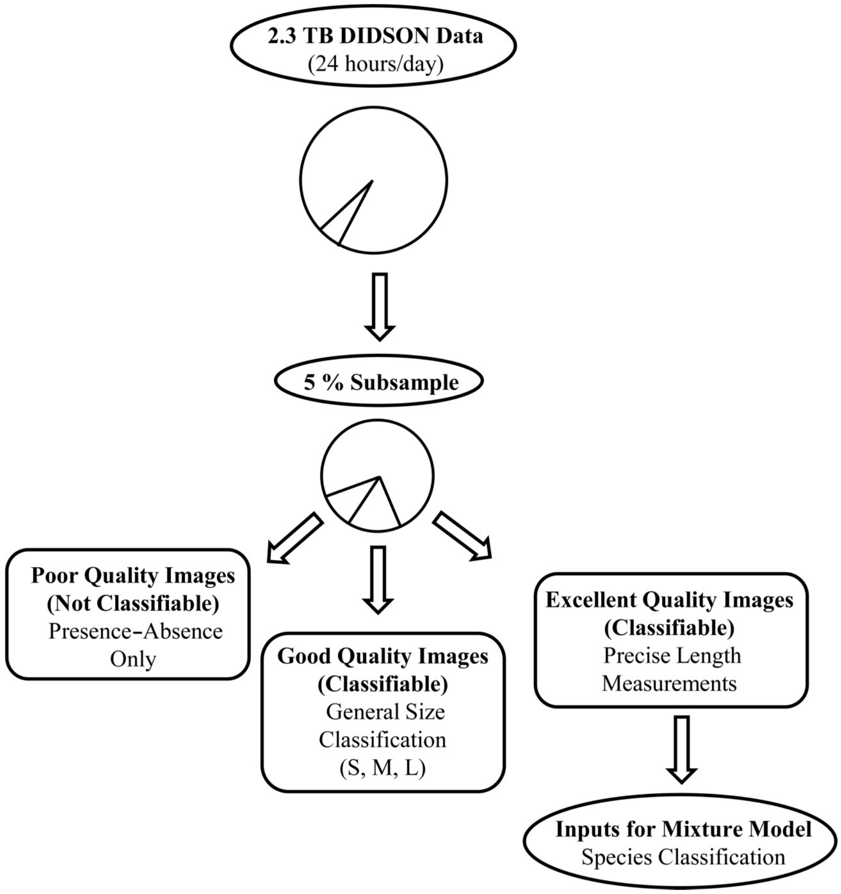
The 2011 data included many dense schools with upwards of 20 fish being imaged simultaneously. Tracking 10 or more concurrent targets was not manageable. Targets occurring in groups of 10 or more were therefore binned into "10+ Schools" where a representative image quality score and size class was assigned to all targets, but individual target metrics were not recorded. This approach enabled readers to focus on accurately reporting the number of targets and representative size class for each 10+ School. In rare cases where a 10+ School was composed of mixed-size targets, the larger targets were reported separately from the 10+ School's representative image score and size class values.

Reader effects

Reader effects of manual measuring were assessed using footage from known size fish. Two test fish, a 26 cm alewife and a 33 cm smallmouth bass (*Micropterus dolomieu*), were mounted in a fully extended position and maneuvered in front of the DIDSON unit on a fishing line. Test fish footage was recorded on three days (2 June, 14 June, and 21 July) at flows that represented high, medium, and low summer flows, respectively.

This footage was used to compile a known-size data set of 106 DIDSON data frames containing the test fish (alewife, n = 43; smallmouth bass, n = 63). These ground truth frames were sampled from 16 DIDSON footage clips and included images of test fish in different orientations and at a range of distances from the transducer. Readers reviewed each DIDSON clip and measured

Fig. 3. Data processing workflow for DIDSON files collected at the base of the Veazie Dam in the Penobscot River, Maine, during May–July 2011.



and classified fish images (Excellent or Good; no Poor quality images were included) for the specified data frames. In an attempt to maximize consistency with regular data processing, readers were instructed to evaluate the images according to the standard protocol and did not know the species, size, or number of test fish used to generate the ground truth images. The lengths of images scored as Excellent were compared with the actual known lengths to generate data on reader measurement error.

Reader training and evaluation was ongoing throughout the project, and readers reviewed and scored the test fish data repeatedly after approximately every 50 h of regular data processing. Readers were given feedback on their measurement and classification performance in an attempt to reduce error. Readers conducted between two and five reviews of the test data. The effects of reader identity and review instance on DIDSON-measured length was evaluated using rank-transformed two-way ANOVA and post hoc Tukey's honestly significant difference (HSD) tests, both with an alpha level of 0.05.

Mixture model

The observed DFL distribution and auxiliary FL information from the four species groups were used to estimate proportions of river herring, American shad, 1SW salmon, and MSW salmon in DIDSON files, using a mixture modeling approach (Fleischman and Burwen 2003). The DFL distribution (variable y) was modeled as a weighted mixture of four component distributions as

$$f(y) = \pi_h f_h(y) + \pi_s f_s(y) + \pi_g f_g(y) + \pi_m f_m(y) \quad (1)$$

where π_h, π_s, π_g, and π_m are the species proportions for river herring, American shad, 1SW salmon, and MSW salmon in the DIDSON data, respectively, and $f_h(y)$, $f_s(y)$, $f_g(y)$, and $f_m(y)$ are the length probability density functions (pdfs) for each respective species group. This approach assumed that the observed DFL distribution was composed of four individual FL component distributions.

The observed DIDSON length data were initially modeled using known TL distributions. The TL model produced similar parameter estimates to the FL model with one exception; the variance of the third component distribution was much greater (152.5 rather than 19.56). The model presented here used FLs that were deemed more representative of the observed lengths for two main reasons. First, incomplete fish images (owing to target angles or pixels lost against turbulence) are likely to underrepresent actual fish midline length (as are flexed as against fully extended targets). Second, the reader effects analysis (see Results) indicated that readers tended to slightly underestimate the length of a 30 cm test target, and that same bias was assumed to apply to the larger (shad-sized and salmon-sized) targets as well.

The mixture model was implemented in a Bayesian framework using OpenBUGs (Lunn et al. 2009). Modeled parameters were the mean (μ_i) and variance (σ_i^2) for each component distribution (i) and the proportion of the observation population belonging to each component distribution (π_i). Uncertainty for each parameter was characterized by an estimated 95% credible interval.

One major advantage of the Bayesian approach is that it allows for previously known information (informative priors) to be included directly into models and, in so doing, improves the preci-

Table 2. Image quality scores for DIDSON targets recorded at the base of Veazie Dam, Penobscot River, Maine, during May–July 2011.

Image quality	Targets	Target percentage
Excellent	6 876	15.7
Good	31 965	73.0
Poor	4 952	11.3
Total	43 793	100.0

Note: Excellent and Good quality images contained information on target size, whereas Poor quality images indicated only target presence.

Table 3. Classifiable DIDSON target lengths recorded at the base of the Veazie Dam, Penobscot River, Maine, during May–July 2011.

Size classification	Total classifiable targets	Good targets	Excellent targets	Excellent target percentage
Small (18–31 cm)	2 272	1 748	524	23.0
Medium (32–54 cm)	31 138	25 774	5 364	17.2
Large (55–92 cm)	5 264	4 283	981	18.5
Other (<18 cm)	167	160	7	7.7
Total	38 841	31 965	6 876	100.0

Note: Classifiable observations were defined as those containing Good or Excellent caliber images. Good quality observations were classified as Small, Medium, or Large targets, whereas individual length measurements were recorded for all Excellent quality observations.

sion of the posterior parameter distributions (McCarthy 2007). A second advantage is that Bayesian methods account for imperfect information (uncertainty or error) through the use of prior distributions instead of fixed estimates. This type of error is common in complex natural and ecological systems. Our mixture model incorporated several potential sources of error, including (*i*) length measurement error for the captured fish, (*ii*) modeling error from TL to FL river herring conversions, (*iii*) mathematical or software error in the DIDSON measurement tool, and (*iv*) reader error in the manual measurements of DIDSON images.

A combination of informative and uninformative priors was included in the model formulation. For each species group, an informative normal prior distribution was used for mean FL, based on the observed mean and its variance from the Penobscot-specific length data (Table 1). Informative priors were used because there was excellent system-specific data on the four length distributions of interest.

An uninformative uniform prior with a range of 1–150 was used for each variance parameter (σ_i^2). These parameters were modeled as mixtures of two components: true variance due to underlying variability in fish length and error variance inherent in the manual reader measurements. This latter component was estimated from the test fish length error data set described in "Reader effects" section above. Species proportions (π_i) ranged from 0 to 1 and summed to 1 and were assigned an uninformative multinomial Dirichlet prior.

The model ran on three Markov chains for a minimum of 250 000 iterations. Chain convergence was assessed visually using OpenBUGS (Brooks–Gelman–Rubin diagnostic tool), and all subsequent calculations were made with a 25 000 iteration burn-in period. To reduce autocorrelation, samples were thinned by 100 to 1, with minimum of 6750 samples retained. Goodness of fit was assessed with χ^2 dissimilarity-based posterior predictive check and Bayesian *P* value (Kéry 2010).

Environmental data

Water temperature data were collected at the base of the Veazie Dam with a Solinst Level Logger Jr. (Solinst, Inc., Georgetown, Ontario). Flow data for the project site was estimated from gage heights recorded at the USGS Eddington Bend gaging station located approximately 0.5 km downstream of Veazie Dam.

Results

DIDSON data

The 5% subsample of DIDSON data produced 43 709 total fish targets (Table 2), with 38 841 (88.7%) of the targets considered classifiable (Excellent or Good quality observations). The remaining 11.3% of observations contained no information on target size and were therefore excluded from subsequent size-based analyses. Classifiable images were predominantly Medium-sized (80.1%) and of Good (82.3%), not Excellent (17.7%), quality (Table 3). The percentage of Excellent targets measured by size class ranged from 17.2% to 23.1%, although the actual number of measurable observations in each class varied more widely (524–5364). Of the 6876 Excellent quality targets, 6869 were between 18 and 92 cm in length and were included in the mixture model analysis; seven targets were excluded because they were too small.

Fish were recorded every day that the DIDSON was operational (Fig. 4). The majority of targets were imaged in mid-June, with 25% and 75% of observations occurring by 8 June and 18 June, respectively. Run timing varied by size class, with Small and Medium targets appearing earlier in the spring, and Medium and Large targets persisting later into the summer. The median target observation days were 31 May (Small), 8 June (Medium), and 14 June (Large).

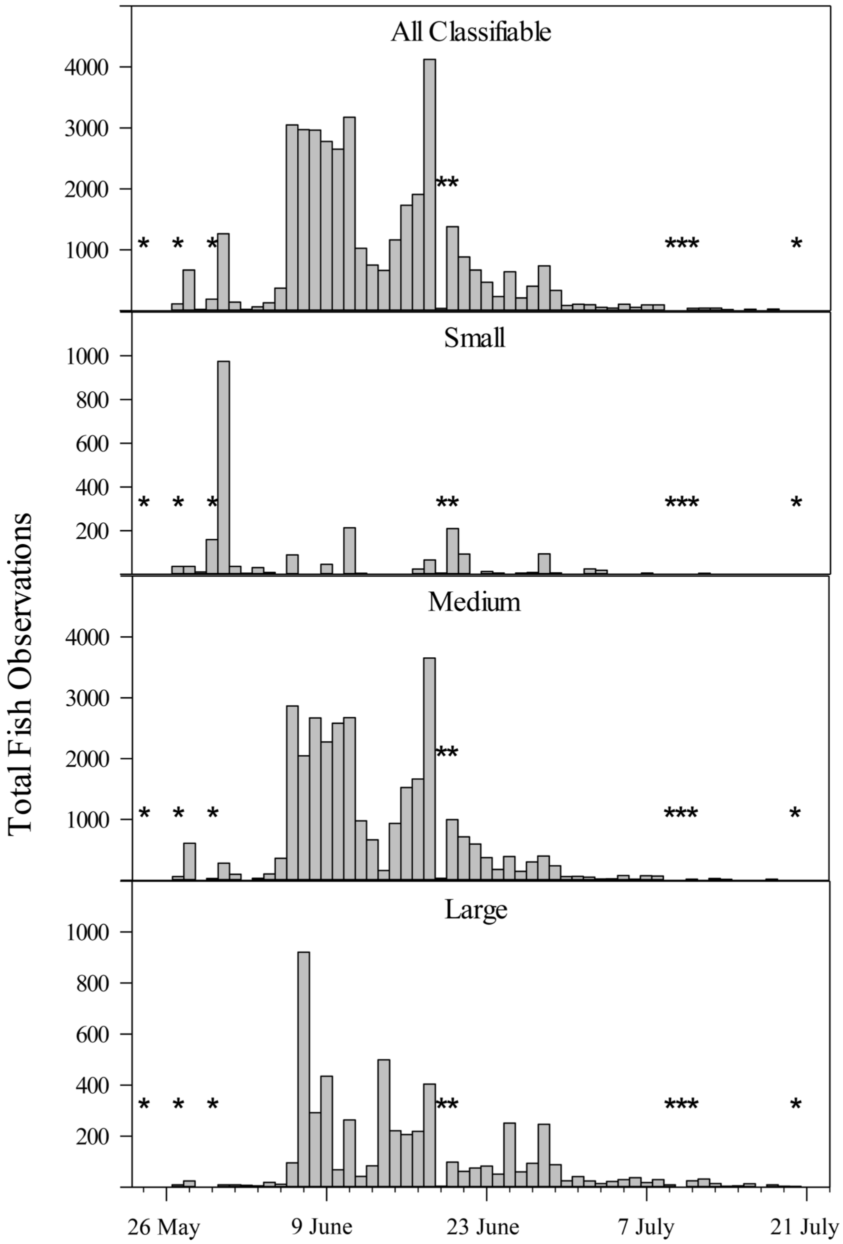
Fish activity at the base of the dam varied with water temperature and water level (Fig. 5). Daily mean water temperature increased from 18.6 °C when 25% of targets were observed to 20.9 °C when 75% of targets were observed. Conversely, daily mean water level decreased from 1.47 m at 25% of observations to 1.31 m at 75% of observations. Small targets were observed at colder median temperatures (17.1 °C) and higher median flows (2.24 m) than either Medium (20.2 °C, 1.40 m) or Large (20.0 °C, 1.39 m) targets.

Fish activity at the base of the dam also varied as a function of both time of day and size class (Fig. 6). Observations of Medium and Large targets followed a similar pattern: Medium (99%) and Large (99%) targets were observed almost exclusively during daylight hours (0500–2059). Medium and Large targets were most conspicuous at midday (1100–1500), when 59% and 61% of observations were recorded, respectively. Observations of Small targets increased in the middle of the day. However, unlike the bigger fish, Small targets were often observed at night, and nearly half (49%) of Small targets were recorded between 2100 and 0459. Nearly all targets (94.3%) were observed in schools, with nearly half (47.0%) recorded in 10+ Schools. As a result of the data-recording protocol for mixed-size 10+ Schools, the proportion of Small, Medium, and Large targets in each schooling category was not calculable. In addition to schooling, many targets demonstrated milling behavior by turning, changing direction, and making multiple passes in front of the transducer. Target-specific milling data were not recorded. Owing to the tendency for fish, and especially milling 10+ Schools, to swim out of the DIDSON range for only a few frames and then (presumably) to swim back into the view, we did not feel confident in our ability to describe milling behavior.

Mixture model

The mixture model generated posterior distributions for the parameters describing the four component FL distributions. The mean parameter estimates from the posteriors were used to define component distributions, which were combined to predict the overall observed length distribution of DIDSON-measured fish. The model fit the observed data well (Bayesian *P* value = 0.465). The fitted distribution compared favorably with the observed FL

Fig. 4. Timing of classifiable (Excellent and Good) DIDSON fish observations recorded at the base of the Veazie Dam, Penobscot River, Maine, during the spring of 2011. Days with partial or no DIDSON data are denoted with an asterisk (*). Size classes of targets are as follows: Small (18–31 cm), Medium (32–54 cm), and Large (55–92 cm).



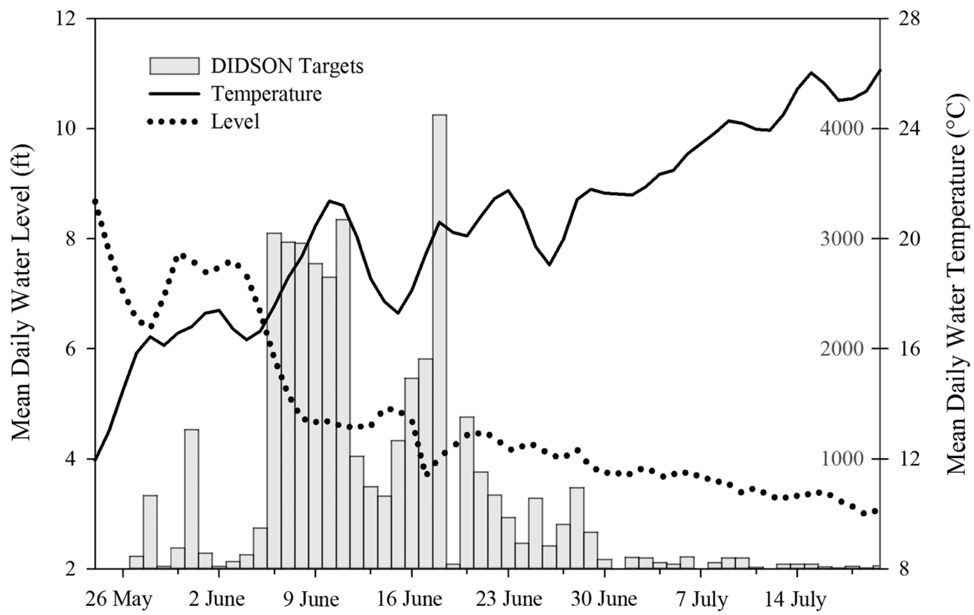
distribution (Fig. 7), with the exception of 20–30 cm target lengths for which length was underestimated.

Mean parameter estimates from the FL posterior distributions are reported in Table 4. In addition to the FL data, the mixture model was also used to apportion observations based on TLs. The TL model produced similar parameter estimates, with the exception of the estimated variance of the third component distribution, which was an order of magnitude greater (152.5) than the FL estimate (19.56).

American shad-size targets dominated the observed DIDSON FL distribution, while the proportions of observations allocated to the river herring and both salmon categories were smaller by an order of magnitude. The 1SW:MSW salmon ratio produced from the model estimates differed from the capture ratio observed in the trap. So while 0.848 1SW were observed at the base of the dam for every MSW fish, only 0.309 1SW were captured for every MSW salmon in the trap. For both salmon FL distributions, the empirical and estimated means were nearly identical, differing by less than 0.11%. The estimates of means for the smaller targets did not match as well; the field-tested mean FL for river herring was 1.45 cm smaller, and the FL mean for shad 3.55 cm smaller, than the model estimates.

Modeling the variance parameters as a combination of true fish-based variation and reader error reduced the magnitude of the fish-based variance estimates for all four component distributions. While the mean lengths and proportion estimates were virtually the same (±0.01) for both versions of the model, river herring variance decreased by 4.48 cm, shad variance by 4.45 cm, 1SW variance by 4.29 cm, and MSW variance by 4.45 cm when reader error was included. In most cases, the 95% credible intervals for the parameter estimates were tight. Three parameters produced credible interval discrepancies greater than 6.5%, the

Fig. 5. Mean gage level (1 foot = 0.3048 m) and water temperature in the Veazie Dam tailrace, Penobscot River, Maine, during the spring of 2011. Counts of classifiable DIDSON fish observations are superimposed.



variances for the river herring (8.3%), 1SW salmon (11.32%), and MSW (9.82%) distributions.

Reader effects

Overall, reader error was less than 3.0% of total length for the Small test fish and 0.8% of total length for the Medium test fish. Reader identity affected measurement error for both the Small (P < 0.001) and Medium (P < 0.001) test fish. Review round did appear to affect length on its own; however, there was a significant interaction effect of reader and round (P < 0.001) on the Medium fish measurements. Significant effects were identified for 68 of 472 pairwise comparisons, but the effect sizes were minimal for both the Small (1.45–3.57 cm) and Medium (0.91–4.21 cm) significant test fish comparisons. When consolidated by reader, the average length error was minimal for both test groups (Fig. 8), although average error was greater for measurements on Small (+0.77 cm) than Medium (–0.25 cm) test fish. Owing to the small overall magnitude of reader error, DIDSON measured lengths were not corrected for subsequent analyses.

Veazie Dam trap data

Capture data from the DMR Veazie Dam fish trap indicate that the vast majority of fish exiting the ladder from 24 May to 21 July 2011 were river herring (2039), sea lamprey (2125), and Atlantic salmon (2918) (Fig. 9). No American shad were recorded at the trap during this time. River herring captures were concentrated over a very short period early in the season. The median capture day for river herring was 28 May, with 47% of the run collected on that day and 90.7% of total captures occurring by 2 June. The sea lamprey run also began early, but extended slightly longer than river herring. Median capture day for sea lamprey was 1 June, and 91.2% of lamprey were trapped by 9 June. Despite large numbers of sea lamprey moving into the trap at the peak of the run, lamprey were not observed in the DIDSON footage.

The Atlantic salmon run ranged from May to October. The median capture day during the 2011 run was 15 June, and 90.2% of salmon had exited the fish ladder by 3 July. Both MSW fish and 1SW were captured throughout the salmon run, with MSW fish generally outnumbering 1SW on a daily basis and the relative proportion of 1SW increasing by mid-June. During the survey interval, 524 individuals of other fish species were captured at the trap. The majority of these were white sucker (*Catostomus commersonii*) (357) and smallmouth bass (152). Although the total number of other species captured was relatively small, their relative proportion increased throughout the season and as the number of anadromous migrants declined.

Table 4. Mixture model posterior parameter estimates derived from DIDSON observations recorded at the base of the Veazie Dam, Penobscot River, Maine, during May–July 2011.

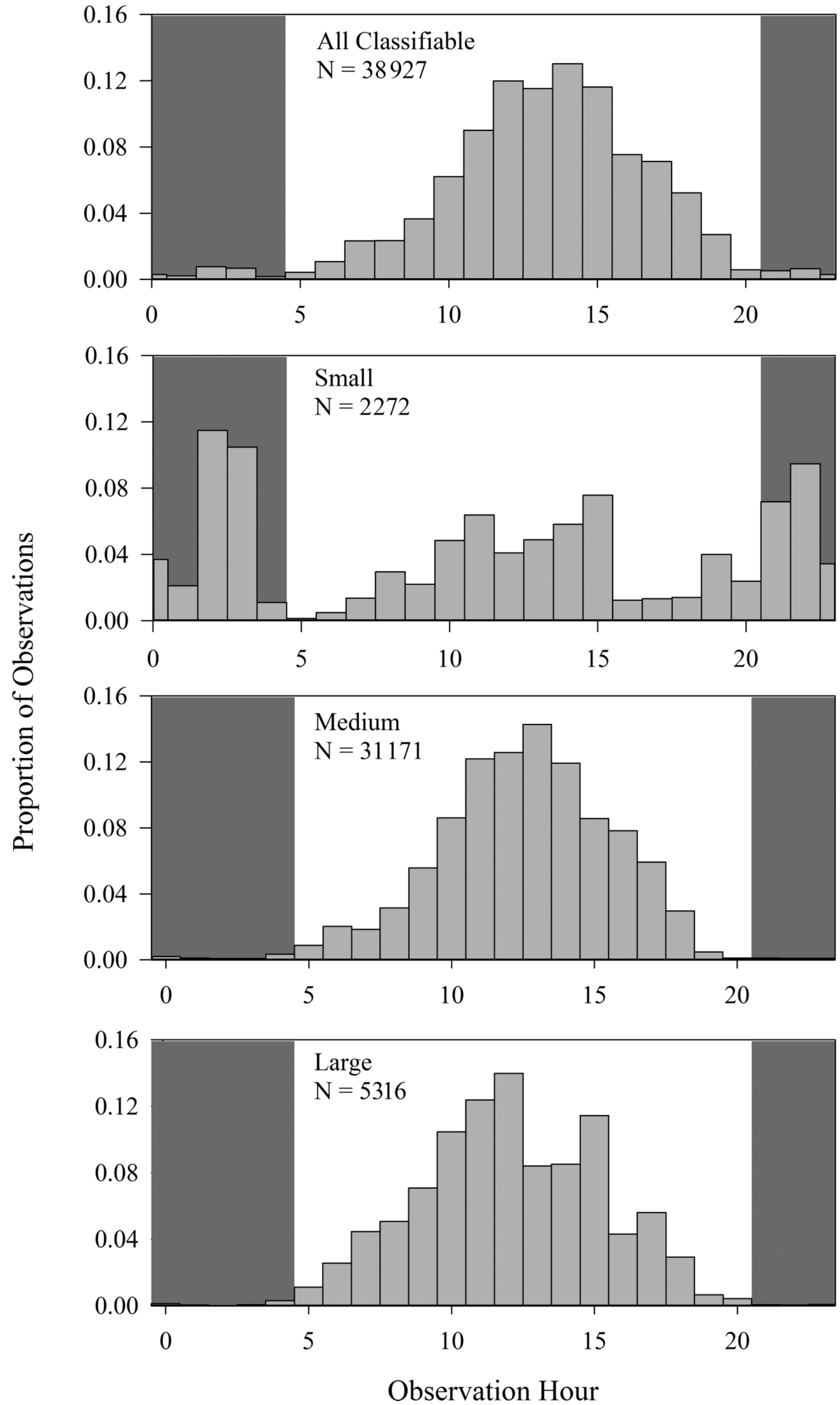
Parameter	Mean parameter estimate	95% credible interval
Percentage(1)	8.16%	7.47%–8.89%
Percentage(2)	76.20%	73.17%–79.35%
Percentage(3)	7.17%	4.15%–10.00%
Percentage(4)	8.46%	7.78%–9.17%
Mean(1)	23.95	23.69–24.21
Mean(2)	46.65	46.40–46.9
Mean(3)	53.49	53.33–53.65
Mean(4)	73.68	73.55–73.80
Variance(1)	17.82	14.01–22.30
Variance(2)	17.45	15.73–19.29
Variance(3)	19.56	12.68–30.88
Variance(4)	28.01	23.45–33.27

Discussion

Mixture model and apportionment

Mixture modeling was an effective approach for evaluating the underlying component distributions observed from DIDSON length measurement data. The fitted model accurately estimated the observed DFL distribution for targets >30 cm, including targets in the 48–54 cm size range where American shad and 1SW salmon overlapped. Although the model did not fit as well for targets <30 cm, this discrepancy may have resulted from reader error in the observed DFLs. On average, readers slightly (+0.77 cm) overestimated the length of the 26 cm test fish. Other work evaluating the precision of DIDSON length measurements has reported a positive bias for small targets (Hightower et al. 2013) and larger measurement errors (Burwen et al. 2010) than were observed in this study. The reader error reported here may have been arti-

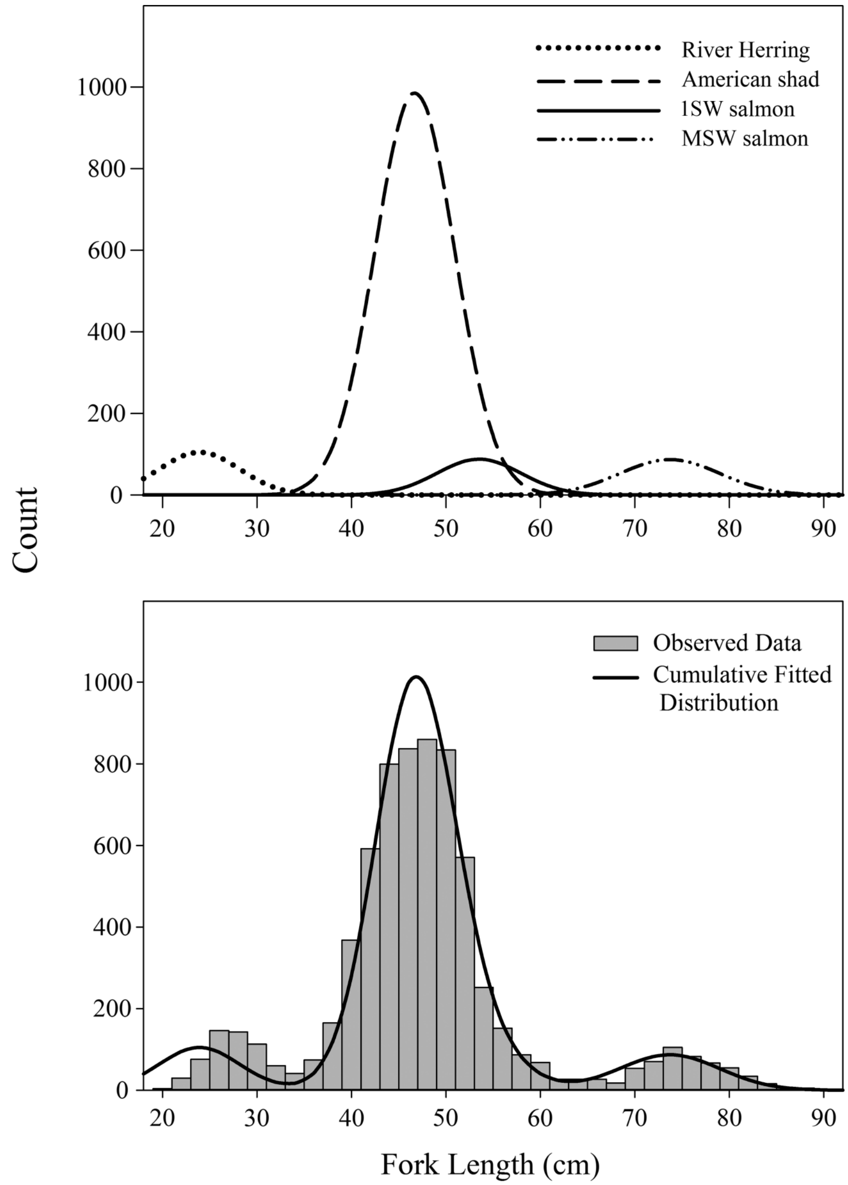
Fig. 6. Diel effects and DIDSON-measured fish observations recorded at the base of Veazie Dam, Penobscot River, Maine, during the spring of 2011. Size classes of targets are as follows: Small (18–31 cm), Medium (32–54 cm), and Large (55–92 cm). The background denotes nighttime (grey) and daylight (white) conditions.



ficially low as a result of imaging test fish that were fixed in a fully extended position, rather than free-swimming fish.

The mixture model estimates closely resembled the Penobscot-specific FL distributions for river herring, American shad, and 1SW and MSW Atlantic salmon. The empirical mean FLs for 1SW and MSW salmon matched the model estimates, and the estimated means for river herring and American shad FLs were marginally greater (<3.6 cm) than the priors. These minimal discrepancies may be explained by several factors. First, larger sample sizes resulted in FL priors that were one to two orders of magnitude more precise for both types of salmon than for river herring or American shad. Reduced prior precision allowed the model more freedom to vary the estimated means for the alosine component distributions. Second, both shad and river herring have deeply forked caudal fins, and unbalanced tail morphology may affect DIDSON length measurements (Hightower et al. 2013), especially if total and not fork lengths were recorded. The FL model results were presented here because FLs were deemed the best metric of DIDSON measured lengths. The Excellent quality images included those where the fishes' bodies were flexed, and

Fig. 7. Mixture model output. The upper panel shows the estimated component distributions for river herring, American shad, and 1SW and MSW Atlantic salmon. The lower panel shows the combined estimated distribution (four components) against the observed fork length distribution of DIDSON targets.



the recorded measurements may have underrepresented total fish length owing to this curvature. In addition, pixels at the edges of the fish images were sometimes difficult to distinguish from the background and may have resulted in underestimations of TL, making FL the appropriate length metric to model.

Of the 6869 Excellent caliber fish observations from this study, 5235 (76.2%) were apportioned as American shad. Some unknown percentage of these encounters was likely misclassified and was actually produced by 1SW salmon or other midsize resident species such as smallmouth bass. The mixture model inputs, especially the means'priors, were tightly constrained. As a result, the presence of other species in the DIDSON footage might skew the model predictions, dependent on the a priori assumption of four species component distributions. Nevertheless, the species composition data and Veazie Dam trap data suggest this is a valid assumption.

The model apportionment predictions were further supported by the raw size class data, and both approaches indicate the presence of large numbers of American shad at the base of Veazie Dam. Based on the size class definitions, it was reasonable to infer that the majority of Small, Medium, and Large targets were likely river herring, American shad, and Atlantic salmon, respectively. Of the 31 965 Good quality DIDSON observations, 25 774 (80.6%) were Medium targets and therefore shad-sized. In addition, this study investigated only a small area at the base of the dam, and just 5% of the recorded DIDSON footage was analyzed in an attempt to limit the effects of repeatedly imaging milling fish. These estimates are therefore conservative and almost certainly underrepresent shad presence across the entire dam. Finally, a companion radio telemetry study confirmed that tagged shad both approached the Veazie Dam and located the fishway entrance during the spring of 2011 (Grote et al. in press). So, while American shad do not effectively pass the Veazie Dam fish ladder, in 2011 shad clearly migrated to the full extent of accessible habitat and approached the Veazie Dam.

Implementing the mixture model in a Bayesian framework conveyed several advantages. Comparing the estimated FL means with the informative FL priors provided a direct means of assess-

Fig. 8. Mean measurement error by review round for DIDSON test fish images. Error bars indicate a single standard deviation (SD). For each review round, the true length of the test fish is within a single SD of the DIDSON-measured mean.

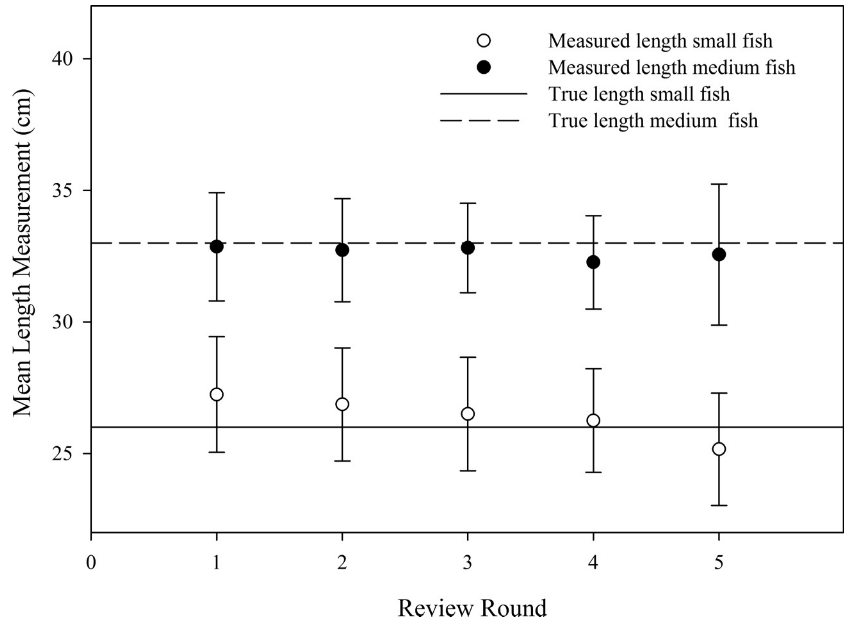
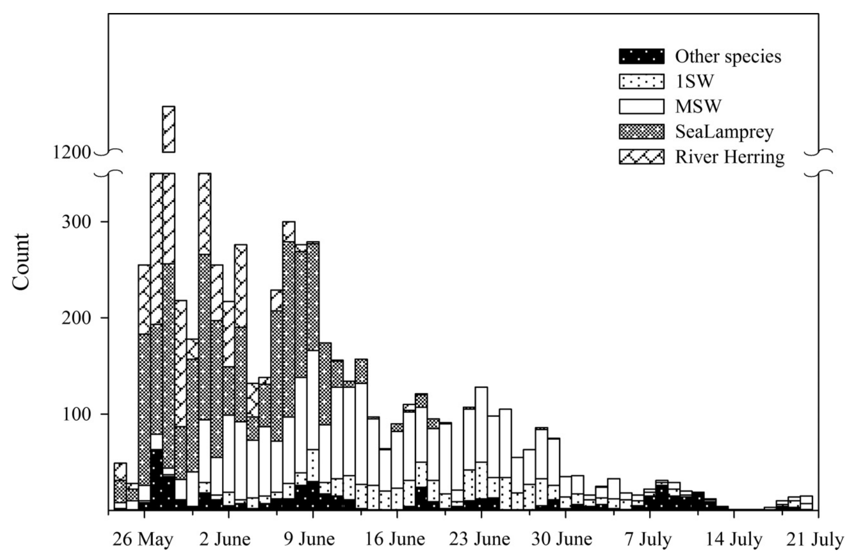


Fig. 9. Fish captures in the Veazie Dam fish trap during the spring of 2011. "Other species" is composed of brook trout, American eel, fallfish, landlocked Atlantic salmon, smallmouth bass, and white sucker.



ing how well the observed DFL distribution matched the hypothesized component distributions. Including auxiliary measures of reader error reduced the underlying fish-based variance estimates. Evaluating uncertainty associated with the parameter point estimates was straightforward using the parameter densities and 95% credible intervals.

The major limitation of this analysis relates to milling behavior. While the mixture model worked well to apportion fish observations into species categories, those observations do not represent actual fish numbers. Although the subsampling process was intended to limit the number of occasions when fish might be imaged repeatedly, schools of fish milled in front of the camera even within the 30 s sampling window. Without species-specific milling information, translating observations into abundance estimates was not possible. If, for example, Atlantic salmon move into the fishway rapidly while American shad mill at the base of the dam, the likelihood of ensonification is unequal. Marking individuals, either visually (external tags) or with transmitters (telemetry), to characterize milling rates might alleviate this problem for future barrier imaging work.

American shad management implications

The presence of American shad at the base of the Veazie Dam indicates that the current population is utilizing the upper extent of accessible habitat in the Penobscot River. While design factors such as fishway slope and cross-sectional area (Haro et al. 1999), or dam operations related to turbulence and attractant flow (Barry and Kynard 1986; Sprankle 2005), may prevent successful American shad passage, Penobscot River shad clearly approach the dam. In 2011, the run peaked over approximately 18 days, during which time thousands of shad-sized targets were recorded milling near the fishway entrance for hours at a time. The frequency and duration of these observations suggest that American shad are not only present, but persist at the base of the dam throughout the spawning season and will therefore be available to access upstream habitat following the removal of Veazie Dam. The recolonization of newly accessible habitat by American shad is well-documented (Bowman 2001; FPL Energy Maine Hydro LLC 2001; Weaver et al. 2003; Burdick and Hightower 2006). With their distribution now confirmed up to Veazie Dam, it is anticipated that shad will expand their migratory range in response to the barrier removal and will re-establish spawning and rearing grounds upstream.

With the removal of the Great Works dam in 2012, the restoration outlook for diadromous fishes in the Penobscot River is increasingly positive; yet the overall effect of improved passage on the recovery of American shad awaits future evaluation. Following the Veazie Dam removal by 2014, American shad will have unimpeded access to an additional 22 rkm of mainstem habitat, and up to 547 rkm of historical habitat will be available upriver of additional fish passage structures (Trinko Lake et al. 2012). Increased connectivity may improve shad access to preferred spawning habitats (Burdick and Hightower 2006) and could increase abundance (Cooke and Leach 2003), but may also result in reduced survival incurred from longer migrations (Leggett et al. 2004) or reduced downstream passage at dams (Haro and Castro-Santos 2012).

In light of these considerations, managers are considering accelerating American shad recovery through stocking (MEDMR 2009). While evaluating the successes (Hendricks 2003) and failures (Hasselman and Limburg 2012) of alosine stocking programs is beyond the scope of this paper (Bailey and Zydlewski 2013), recent work (Hasselman 2010; Hasselman et al. 2010) suggests that stocking practices have negatively affected American shad population structure in the United States and may have contributed to previously observed (Brown et al. 2000) low levels of genetic variation. Unlike many New England rivers, the Penobscot River system has never received large-scale or systematic American shad stock transfers. This study provides compelling evidence that American shad are present in the lower Penobscot River and in greater numbers than were previously known. In the event that shad stocking is implemented, managers may reconsider using only local brood stock collected from Penobscot River as an alternative to exogenous stock transfers.

Migration dynamics

Seasonal trends were evident in fish movement at the base of the dam, and patterns in the DIDSON footage often matched observations from the Veazie Dam fish trap. Small targets, presumably river herring, migrated early in the season, at high flows and water temperatures below 17 °C. The river herring run appeared very condensed with most captures and observations occurring over a 10-day span beginning in late May. Although increased numbers of Small targets were observed on 11 June and 20 June, the trap capture data do not suggest that these targets were upriver migrants. Instead those targets may have been outmigrating postspawn river herring or other resident species such as smallmouth bass or white sucker, both of which were captured in the trap on those days.

Medium targets, presumably American shad, were present from late May to early July. Shad-sized observations were highest in mid-June, at average daily water temperatures ranging from 17.5 to 21.5 °C. These temperatures are consistent with what has been reported for peak American shad spawning (Walburg and Nichols 1967; Leggett and Whitney 1972; Ross et al. 1993).

Large targets, presumably salmon, were encountered throughout the survey interval from late May through mid-July. Not surprisingly, Atlantic salmon-sized observations and salmon trap captures both occurred over the full range of observed daily average water levels (2.64–0.95 m) and temperatures (11.9–26.6 °C). While the DIDSON and trap seasonal results were generally similar for both classes of salmon, the ratio of 1SW to MSW fish was considerable higher for the imaged than the captured fish. The greater representation of 1SW in the DIDSON data may have resulted from different milling rates if the 1SW spent more time at the base of the ladder than the larger fish. Alternatively, 1SW images may have been overrepresented because they are smaller and were more likely to fit completely within DIDSON field of view, resulting in more Excellent quality 1SW images in the DIDSON data. Finally the lack of distinct shad-sized and 1SW modes in the DFL distribution may have resulted in a misestimated proportion of 1SW fish.

Diurnal patterns were also observed in fish movements at the base of Veazie Dam. Salmon and American shad-sized targets were recorded almost exclusively during daylight hours, and for both of these groups observation activity peaked at midday. These results are consistent with other work indicating that passage movements of American shad and Atlantic salmon occur mainly in daylight (Gowans et al. 1999; Haro and Castro-Santos 2012). Small, river herring-sized targets exhibited very different diurnal behaviors. As with the larger fish, river herring-sized target observations increased at midday. However only half (51.1%) of all Small observations were recorded during daylight hours, suggesting river herring may try and pass the dam at night. Work with alewife in other New England rivers (Saila et al. 1972; Franklin et al. 2012) indicates that passage activity is typically highest during the day, but that some passage does occur at night, especially when water temperatures remain high (Richkus 1974). Future fish lift operations at the Milford Dam may need to account for differences in both seasonal and daily approach behavior to optimize passage for a variety of anadromous species.

DIDSON survey approach

The ability to survey without capturing, handling, or disturbing fish makes multibeam sonars well-suited for use in systems containing Threatened and Endangered species. In addition, the DIDSON system is capable of collecting data continuously, even in low light and turbid conditions, thereby producing 24 h data sets for each survey day. Both of these advantages were critical to this work describing the migration characteristics of anadromous fish runs in the lower Penobscot River prior to dam removal.

The majority of enumerative DIDSON fisheries research has focused on systems where individuals were surveyed once, either because they were migrating upstream (Holmes et al. 2005; Burwen et al. 2007; Pipal et al. 2012) or because they were sedentary relative to mobile survey vessels (Han and Uye 2009; Lachapelle et al. 2013). This study is part of a growing body of work using DIDSON to identify and quantify fish interacting with anthropogenic barriers, such as dams (Baumgartner et al. 2006) and flood gates (Doehring et al. 2011). Although species identification with hydroacoustics remains challenging (Burwen and Fleischman 1998; Horne 2000; Doehring et al. 2011), efforts using multibeam sonars are increasingly successful (Mueller et al. 2010). This study demonstrates how DIDSON can be an effective tool for estimating species proportions based on length frequencies, provided that limited numbers of species are present and size overlap among them is limited. The DIDSON was also effective for characterizing anadromous fish runs, even when individuals could not be uniquely identified.

The DIDSON limitations encountered during this study were mainly related to unit placement and data processing. DIDSON files are large (gigabytes of data per hour) and ideally the unit deployment utilizes a fixed background that can be removed to identify and eliminate "empty" frames containing no targets in motion (Boswell et al. 2008). For this study, the area of interest was located in the extremely turbulent Veazie Dam tailrace where no fixed background was available, and plumes of entrained air may have resembled fish targets. Future studies would do well to deploy in calmer waters with laminar flows. Moreover, the position of the camera up in water column appears to have been effective for sampling free-swimming and surface-oriented targets, but not bottom-oriented fishes. The lack of lamprey observations from the hydroacoustic data demonstrates how DIDSON may have species-specific applications limited by deployment orientation and target species behavior. Finally the DIDSON data included large schools of fish with overlapping and occluding images, which further confounded efforts to automate target detection. To address this issue, data were manually processed, which was time- and resource-intensive, and introduced the possibility of reader bias. While the bias analysis identified effects too small to warrant correction, this may not always be the case, and DIDSON studies relying on manual processing will need to account for this potential source of error.

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