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ARTICLE

Assessment of River Herring Spawning Runs in a Chesapeake Bay Coastal Plain Stream using Imaging Sonar

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Abstract
Recent declines in anadromous river herring (Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis*) have been documented in much of their range using fishery-independent spawning run counts. A lack of rigorous long-term run counts and demographic data for Chesapeake Bay spawning stocks resulted in the declaration of unknown stock status in a 2012 stock assessment and made it difficult to evaluate responses to conservation and restoration efforts. The objectives of the present study were to (1) conduct the first spawning run counts of river herring in the Choptank River, Maryland, since the run counts performed over a 2-year period in 1972 and 1973, (2) evaluate population structure and dynamics, and (3) identify environmental variables associated with run timing. Spawning runs of Alewives and Blueback Herring were recorded from March 10 to June 4, 2014, using imaging sonar and processed manually to produce hourly run counts of fish with TLs ranging from 200 to 350 mm. A total of 1,659,090 ± 91,250 fish with TLs of 200–350 mm (errors estimated using a CV of 5.5%) were estimated to swim upstream past the sonar unit. Boat electrofishing was conducted at weekly intervals to estimate species composition and obtain samples for demographic analysis. Using these species composition data to apportion run counts resulted in an estimated count of 581,275 ± 31,970 Alewives and 726,450 ± 39,955 Blueback Herring. Fish age by otolith analysis varied from 2 to 7 years and total instantaneous mortality (*Z*) was estimated at 1.47 (SE, 1.8×10^{-5}) for Alewives and 1.91 (SE, 1.1×10^{-5}) for Blueback Herring. Upstream migration occurred primarily in the afternoon and evening associated with increasing water temperature, and downstream migration occurred at low and decreasing levels of discharge. The present study established a new fishery-independent population monitoring effort for river herring in Chesapeake Bay and identified associations between environmental drivers and upstream and downstream movements.

Historically abundant spawning runs of river herring (Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis*) in rivers of the Atlantic coast of North America have declined to historical lows and are considered as species of concern (ASMFC 2012; Hall et al. 2012). River herring are anadromous species during spring in freshwater habitats, and

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run timing likely is associated with warming water temperature, increased outflow, and the light: dark cycle (Richkus 1974; Ellis and Vokoun 2009). Larvae and juveniles remain in freshwater lakes and ponds, as well as in streams and estuaries, for several months to more than a year before moving into continental shelf waters (Turner and Limburg 2012; Payne Wynne et al. 2015). Adult river herring typically enter the spawning migration beginning at age 3–5, are iteroparous, and reach a maximum age of 8–11 years (ASMFC 2012).The range of Alewife extends from Newfoundland and Labrador to South Carolina and that of Blueback Herring from the Gulf of St. Lawrence in Canada to the St. Johns River, Florida (Loesch 1987). Causes of the population declines have included loss of spawning habitat due to construction of dams and culverts, overfishing in directed and bycatch fisheries, and degradation of water quality and benthic habitats due to changes in land use (Hightower et al. 1996; Limburg and Waldman 2009; Hall et al. 2011, 2012). The mid-Atlantic stocks of river herring, which include Chesapeake Bay spawning runs, are of high priority for conservation based on trends in fishery landings and mean fish length (Palkovacs et al. 2014) and are among the most susceptible to bycatch in the fishery for the Atlantic Herring *Clupea harengus* (Hasselman et al. 2016).

Stock status in most regions has been determined based in part on fishery-independent spawning run counts conducted at fish passage structures by visual census or electronic resistivity fish counter (ASMFC 2012). In contrast, fish passage structures in tributaries of Chesapeake Bay where run counts are regularly conducted pass very few river herring (ASMFC 2012). These structures include the fish lift at Conowingo Dam on the Susquehanna River near Havre de Grace, Maryland, and Bosher's Dam on the James River near Richmond, Virginia. In other tributaries, the potential for establishing run counts at fish passage structures is complicated by the current focus of fish passage efforts on dam removal and poor water clarity preventing inexpensive visual or video counts. Due to the lack of fishery-independent data in the Chesapeake Bay watershed, the status of all stocks in the region was determined to be unknown in the most recent coastwide stock assessment (ASMFC 2012), and fisheries were placed under moratoria in December 2011. The Chesapeake Bay region is also poorly represented in coastwide assessments of river herring population structure, population dynamics, and run timing with respect to environmental variables. Long-term data on population structure and dynamics are only available from fishery-dependent sampling in the Nanticoke River, Maryland, and limited, often decades-old data exist for other spawning streams (ASMFC 2012). Regardless, river herring that spawn in Chesapeake Bay tributaries are part of the mid-Atlantic stocks of both Alewife and Blueback Herring, which, along with those in southern New England, have suffered the greatest population declines (Palkovacs et al. 2014).

The development of imaging sonar provides a means to enumerate fish in turbid coastal plain streams common to the Chesapeake Bay watershed. Electronic fish counters and video recordings have been used in other regions to conduct near-continuous river herring run counts, but these methods can impede fish in the spawning run due to the need for narrow fish passage structures, can be biased low in the case of electronic counters, and are less effective in turbid streams or at night in the case of video recordings (Hiebert et al. 2000; Sheppard and Bednarski 2015). Imaging sonar has proven to be a powerful tool for conducting run counts for stock assessment in shallow streams several meters or less in depth and, importantly, can be used in turbid streams without narrow fish passage structures (Holmes et al. 2006; Martignac et al. 2014). Although river herring are small (200–350 mm TL) and thus challenging to image using sonar (Hightower et al. 2013), imaging sonar has been used to conduct run counts for a variety of species groups including river herring (Magowan et al. 2012) and salmonids (Burwen et al. 2010; Mueller et al. 2010; Pipal et al. 2010; Jones and Petreman 2015) and multispecies assemblages that include river herring (Grote et al. 2014; Hughes and Hightower 2015). It is not possible to differentiate between Alewife and Blueback Herring using imaging sonar, necessitating additional biological sampling to estimate species-specific run counts for river herring (Magowan et al. 2012; Grote et al. 2014; Hughes and Hightower 2015).

Establishing monitoring programs for Chesapeake Bay stocks of Alewife and Blueback Herring that document population size (run counts), structure, and dynamics will be critical for improving future coastwide stock assessments and assessing the effectiveness of river herring conservation and restoration efforts. Restoration efforts have included dam removal, improvement of fish passage at dams and culverts, fishery moratoria, and bycatch reduction. The objectives of the present study were to (1) initiate fishery-independent monitoring of population size and dynamics for Alewife and Blueback Herring in an important spawning stream in Chesapeake Bay, (2) explore relationships between run timing and potential environmental forcing factors (temperature, water level, flow, daylight), and (3) compare modern population estimates with available historical data. The results of the study provide initial run counts and population data to begin assessing the effectiveness of bycatch reduction, fish passage improvements, stream restoration, and other conservation and restoration efforts and could eventually contribute to the development of a sustainable fishery management plan.

STUDY SITE

The study site was just upstream of tidal influence on the Choptank River, a coastal plain stream on the Eastern Shore of Chesapeake Bay, Maryland (Figure 1). The imaging sonar station was located 280 m upstream from a Maryland Department of Natural Resources (MD DNR) anadromous

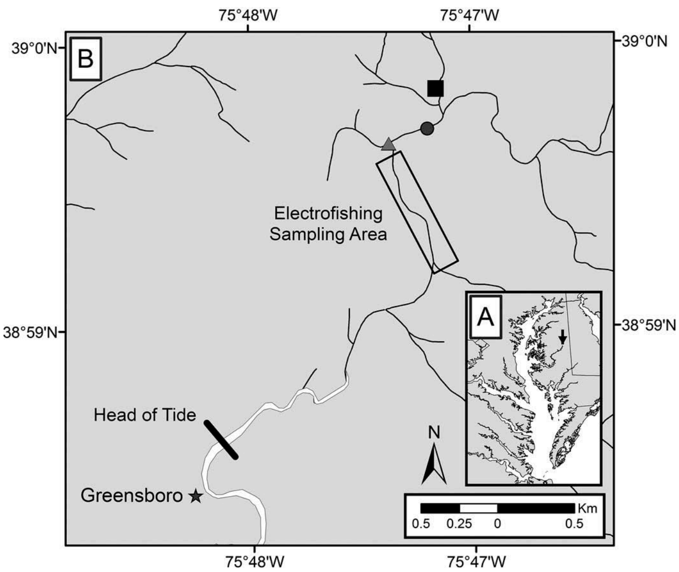

FIGURE 1. **(A)** Chesapeake Bay with the Choptank River study area indicated by arrow. **(B)** Imaging sonar location (gray circle), location of 1972–1973 fish weir (gray triangle), electrofishing sample area (rectangle), and location of USGS weir and stream gauge (black square).

fish run count conducted in 1972 and 1973. This location maximized the portion of the river herring spawning runs enumerated in the present study, although spawning is also known to take place downstream in tributaries branching off the tidal portion of the river. Discharge in the Choptank River varies annually with rainfall (Fisher et al. 1998) and was 95–2,160 ft^3/s (2.7–61.1 m^3/s) during the study period at U. S. Geological Survey (USGS) gauging station 01491000, which was located 315 m upstream from the sonar station. Sediment types near the sonar station were silt and sand in slower currents and gravel and hard clay in riffles and other areas of relatively high flow (including the sonar station).

METHODS

Environmental data.—Water temperature, water level, and streamflow data were obtained for locations at or near the sonar station. Water level and temperature data were collected using a pair of HOBO U20-001–2-Ti Water Level Data Loggers (Onset Computer Corporation, Bourne, Massachusetts). One logger was suspended in a PVC housing attached to the base of the sonar mounting frame to record pressure and temperature ~25 cm above the streambed. The second logger was located ~10 m away and was suspended in a PVC housing buried in the ground at a depth of ~0.5 m as an atmospheric control. Stream discharge data were obtained from USGS gauging station 01491000 located 315 m upstream from the sonar station (Figure 1). Stream discharge and water level were highly correlated (r^2 = 0.86), and only discharge was used in analyses.

Sonar fish counts.—Fish were monitored throughout the spawning run from March 10 to June 4, 2014 using a dual-frequency identification sonar (DIDSON, Sound Metrics Corporation, Bellevue, Washington) acoustic camera. The site was carefully chosen so that the entire width and depth of the river could be ensonified at normal flow conditions and tidal influence was negligible. The sonar unit was deployed on an aluminum frame secured using rebar next to the eastern bank of the stream and aimed perpendicular to the streamflow. The imaging sonar was positioned on the frame at a depth of approximately 0.25 m under normal flow conditions and aimed at a fixed angle of 4–5° below horizontal, so that the upper sonar beams nearly reached the surface in the field of view and the lower beams intersected the bottom about 2 m in front of the sonar. Perforated orange plastic safety fencing was used at both banks to prevent fish from swimming behind or less than 2 m in front of the sonar unit and from swimming beyond the far end of a 10-m recording window. This setup allowed for recording nearly all fish passing the sonar unit during normal and low flow conditions and prevented the vertical distribution of fish in the water column from affecting the number of fish in the sonar image, as was observed by Kirk et al. (2015) when water depth exceeded that of the imaging sonar field of view. For the majority of the run, water depth was approximately 1.25 m at the deepest point in the field of view, although the imaging sonar did need to be lowered on the frame approximately 0.25 m to ensure that it remained below the surface late in the season when water level declined substantially. For 25% of the time the water rose above this level, and fish could have passed above the field of view, but water exceeded this level by more than 0.25 m and 1 m only 10% and 4% of the time, respectively. Power was provided using a 120-V AC source backed up with a bank of four 6-V deep-cycle batteries (two sets of two connected in series to generate 12 V, then in parallel). The sonar unit was set to 1.8 MHz with a standard lens, seven frames per second, and a window start of 2 m. The imaging sonar unit was set to record for 10 min each hour, with hourly start times selected at random using the DIDSON V5.25.52 Control and Display software (Sound Metrics). This sampling strategy is commonly used for high-abundance anadromous fish migration studies and can result in a CV (100·SD/mean) of 5.5% (Xie and Martens 2014). This value of CV is used throughout the present study to estimate error associated with run counts.

Imaging sonar files were processed manually to determine the number of fish in spawning runs. The DIDSON V5.25.52 software was used for playback and measurement of fish targets. Due to their small size and relatively rigid body shape fish were measured using a straight line, and all fish within the size range of 200–350 mm TL were counted to generate counts of fish within the size range of adult river herring. Counts from 10-min files were multiplied by a factor of six to generate hourly fish counts. A total of five observers participated in sonar data processing after completing training using a standard set of training files. Observers measured all fish during initial training, but for most files measured a subset of fish (one measurement per fish), focusing on those at the upper and lower ends of the size range of interest, and recorded fish numbers using hand-held counters. This method was applied due to the large number of fish within the size range of 200–350 mm TL in sonar images and relative rarity of fish just outside this range. Separate counts were conducted for upstream and downstream migrants in each sonar file, and most files were reviewed independently except for training files and an additional 20 files reviewed by multiple observers for quality assurance purposes. Trained observers can produce fish counts that are not statistically different across a range of fish abundance (Petreman et al. 2014).

Biological sampling.—The species composition of fish passing the sonar stations was determined weekly using boat electrofishing. Electrofishing was conducted during late morning or early afternoon approximately 500 m downstream from the sonar station due to large trees obstructing access and the common presence of anglers at and above the sonar site (Figure 1). To the best of our knowledge, based on other sampling efforts, the lack of side tributaries, and conversations with experienced local anglers, there was no difference in species composition among the electrofishing and sonar stations. Electrofishing was conducted for 600 s during each sampling event. On 6 of 12 sampling dates, the number of fish collected was small (<50 individuals) and a second 600-s sample was taken just downstream from the first to increase sample size (about 750 m downstream from the sonar station). All fish collected were identified visually in the field to sex and species, and TL was measured.

A subset of river herring was retained each week to confirm species identity based on the color of the peritoneum and for determination of age and spawning history following the recommended methods of the River Herring Ageing Workshop (ASMFC 2014). Samples were obtained weekly throughout much of the run to account for potential shifts in sex or age composition over time. Three scales were removed from each fish, cleaned with soap and water, and pressed between two glass microscope slides that were taped together at the ends following standard protocols used by MD DNR (ASMFC 2014). Spawning marks were counted on a microfiche reader. Spawning history is described herein as 0 (first spawning year), 1 (first repeat spawning year), and so forth. Fish were dissected to remove right and left otoliths and aged by counting annuli under a dissecting microscope. Annuli were counted following Libby (1985) preferentially on left otoliths, and right otoliths were used when the left otolith was missing or lost. A standard magnification of 6.5× was used for aging and lower or higher magnifications were sometimes used to differentiate true and false annuli. Scales were evaluated by two readers and were reread by both readers together when there was disagreement on the number of spawning marks. Otoliths were evaluated by three readers, and only consensus ages were used for analysis. Consensus ages were those for which at least two readers were in agreement and the third did not differ by more than 1 year following Davis and Schultz (2009).

Historical data.—Anadromous fish runs in the Choptank River were monitored by MD DNR in spring of 1972 and1973 (Speir et al. 2008). Upstream migrant fish were enumerated at a fish weir (2.54-cm, diamond-pattern, chicken wire mesh) using a Smith-Root Model 602 electronic fish counter mounted inside three, large, chimney flue liners (location shown on Figure 1). Fish were collected in a single-throated box trap for species identification. The weir was sampled at least daily, often several times each day during high run counts, from March 15 to early June, but accurate counts could not be obtained on nearly 25% of days due to high water that allowed fish to pass over the weir. Run counts on these days were estimated to account for less than 20% of the total run. Linear interpolation was used to fill data gaps due to high flow events. Original data for the study are no longer available. Data available for comparison in the present study consisted of biweekly species-specific run counts (the sum of daily run counts) and sex ratio. For comparison with fish counts from the present study, we determined the 75th percentile discharge rate for 1972 and 1973 and assumed that the weir was not sampled at higher rates of discharge. The 75th percentile was chosen because run counts were obtained on 75% of possible sampling days in 1972 and 1973. This discharge rate was then applied to daily counts from the present study to determine high water days in 2014 when water would have overtopped a weir, and the daily counts for these high-water days were estimated as described above. Biweekly run counts were then calculated for 2014 for comparison with historical data. Mean daily discharge in 2014 was approximately 1.3 times that of 1972 and 1973, largely due to the two high-flow events, each of which had a peak discharge greater than twice that of the highest discharge in the earlier study.

Data analysis.—Fish counts were apportioned among species using species composition data collected by boat electrofishing. The proportion of fish within the size range of adult river herring (200–350 mm TL) was determined for each electrofishing sample date. These data were then converted to daily values of species composition using linear interpolation. Daily species composition data were then applied to all hourly sonar fish counts for that date. This method resulted in smooth shifts in species composition from day to day rather than sharp breaks from the end of one week to the beginning of the next as in Hughes and Hightower (2015). The sole exception to this method was the beginning of the Blueback Herring migratory run, when a large influx of fish rapidly changed the species composition of fish with TLs of 200–350 mm. The species composition recorded on the first date of electrofishing after the start of the Blueback Herring run was also used for days with high run counts immediately prior to the electrofishing date to minimize the extent to which the arrival of large numbers of Blueback Herring might artificially inflate the Alewife run count. The final run count for each species was determined by summing the daily species-specific counts and applying the same CV of 5.5% used for the run count of all fish in the 200–350-mm size range.

Temporal variability in the runs was evaluated to identify potential relationships with cyclic environmental variables such as diel and tidal cycles. Species-specific run count data were examined using wavelet analysis, which identifies period lengths associated with variability in the data. Hourly data were analyzed following Torrence and Compo (1998), and statistical significance of peaks in the global wavelet spectrum was determined using 95% CIs. Potential differences in the timing of the run each day were explored by calculating the time of day at which the 50th percentile of the daily run was reached. A start time of 0600 hours was chosen to represent the start of each day for this analysis because visual inspection of the data indicated that some periods of high run counts started in the evening and persisted for several hours after midnight.

Relationships between changes in run counts and environmental variables (temperature and discharge) were evaluated using daily data. Using daily sonar run count data removed the strong influence of the diel cycle on both run count and temperature data. A weighted index of change in daily mean temperature was calculated as $\Delta T = [(T_0 - T_1) \times 3 + (T_1 - T_2) \times 2 + (T_2 - T_3)] /6$, where T_0 was daily temperature, and T_1, T_2, and T_3 were the temperatures 1, 2, and 3 d earlier, respectively. The resulting index struck a balance between changes in temperature during the day immediately prior to a run count and longer-term (3 d) changes in temperature reflective of multiday warming and cooling trends. The weighted temperature was compared with the $\log_{10}$ of the daily change in run count using cross-correlation analysis with 95% CIs calculated following Wing et al. (1995) and using linear regression. In cross correlations, lags of up to 4 d were considered because longer lags were unlikely to be the result of a behavioral response to temperature changes. Daily changes in run counts were also compared with the $\log_{10}$ of changes in flow.

Population structure and dynamics were evaluated using a combination of run count, age based on otolith aging, and spawning mark data sets. Age composition and spawning history were calculated for Alewife and Blueback Herring separately for each weekly electrofishing sample. Within a species, males and females were combined to maximize the weekly sample size (11–36 individuals). Species-specific run count data for each week were divided among age-groups and spawning-mark groups to determine the age and spawning history distribution of the total run. This accounted for an observed shift from older to younger fish over the course of each species' spawning run and differences in the number of fish migrating upstream each week. Instantaneous total mortality was estimated using catch-curve analysis with the first age-group 1 year older than the age of peak abundance (Smith et al. 2012). For Alewife, only ages 5–7 were used for catch-curve analysis because maximum female abundance was not reached until age 4 and ~50% of fish aged 4 years or older were female. Total mortality was estimated using the Chapman and Robson (1960) mortality estimator with the variance estimator corrected for overdispersion (Smith et al. 2012).

RESULTS

Species Composition

A total of 968 fish were collected during electrofishing of which 517 were within the 200–350-mm-TL size-class analyzed in sonar run counts (Table 1). River herring dominated the catch

TABLE 1. Species composition from 2014 boat electrofishing and weir sampling from 1972 to 1973 conducted from mid-March to early June in the Choptank River. Data from 2014 include the total number of fish (*n*) caught and percent (%) by species, the percent of individuals of each species within the 200–350-mm-TL size range of adult river herring, and the number of fish (*N*) and percent by species within the 200–350-mm-TL size range. Percent composition of weir catch by species (1972 and 1973) from Speir et al. (2008) are included for comparison with percent of total electrofishing catch; several species were not recorded (NR) in that study.

Species	Total *n*	% of total	% in size range	*N* in size range	% of size range	1972	1973
Alewife	220	22.7	100.0	220	42.6	4.7	5.5
Blueback Herring	190	19.6	100.0	190	36.8	63.0	43.2
Chain Pickerel	1	0.1	100.0	1	0.2	NR	NR
Channel Catfish	2	0.2	100.0	2	0.4	NR	NR
Gizzard Shad	5	0.5	100.0	5	1.0	NR	NR
Hickory Shad	1	0.1	100.0	1	0.2	NR	NR
Striped Bass	24	2.5	41.7	10	1.9	NR	NR
White Perch	360	37.2	13.4	48	9.3	31.9	51.0
Yellow Perch	165	17.0	24.4	40	7.8	0.1	0.1
Grand total	968		53.5	517			

of electrofishing samples, making up 42% of the total collection and 79% of fish within the 200–350-mm-TL size-class. All river herring were 200–350 mm TL whereas 42% of Striped Bass *Morone saxatalis*, 24% of Yellow Perch *Perca flavescens*, and 13% of White Perch *M. americana* combined made up 19% of all fish in this size-class. Gizzard Shad *Dorosoma cepedianum*, Channel Catfish *Ictalurus punctatus*, Hickory Shad *A. mediocris*, and Chain Pickerel *Esox niger* made up the remaining less than 2% of fish in the 200–350-mm-TL size-class. Alewives first appeared in samples on March 14 and were encountered through May 5. Blueback Herring first occurred on April 14 and were last collected on May 28. No river herring were collected on June 4.

Run Counts

Within the 200–350-mm-TL size range, a total of 276,515 upstream migrants and 76,999 downstream migrants were counted in 10-min imaging sonar files (N = 2,058). Upstream migrants varied from 0 to 2,130 fish in a 10-min file and from 594 to 81,270 fish/d. Downstream migrants varied from 0 to 1,649 fish in a 10-min file and from 186 to 43,404 fish/d. Expansion for sample time resulted in an upstream run count of 1,659,090 ± 91,250 fish (all run count error estimates are based on an assumed CV of 5.5%) and downstream run count of 461,994 ± 25,385 fish within the 200–350-mm-TL size range. Apportioning these counts using species composition data from electrofishing, upstream migrants were estimated at 581,275 ± 31,970 Alewives and 726,450 ± 39,955 Blueback Herring, and downstream migrants were estimated at 141,201 ± 7,766 and 203,763 ± 11,207, respectively. Based on the sonar run count apportioned by species using electrofishing data, the Alewife run was initiated (first 5% of the run) on March 21 at a mean daily water temperature of 9.3°C, and the Blueback Herring run was initiated on April 23 at a mean temperature of 14.8°C. Both upstream migration and downstream migration were highly episodic in nature (Figure 2).

There was a diel pattern in upstream migration, but patterns of downstream migration were less clear. Circular histograms were indicative of most upstream migration for both species occurring during the afternoon and evening and pulses of downstream migration near the times of dawn and dusk (Figure 3). In wavelet analyses, both Alewives and Blueback Herring had significant cycles in upstream migration with a period length of ~24 h (actual period length tested, 23.4 h) as indicated by peaks in power of the global wavelet spectrum exceeding the 95% CIs (Figure 4). No diel or other short-term cycles were detected in downstream migration. All time series exhibited significant periodicity at

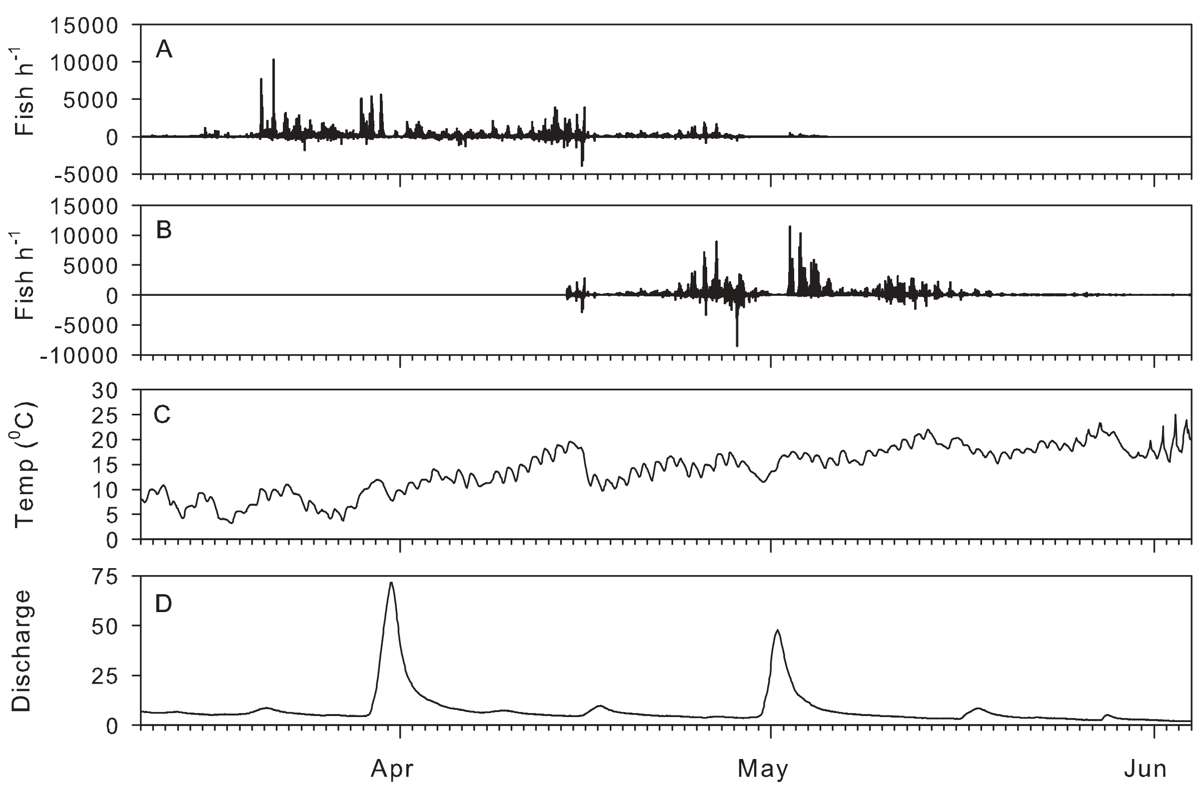

FIGURE 2. Time series of estimated Alewife and Blueback Herring run counts and environmental data in 2014. **(A)** Hourly run counts of Alewives swimming upstream (positive values) and downstream (negative values). **(B)** Hourly run counts of Blueback Herring swimming upstream (positive values) and downstream (negative values). **(C)** Water temperature 0.25 m above the stream bottom at the imaging sonar station. **(D)** Discharge (m^3/s) at USGS gauging station 01491000.

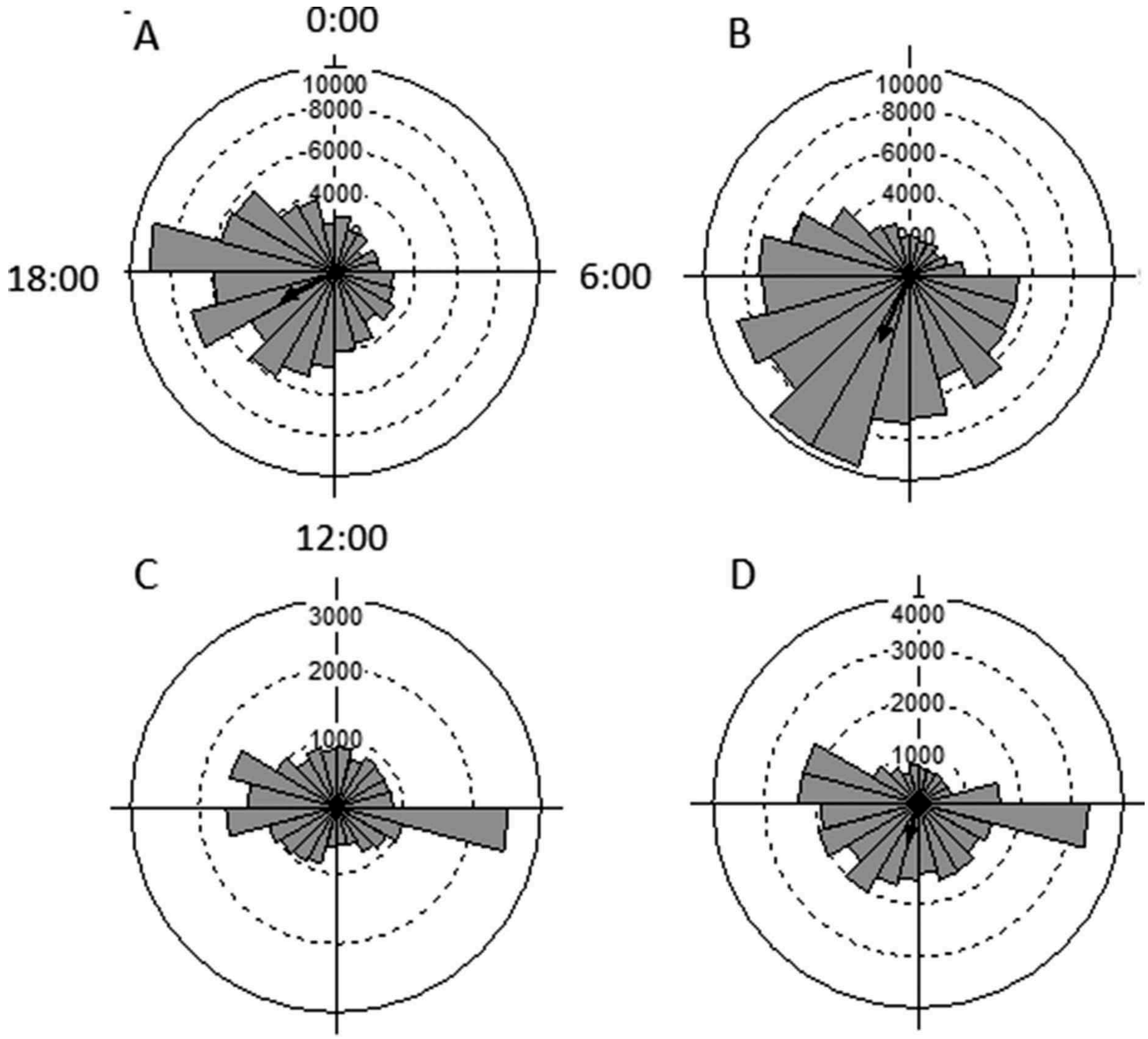

FIGURE 3. Circular histograms representing the time of day of upstream and downstream migrations. Gray wedges indicate the total number of fish by hour for Alewives **(A, C)** and Blueback Herring **(B, D)** moving upstream (A, B) and downstream (C, D). Note that scales differ. Black arrows indicate the direction and length of the mean vector, which varies from 0 to 1, where 1 is represented by the outer solid circle. All mean angles are statistically significant ($P < 0.001$).

greater than 100 h, but the period length was not consistent among data sets nor was it related to the lunar cycle.

Closer examination of the diel timing revealed that the time of day of the maximum hourly run count and the hour at which the 50th percentile of the daily run count of upstream migrants occurred shifted earlier over the course of the spawning season for each species (Figure 5). When the run consisted primarily of Alewives (March 11–April 14, 2014), the 50th percentile was reached as late as a weekly mean of 2300 hours at the beginning of the run and as early as 1500 hours later in the run. When Blueback Herring were most common (beginning the week of April15), the 50th percentile was reached earlier in the day in general and a shift from 1900 hours to 1200 hours was observed. There was an inverse nonlinear relationship between the time of day at which the 50th percentile of the run was reached and the maximum daily water temperature using combined data for both species ($r^2 = 0.490$, $P < 0.001$).

Increases in daily run counts were associated with changes in temperature and discharge (Figure 2). There were significant ($P < 0.001$) positive relationships between run counts of both upstream and downstream migrants and weighted 3-d change in temperature, and the strongest relationships occurred at a lag of 1 d (Table 2; Figure 6). There was no apparent relationship between discharge and run counts of upstream migrants (Figure 6). However, run counts of downstream migrants were strongly associated with slow declines in discharge (Figure 6), which tended to occur at times when water levels were already low.

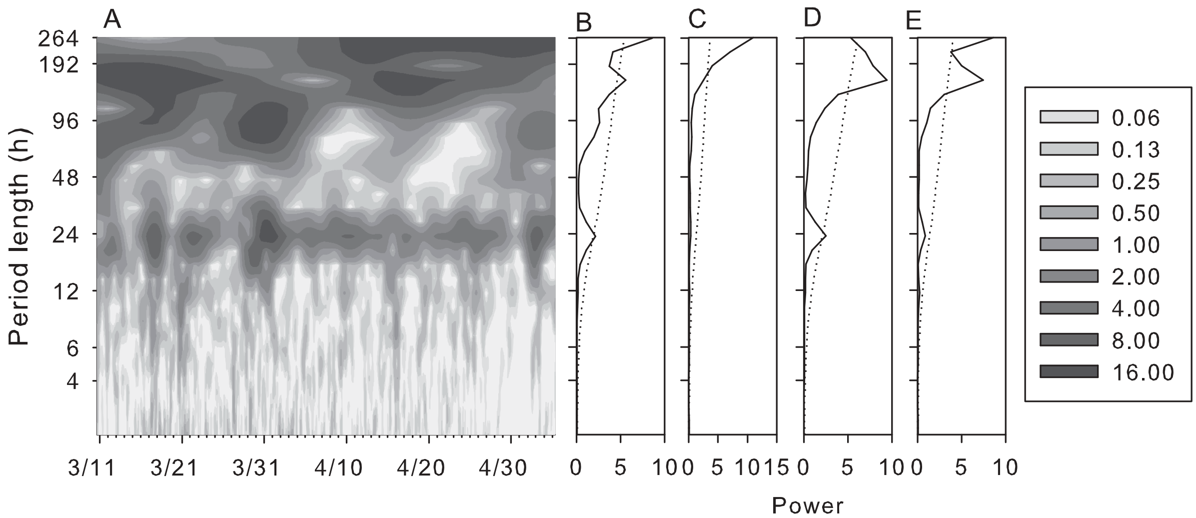

FIGURE 4. Wavelet analysis of hourly imaging sonar run count data. **(A)** Contour plot of wavelet power spectrum for Alewives swimming upstream with levels of power indicated by the color ramp at right. Global wavelet spectra (solid lines) for **(B)** Alewives swimming upstream, **(C)** Alewives swimming downstream, **(D)** Blueback Herring swimming upstream, and **(E)** Blueback Herring swimming downstream. Dotted lines indicate the 95% CI. Peaks in power that exceed the CI are statistically significant.

Age and Growth

Alewives tended to be older than Blueback Herring and had a lower rate of total mortality (Figure 7). The otolith age of Alewives varied from 2 to 7 years with a median age of 4 years, whereas Blueback Herring varied from 2 to 6 years of age with a median age of 3 years. Females were older than males for both species with median otolith ages of 4 and 3 years, respectively. Estimates of total instantaneous mortality (Z) were 1.47 (SE, 1.8×10^{-5}) for Alewives and 1.91 (SE, 1.1×10^{-5}) for Blueback Herring. Repeat spawners made up 55% of Alewives (0–2 spawning marks) and 54% of Blueback Herring (0–3 spawning marks).

Comparison with Historical Data

Run counts of Alewives were substantially higher in 2014 than in 1972 and 1973, whereas Blueback Herring counts were equivalent. After accounting for high-water events in 2014 during which the fish weir would not have been sampled, an estimated 376,669 ± 20,717 Alewives were observed moving upstream compared with 39,397 in 1972 and 34,297 in 1973. Blueback Herring were estimated at 494,945 ± 27,222 in 2014 compared with 531,146 in 1972 and 271,497 in 1973. Discharge exceeded the rate at which the fish weir would have been sampled on 27 d (39%) in 2014. Run counts for 2014 estimated using the correction method for high discharge were 65% and 68% of the complete imaging sonar run counts for Alewives and Blueback Herring, respectively.

DISCUSSION

River herring spawning runs in the Choptank River, Chesapeake Bay, Maryland, were monitored using imaging sonar during spring 2014, and run count estimates provided strong evidence that both Alewife and Blueback Herring runs contained hundreds of thousands of adult fish. The total number of fish within the 200–350-mm-TL size range of adult river herring swimming upstream and recorded by the imaging sonar was estimated to be 1,659,090 ± 91,250 fish. This count was apportioned by species based on the catch of a weekly boat electrofishing survey, in which river herring made up nearly 80% of the total catch within the 200–350-mm-TL size-class. The resulting Alewife run count was estimated at 581,275 ± 31,970 fish and the Blueback Herring run count was estimated at 726,450 ± 39,955 fish, counts that are comparable with those for many rivers in the northeast United States (ASMFC 2012). Although milling behavior was minimal within the imaging sonar field of view, it is possible that individual fish were counted more than once. Avoidance of the sonar beam did not appear to prevent fish from swimming through the viewing area, which is consistent with prior studies using imaging sonar for river herring (Magowan et al. 2012). In future studies, tagging and tracking of individual fish could be used to understand the movements of individual fish within the system (Raabe and Hightower 2014), particularly the extent to which individuals pass the sonar station multiple times, potentially resulting in positively biased run counts. Regardless, imaging sonar and other near-continuous run monitoring methods provide valuable counts of fish swimming upstream that are difficult to obtain from other methods. Combined with biological sampling to apportion the counts to species, imaging sonar provides a solution for conducting species-specific anadromous fish run counts in streams without narrow constrictions (e.g. fish ladders) or in clear water that would allow the application of more traditional visual or electronic counting methods.

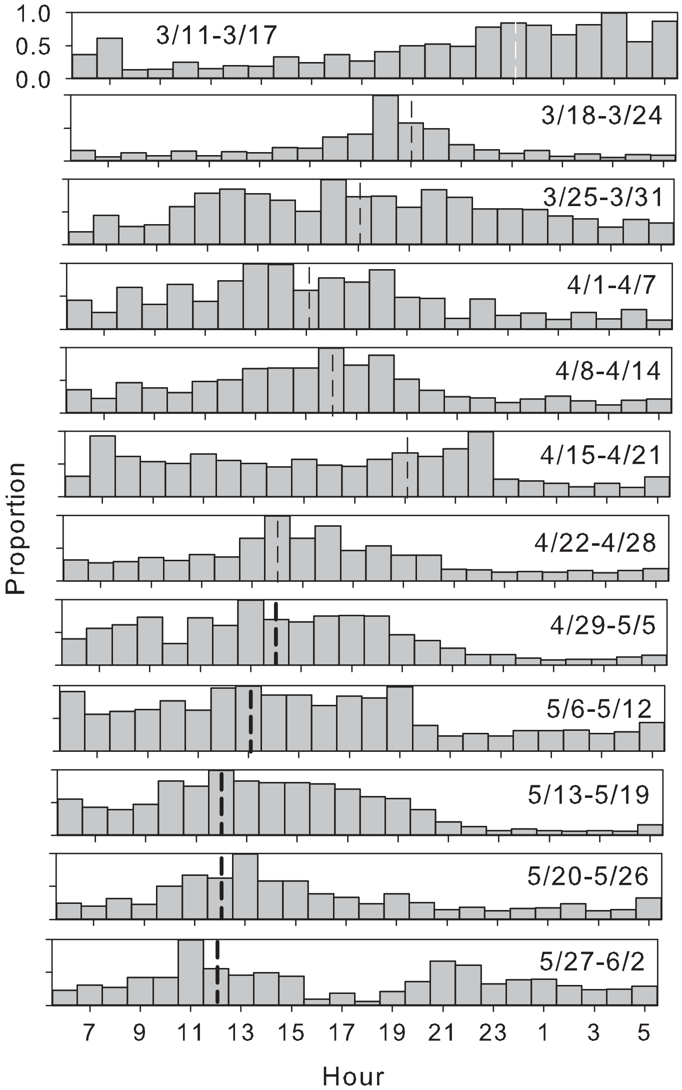

FIGURE 5. Timing of weekly maximum and 50th percentile of imaging sonar run counts for all upstream migrants having a TL of 200–350 mm. Gray bars are mean hourly run count by week and are scaled to the maximum hourly mean each week. Dashed vertical lines indicate the mean hour each week during which the 50th percentile of each daily run count is reached. Note that each day is considered to start at 0600 hours for calculating the maximum and 50th percentile of hourly run counts.

TABLE 2. Cross correlation comparing the change in the log of daily imaging sonar counts of river herring (Alewife and Blueback Herring combined) swimming upstream (up) and downstream (down) and change in daily water temperature. Significant correlation coefficients (bold italics) were determined using a 95% CI.

Lag (d)	Up	Down
0	***−0.410***	***0.289***
1	***0.493***	***0.490***
2	0.105	***0.307***
3	***−0.342***	−0.045
4	***−0.324***	−0.164

Run counts for Alewives and Blueback Herring in the present study were equivalent to or higher than the limited available historical run counts in the Choptank River, but methodological differences make it difficult to infer potential differences in population size. Imaging sonar run counts from the present study were adjusted prior to comparison to match MD DNR methods for estimating run size during high flows in 1972 and 1973 when the fish weir was overtopped by high water. The adjusted sonar run counts were 376,669 ± 20,717 Alewives and 494,945 ± 27,222 Blueback Herring, compared with 1972 and 1973 electronic counter run counts of 34,297–39,397 Alewives and 271,497–531,146 Blueback Herring (Speir et al. 2008). The results of the present study also indicated that the spawning runs may have been larger than estimated in 1972 and 1973 because 2014 sonar run counts were higher on high-discharge days when the weir would not have been operated than on days of moderate or low discharge (32–35% of the sonar run count in 2014 during high discharge versus an estimated 20% in 1972 and 1973). Run counts by electronic resistivity counters can also be biased low to restricted fish passage and undercounting at high passage rates (Sheppard and Bednarski 2015). In the late 1980s, the Choptank River Alewife run was considered “a remnant population that is at a very low level of abundance and may be declining” and the Blueback Herring run was considered “a moderately abundant population that appears to be stable” (Klauda et al. 1991). Despite historical data indicative of very small Alewife populations relative to Blueback Herring, our imaging sonar run counts and species composition data from electrofishing (Table 1) both indicate that Alewives in the Choptank River are now similar in abundance to Blueback Herring. Methodological differences—electronic fish counters supplemented with hoop nets in 1972 and 1973 and imaging sonar supplemented with boat electrofishing in 2014—make it difficult to determine whether this shift in relative abundance was due to an increase in the Alewife population or decrease in the Blueback Herring population. Genetic analyses suggest that the mid-Atlantic stock of Blueback Herring is more strongly affected by bycatch in offshore fisheries than is the mid-Atlantic stock of Alewife (Hasselman et al. 2016). Alternatively, historical fisheries (now under a moratorium) might have removed a higher proportion of Alewives than Blueback Herring in the 1970s due to their earlier arrival in the spring or somewhat larger size. Nevertheless, run counts totaling 1.31 million river herring in the present study were surprising because anecdotal accounts have suggested that populations declined substantially in recent decades.

Time of day was an important factor in upstream migration with the highest counts tending to occur in the afternoon or evening, coinciding with the time of day during which preferred temperatures occurred for each species. When mean

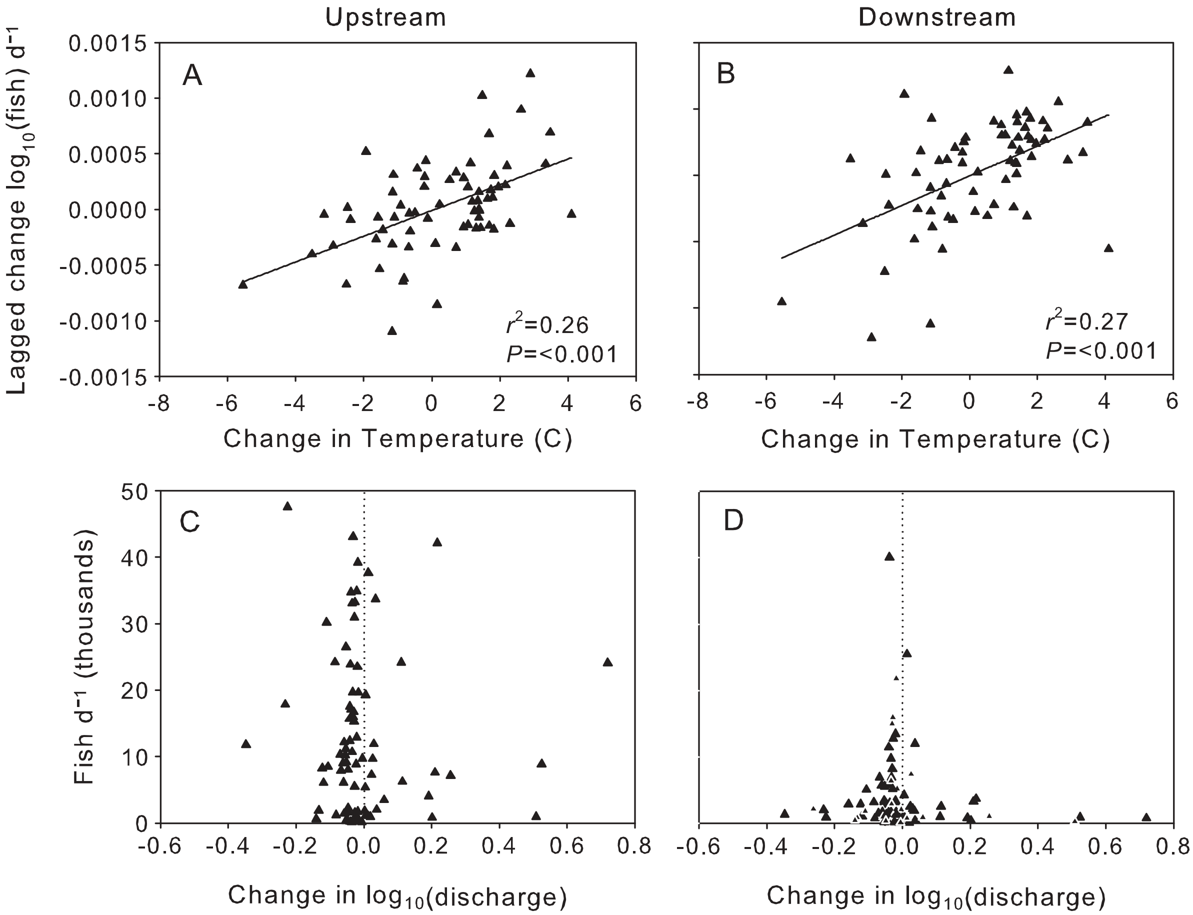

FIGURE 6. Comparisons between imaging sonar run counts (estimated Alewife and Blueback Herring counts combined) and environmental variables. **(A, B)** Linear regressions between the change in the log of daily counts of river herring swimming upstream and downstream (lagged 1 d) and change in daily average water temperature. Regression lines represent statistically significant relationships. **(C, D)** Relationships between change in the log of daily mean discharge and river herring run counts. Dotted line indicates no change in discharge.

daily temperature was lower than the preferred temperature range for each species, the 50th percentile was reached late in the day during the time when water temperature was greatest (as late as midnight). Later in the runs when water temperature was at or above the preferred temperature range, the 50th percentile of the run was reached earlier in the day prior to the peak daily temperature. Richkus (1974) observed Alewives ascending a fish ladder during the day in Rhode Island, suggesting that the diel pattern observed for upstream migrants is consistent across a wide geographic range. Variability in stream temperature within a watershed is strongly influenced by position within the watershed and dams, land use, and other human impacts (Isaak et al. 2014), such that the exact timing of the spawning run might vary across a watershed. Time-series analyses did not suggest a diel pattern of downstream migration, although the number of downstream migrants was greatest around the times of dawn and dusk. Understanding the timing of migration is critical to the design of population-monitoring efforts, especially when visual or video-based counts rely on daylight to see fish, and for maximizing fish passage at facilities that only allow passage during limited time periods each day. Our results indicate that a substantial portion of Alewife and Blueback Herring spawning runs could occur after dark, which could result in negatively biased run counts for studies that do not include nighttime counts.

Variability in run strength at scales of days to weeks in both upstream and downstream run counts was associated with changing environmental conditions. Periods of high upstream migration were associated with warming trends lasting several days and sometimes stopped abruptly during rapid declines in temperature. This finding is consistent with periods of high run counts observed during increasing temperature in Rhode Island (Richkus 1974) and strong associations between the seasonal timing of river herring spawning runs and water temperature (Ellis and Vokoun 2009). There was not a significant relationship between upstream migration and discharge, although discharge was at or above average in the

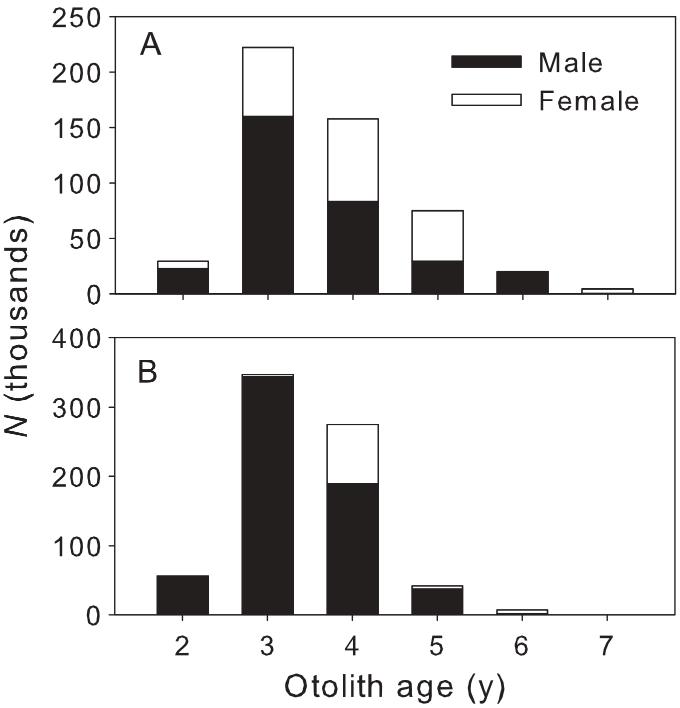

FIGURE 7. Estimated age and sex distributions of **(A)** Alewife and **(B)** Blueback Herring spawning runs. Bars indicate estimated number (*N*) of male and female fish migrating upstream past the imaging sonar station by age. Age structure was estimated using the run count of fish having a TL of 200–350 mm and moving upstream past the imaging sonar each week subdivided by species and fish age based on otolith analysis from weekly electrofishing samples. This method accounted for shifts in species, sex, and age composition from week to week during the spawning season.

Choptank River for most of the spawning season in the present study. Drought conditions could potentially have a negative effect on spawning migrations at the study site as discharge can be lower in some years. Downstream migration, in contrast, appeared to be associated with both increases in temperature and periods of low and decreasing discharge. The association with temperature is likely a byproduct of the relationship between upstream migration and temperature—downstream migration can only be high after large numbers of fish move upstream. Migrating downstream during periods of low water and decreasing discharge may be a behavioral response that reduces the likelihood of fish becoming stranded at low water levels. This hypothesis is difficult to evaluate using our data because fish may also have moved downstream during high discharge events and could have been missed when water levels exceeded the ensonified portion of the water column. Dead river herring that had been stranded in pools in the floodplain forest were observed on May 11 following a major flood, but it is unclear whether these fish had been moving upstream, moving downstream, or merely trying to hold their position in the flooded river in areas of low current speed. Associations between the timing of migrations and changes in environmental variables such as temperature and discharge are indicative of a driving influence of synoptic scale weather events on river herring spawning runs, which likely determine both the number and timing of pulses of upstream and downstream migration each year.

The biological sampling required for interpreting imaging sonar fish counts also provided critical information on population structure and dynamics that can be used as additional metrics for population monitoring. Spawning runs for both species were dominated by males, with females only making up 32% of Alewives and 16% of Blueback Herring sampled by electrofishing. In contrast, 54–56% of Alewives and 35–41% of Blueback Herring were females in 1972 and 1973 (Speir et al. 2008). The runs were dominated by age-3 and age-4 fish, and approximately 55% were repeat spawners, within the range of repeat spawning rates observed for the nearby Nanticoke River (ASMFC 2012). Total instantaneous mortality was estimated to be 1.47 for Alewives and 1.91 for Blueback Herring, which are higher than the 2009 ranges for Z of 1.08–1.12 and 1.17–1.65, respectively, estimated for the nearby Nanticoke River from fishery-dependent sampling but are within the range of many other U.S. stocks (ASMFC 2012). Discrepancies among otolith- (Choptank River in the present study) and scale-aging methods (Nanticoke River) and a lack of known-age fish make it difficult to determine whether these differences are due to actual differences in mortality among populations or due to the different aging methods used (ASMFC 2014). Physiological stress during spawning (Raabe and Hightower 2014), predation, and stranding after high-water events likely account for some of this mortality, which is consistent with downstream run counts that were 24–28% of upstream counts. The ratio of upstream to downstream migrants in this study likely does not provide a reliable estimate of mortality during the spawning run, as substantial downstream migration might occur during flood events when a relatively small proportion of the stream is ensonified. Telemetry studies would provide a more robust method for determining the relative contributions of mortality occurring during the spawning run versus other times of the year.

The type of biological sampling used to apportion run counts using imaging sonar or other methods that are not inherently species-specific has the potential to affect the resulting run counts. In the present study, boat electrofishing was chosen for biological sampling because it could be conducted safely under all flow conditions except very high flows, provided an unbiased sample for size and age structure, yielded sufficient sample sizes for species apportionment, and was nonlethal for both target and nontarget species. Fyke nets were not chosen because the water was often too deep or fast-flowing to allow effective sampling at the study site, and gill nets were avoided due to concerns about the effect of size selectivity on assessments of size and age structure and the potential for high mortality rates of target and nontarget species. An important drawback of electrofishing was that the swimming direction of fish was unknown. Because most fish within the size range of 200–350 mm TL counted in sonar images were river herring, this was most likely an issue for apportioning counts during the period when both Alewives and Blueback Herring were present. It is possible that the Alewife run could be overestimated (and the Blueback Herring run underestimated) if Alewives were present in the study area but no longer moving upstream when the Blueback Herring run started. However, this does not explain the shift in the relative size of the Alewife and Blueback Herring runs that appears to have occurred since the 1980s, as more than two-thirds of the Alewife run count occurred before the first Blueback Herring was collected by electrofishing. Tracking of individual fish movements would be an effective method for determining the extent to which Alewives continue to run upstream after the Blueback Herring run is initiated. Capture by electrofishing also has the potential to negatively affect the ability of fish to continue normal spawning migration behavior due to shocking and handling stress, but this was unlikely to substantially affect our run counts as the number of fish subjected to electrofishing was negligible compared with the total run count. More frequent sampling could increase the precision of species composition data but also comes with added costs in staff time and impact on the ecosystem. Each method of biological sampling for species apportionment of imaging sonar run counts has positive and negative aspects, but it will be critical to use these relatively low cost methods to distinguish Alewives and Blueback Herring in population-monitoring studies in order to detect species-specific responses to harvest, management actions, and environmental change.

Coastal plain spawning streams like the Choptank River present a unique challenge for conducting run counts because the upstream extent of tidal influence can be many kilometers upstream from the river mouth (approximately 40 km in the case of the Choptank River) and there can be many small tributaries connecting to the tidal portion of the river. The study site was a good location for imaging sonar operation just at the upstream end of tidal influence where flow was unidirectional and the stream channel could be fully ensonified during most flow conditions. However, river herring were historically caught and are known to spawn in many of the downstream tributaries (O'Dell et al. 1984), such that both the historical and modern run counts likely substantially underestimated the total populations of river herring spawning in the Choptank River and its tributaries. Lack of understanding of spatial variability in spawning runs is an additional drawback of anadromous run monitoring methods that operate at a fixed location. Nevertheless, the present study provides rigorous, fishery-independent methods for monitoring population size, structure, and dynamics in response to conservation and restoration efforts.

Establishing baselines is important for setting restoration targets and developing sustainable fisheries management strategies (Pauly 1995; ASMFC 2012). The present study provides an example of how imaging sonar and biological sampling can be integrated to establish long-term monitoring programs for river herring population size, structure, and dynamics for evaluating responses to conservation and restoration efforts, and could potentially underpin a sustainable fishery management plan. The 1972 and 1973 run counts reported by Speir et al. (2008) provide some historical context for the Choptank River, but older historical information could also be relevant to setting restoration goals, even in cases where estimates indicate populations were likely much larger (Hall et al. 2012; McClenachan et al. 2012; Ferretti et al. 2015). As an example, catches of river herring (reported collectively as Alewives) in the Choptank River and its tributaries were estimated at nearly 2.1 million fish in 1909 and 336,000 fish in 1915 (U.S. Bureau of Fisheries 1916). Historical accounts suggest that the 1909 harvest may have been a particularly good year in many Chesapeake Bay tributaries, whereas the 1915 harvest was low enough to cause concerns about overfishing (U.S. Bureau of Fisheries 1916). The estimated 1.3 million river herring in the present study is in this range, but additional detailed analysis would be needed to estimate the population in the early 1900s from which these fish were harvested and the fraction of the modern population spawning in tributaries downstream from the site of the present study. Consideration of both modern and historical population sizes will be critical to the development of successful river herring conservation and restoration strategies. Imaging sonar combined with biological sampling was an effective method for monitoring river herring spawning runs in a turbid coastal plain stream.

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