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## NOTE

# Use of Dual-Frequency Identification Sonar to Monitor Adult River Herring in a Small Coastal Stream

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### Abstract

A standard dual-frequency identification sonar (DIDSON) was deployed in the Herring River, Harwich, Massachusetts, for 3 d in late April 2011 to capture video-like images of migrating adult river herring (alewife *Alosa pseudoharengus* and blueback herring *Alosa aestivalis*). Images recorded 24 h a day were used to manually count and assign species based on DIDSON images of fish size, shape, and behavior. From these counts, the run size was estimated to be 1,976–2,059 individuals during the study. At first, river herring often hesitated to swim through the sample area where the weirs and DIDSON were deployed; however, they eventually did pass, often multiple times. This unique hesitation behavior complicated counting efforts, though it was beneficial to discerning species using DIDSON images. In addition, extremely shallow water upstream of the study site, lack of tree cover, and a high threat of avian predation likely contributed to river herring milling activity at the study site. By providing many clear images of river herring, DIDSON proved to be an effective type of sonar with which to monitor and count river herring continuously in a small coastal stream.

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The primary objective of this project was to assess the ability of dual-frequency identification sonar (DIDSON) to monitor migrating anadromous alewife *Alosa pseudoharengus* and blueback herring *Alosa aestivalis* (collectively known as “river herring”) in a small Massachusetts coastal stream. Since 2006, a moratorium on river herring harvest has been in place in Massachusetts due to concerns about low population levels (Massachusetts Division of Marine Fisheries, Regulation of Catches, River Herring 2006). Annual river herring population estimates are largely based on data collected by dedicated volunteers, who count upstream-migrating river herring at fish pas-

sage structures each spring as these fish leave the ocean seeking freshwater spawning grounds. Since it is unrealistic to count fish every minute of each day, the volunteers often employ some type of random sampling design to set up a sampling schedule (Nelson 2006). Volunteer river herring counts are then extrapolated to the daylight hours (0700–1900 hours) to estimate the daily run size from early April to mid-June (Nelson 2006).

In this project, Barnstable County Cooperative Extension and Woods Hole Sea Grant collaborated with the Harwich Conservation Trust and the Town of Harwich, Massachusetts, to evaluate the ability of DIDSON to image river herring. DIDSON is a relatively new sonar technology designed by Sound Metrics Corp. in Lake Forest Park, Washington. When used in high-resolution (1.8-MHz) mode, the standard DIDSON unit constructs video-like images using 96 acoustic beams that combine to produce a field of view that is 29 degrees wide  $\times$  14 degrees high (Belcher et al. 2001). Frames are typically recorded at a rate of 5–21 per second, with a series of frames producing a detailed video that captures fish movements and shape (Belcher et al. 2001). DIDSON is widely used in Pacific coastal streams to enumerate Pacific salmon *Oncorhynchus* spp. (Pipal et al. 2010). A study by Maxwell and Gove (2007) of the Alaska Department of Fish and Game showed that DIDSON counts of migrating Pacific salmon were similar to visual observations at the same site. Fish smaller than adult Pacific salmon can also be detected by the DIDSON; while observing baited fishing pots, Rose et al. (2005) noted that DIDSON can image and track fish as small as 20 cm at a sample range of 9 m. Twenty to thirty centimeters (total length) is roughly the size range of adult river herring in springtime migrations in Massachusetts (Nelson et al. 2011).

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## STUDY AREA AND TIMING

The two study sites chosen were in the Herring River, which drains 24 km<sup>2</sup> of eastern Cape Cod, Massachusetts (USGS Water Resources 2011), and has a population of river herring which return to spawn annually in the ponds that feed the river. The river (Figure 1) is approximately 11 km in total length and flows from Long Pond in Harwich through Hinckleys Pond and West Reservoir before emptying into Nantucket Sound (Reback 2004). The Herring River is a small coastal stream about 8 m wide on average and generally less than 1 m deep, with sand, silt, and gravel substrate and clear water.

The first study site was located about 0.1 km north of Great Western Road in Harwich, approximately 7 river kilometers from Nantucket Sound (Figure 1). The Herring River at this point is free of tidal influence due to a water level control–fishway located at the outlet of West Reservoir approximately 1.2 km downstream of site 1. This section of the river is a reclaimed cranberry bog and consequently the riparian habitat is predominated by shrubby vegetation instead of trees, leaving the river exposed (Figure 2). This site was chosen because the river is contained within a single channel with gently sloping banks, has clear water and a flat surface, and has adequate width

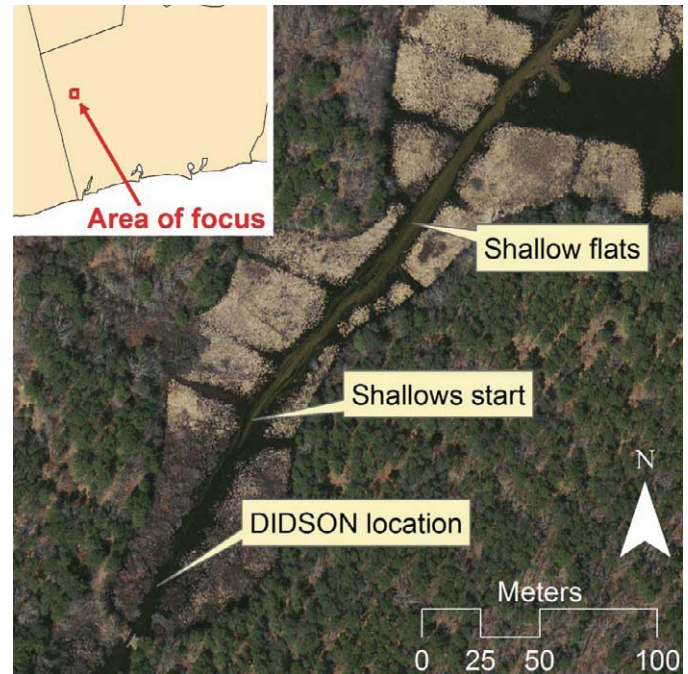


FIGURE 2. Aerial view of study site 1.

and depth to accommodate the vertical width of the sound beam (Figure 3). Also, it was assumed that migrating river herring would actively move through this stretch of river to reach their spawning grounds.

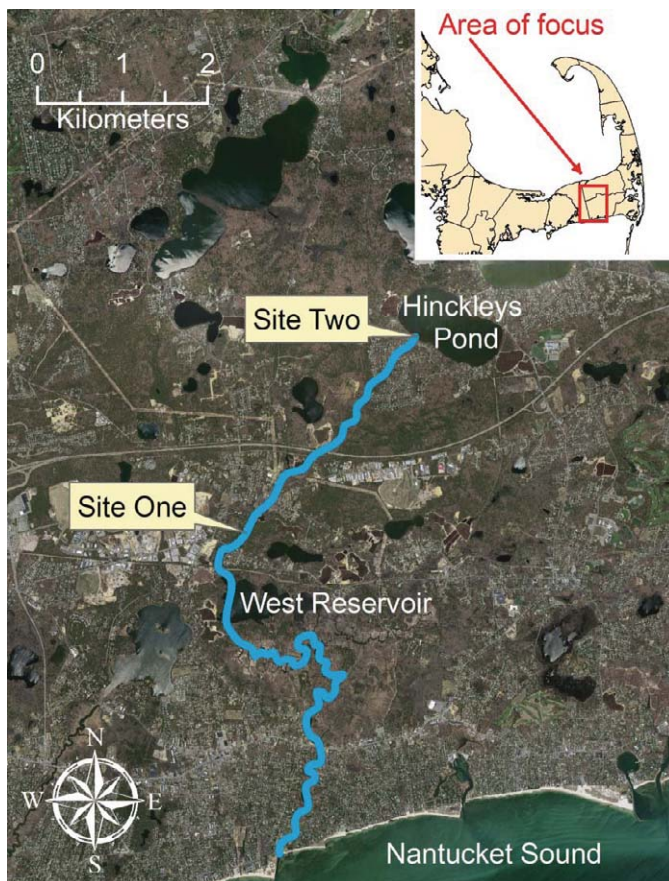


FIGURE 1. Aerial view of study sites on the Herring River (blue line), Harwich, Massachusetts.

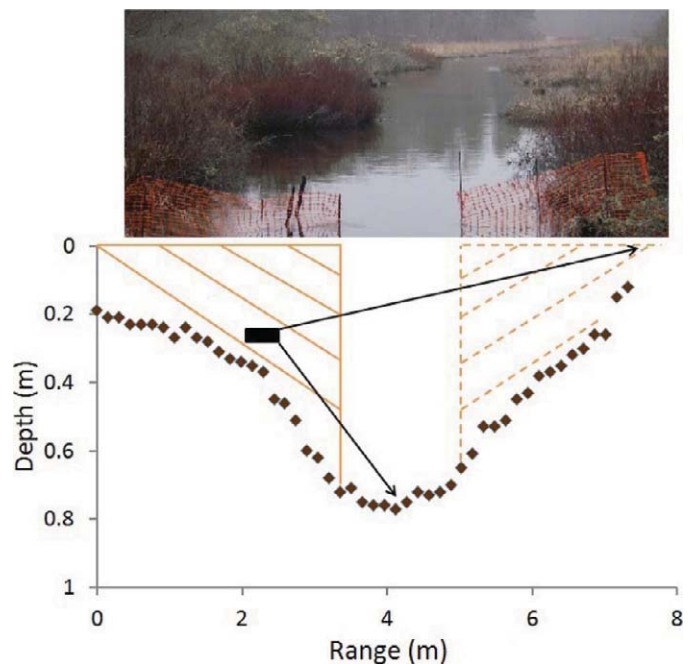


FIGURE 3. The top panel is a photograph of study site 1 looking upstream. The bottom panel is the river channel profile showing the approximate location of the DIDSON (rectangle) and the acoustic beam. The diamonds denote the river bottom. The black lines represent the boundaries of the acoustic beam. The solid orange lines depict the weir on the west bank of the river, while the dashed orange lines represent the boundaries of the second weir that was added later.





FIGURE 4. Photograph of study site 2 at the outlet of Hinckleys Pond. The DIDSON, attached to the black frame in the lower portion of the photograph, is aimed toward the opening of the fishway.

The second study site was located above the level control dam and fishway structure at the outlet of Hinckleys Pond, approximately 10.5 river kilometers from Nantucket Sound (Figure 4). This site was selected to determine whether DIDSON could image upstream-migrating river herring as they exited the fishway into Hinckleys Pond. Monitoring at this site also facilitated comparison with visual counts, as it was easy to visually count the fish passing into the lake through the concrete pond outlet.

Though it was anticipated that the starting date of this project (April 19, 2011) would coincide with the typical peak of the herring migration, water temperatures were slow to reach the typical run thresholds and delayed the run by about 1 month, so that the study was actually concurrent with the onset of the herring migration in the Herring River (Ryan Mann, Harwich Conservation Trust, personal communication). The weather was seasonably cool during the entire project, averaging 9.6°C, and it was overcast or partly cloudy with occasional rain showers throughout the study period, masking both moon and sun. Water temperature during the study averaged 10°C, which is close to the 10.5°C trigger for alewife migration in Massachusetts (Nelson et al. 2011).

## METHODS

**Data acquisition.**—A standard DIDSON 300 was loaned to Barnstable County Cooperative Extension for this study by Ocean Marine Industries, Inc., Chesapeake, Virginia. The DIDSON was attached to a customized welded steel frame and deployed at study site 1 about 2.5 m from the west riverbank in a “side-looking” fashion, directing the acoustic beam perpendicular to the flow and close to the river bottom (Figure 3). A weir made of plastic mesh construction fence was placed immediately downstream of the DIDSON, and ran from the west riverbank to a piece of rebar located about 1 m from the face of the DIDSON. The weir prevented migrating fish from swimming behind the DIDSON, an area where they would avoid detection. A second weir was added later on the far shore directing fish into the middle of the river channel for improved imaging of passing fish. The DIDSON was operated using the high-resolution (1.8-MHz) mode, with window start distances of 0.42 and 0.83 m and window lengths of 2.5 and 5.0 m, recording at a rate of 10 frames per second. This survey was considered a complete census of the population of migrating fish because the DIDSON nearly sampled the entire width of the river channel and the entire water column. The position and aim of the

DIDSON were adjusted when necessary to ensure that the acoustic beam was close to the bottom and sampling the majority of the water column; an artificial fish target was used to confirm the aim. The DIDSON was operated almost continuously at study site 1 from 1200 hours on April 19 to 0730 hours on April 21 powered by a small portable gasoline generator (Honda EU1000i). The DIDSON was moved upstream to study site 2 on April 21 and operated from 1740 hours to 2140 hours. Data files were saved every 10 min to a laptop computer (Dell Inspiron N7010) in the field; the 43-cm computer screen also allowed for viewing DIDSON images in real time.

**Visual species identification and fish behavior.**—Fish were visually observed as they approached the study area by a single observer positioned on a riverbank near the DIDSON; the observer refrained from motion to avoid alarming the fish or inhibiting their behavior. Fish passing the site were visually identified to the extent possible, and basic notes were made on the number of fish and their behavior as they moved through the study site. An observer was present for the entire duration of the study, but fish observations were limited to the daytime except for a few brief spotlighting efforts at night.

**Data processing.**—Data files were postprocessed using DIDSON software version V5.25.24 (Sound Metrics Corp., Lake Forest Park, Washington). A single observer reviewed the entirety of every DIDSON data file using three different fish counting methods: tally counting, mark and measure, and autocount. The first method, tally counting, involved manually counting the fish in fast-playback mode, during which fish moving past the DIDSON were visually classified as river herring, American eel *Anguilla rostrata*, or other species and then counted as upstream or downstream migrants and recorded on paper for each 10-min file. Visual classification was based on fish behavior, size, and shape, while river herring run size was determined by subtracting the downstream counts from the upstream counts. Twelve files were then randomly selected, one from every 2 h of April 20, 2011, to be analyzed by two other observers. Data from the tally counts of the three separate observers were used to calculate the observer coefficient of variation ( $CV = 100 \cdot SD / \text{mean}$ ). Files in which no herring were recorded passing were not used for the CV calculations. Processing time was recorded for each data file.

With the second method, mark and measure, the same observer who read each file using the first method reviewed the data in fast-playback mode while manually marking and measuring each fish using DIDSON software. All measured fish within each 10-min file were counted and automatically saved to a text file. In addition to containing count data, these text files contain information about each fish measured, including the date, time, frame in which the measurement was taken, direction of travel, species identification (entered by the observer based on behavior, size, and shape), and quality of the image (entered by the observer). Fish total length was estimated using the DIDSON fish-measuring tool. The observer measured all fish images, by using the mouse to draw a line from the head to the tail of each

fish. All measurements were started from the head, as this information is used by the computer to record the direction of travel for each fish as either upstream or downstream. In this study, a fish swimming from right to left across the computer screen is an upstream migrant; run size was determined by subtracting the downstream counts from the upstream counts. Processing time was recorded for each data file.

In measuring fish using the mark-and-measure method, the observer attempted to choose a frame for measurement in which the full length of the fish was visible. However, this was not always possible, so the quality of all images of fish were rated 1 through 5 within the DIDSON software. In this study, a rating of 5 indicated a clear image of an entire fish that could be used to identify the species based on that image alone, a rating of 4 indicated a clear image of an entire fish in which the species could not be determined, a rating of 3 indicated a full but degraded image of a fish, and a rating of 2 or less indicated an incomplete image of a fish. Only fish with a quality score of 3 or higher were used to analyze total length, though fish of all quality scores were counted, using swimming behavior as well as size and shape from the individual images to aid in species detection.

Since fish processed using the mark-and-measure method receive a time stamp, we used these data to examine fish passage by hour of the day. Specifically, we examined river herring run size by hour of the day, where run size was the number of river herring after subtracting downstream movers from upstream movers during each hour. Random subsamples of the mean total lengths of river herring moving during the day ( $n = 50$ ), at night ( $n = 50$ ), and during twilight ( $n = 50$ ) were compared by means of analysis of variance (ANOVA). Test results were considered significant at the  $\alpha = 0.05$  level.

In the last method, autocount, automated counts of fish moving past the DIDSON regardless of direction and species were made using the echogram tool provided with the DIDSON software. The tool also automatically provides total length estimates for each fish counted, but its functionality was limited because we were unable to discern species or direction of travel. Processing time was recorded, as the observer was still required to set processing parameters and run the program.

## RESULTS

### Data Acquisition

At study site 1, a total of 42 h of data were collected. A small amount of data from this deployment were lost due to moving the DIDSON and adjusting the aim. At study site 2, a total of 4 h of data were collected. The deployment at this site was limited due to a lack of migrating fish in this stretch of the river and inclement weather.

### Visual Species Identification and Fish Behavior

River herring often hesitated to swim through the sampling area where the weirs and DIDSON were deployed. River



herring were routinely observed swimming upstream into the edge of the acoustic beam and proceeding toward the center of the beam, only to quickly turn around and swim downstream (Video 1). However, after several attempts the fish would swim through the beam (usually as a school), avoiding a backup of fish below the study site. This unique behavior was used along with fish size and shape to distinguish river herring from other species during data processing. Fish other than river herring were seen swimming past the weir–DIDSON site without hesitation. River herring were treated as a collective category, as it was not possible to differentiate alewives from blueback herring using the image files. Visual observations confirmed that fish moving during daylight hours were mostly river herring. The only other fish seen during the day were much smaller than the river herring (less than 10 cm when measured using DIDSON software) and were darters (*Etheostoma* spp.). At night, river herring, American eel, and other species were clearly imaged (Videos 2–4). River herring and white suckers *Catostomus commersonii* were seen during limited spotlighting efforts at night.

River herring were also visually observed “milling,” meaning that they would swim upstream through the study area and a few minutes later would swim downstream past the DIDSON, only to turn around and repeat this movement pattern. Although milling river herring were observed in DIDSON files at all times of the day, the number of such herring appeared to be greater during daylight hours. This back-and-forth behavior inflated total fish counts during daytime hours, while the effective run size (cumulative upstream migrants) was lower than at night (Figure 5). For every two upstream-migrating herring during the day ( $n = 1,361$ ), there was one downstream migrant ( $n = 681$ ), compared with approximately 5 upstream migrants ( $n = 1,560$ ) per downstream migrant ( $n = 300$ ) at night; at twilight

the pattern was about one downstream migrant ( $n = 49$ ) for every 3.5 upstream migrants ( $n = 168$ ) (Figure 5).

### Data Processing

The 42 h of data collected at site 1 were processed using the fast-replay tally counting method, which took 19.5 h to count 4,312 fish, of which 4,134 (96%) were classified as river herring (Table 1). The river herring run size was estimated to be 1,976 individuals, with fish counts ranging from 0 to 317 fish per 10-min file. Processing time ranged from 2 min for an empty file to 17 min for a busy file, with an average of about 4.5 min.

Only five of the twelve 10-min files randomly selected for multiple-observer tally counting had passing herring. The coefficient of variation for these five files ranged from 0% to 24.6%, with an average of 8.6%. The number of passing fish ranged from 3 to 33 in these files, with the highest CV (24.6%) occurring in a file in which a group of 20+ river herring moved downstream together.

The same 42 h of data were also processed using the mark-and-measure method. It took 33 h to count 4,310 fish, of which 4,119 (96%) were classified as river herring (Table 1). The run size was estimated to be 2,059 individuals with this method. Fish counts ranged from 0 to 300 fish per 10-min file, with processing time ranging from 2 min for an empty file to 49 min for a busy file. Average file processing time was about 8 min with this method, much longer than either of the other methods due to the manual measurement of each fish.

Of the 4,119 river herring measured using the mark-and-measure method with the DIDSON measuring tool, 1,519 received a quality score of 3 or higher. The total length of river herring averaged 27 cm, ranging from 19 to 33 cm (Table 2; Figure 6). A total of 25 American eels and 123 other species received a quality score of 3 or higher. The total length of American eels averaged 27 cm, ranging from 14 to 75 cm, while the

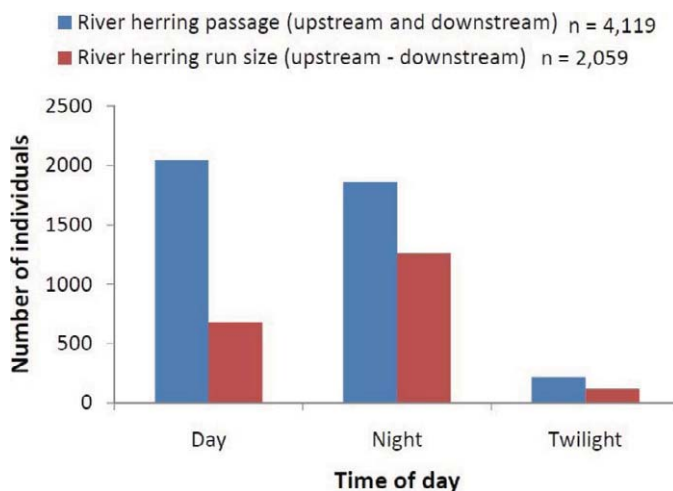


FIGURE 5. Total river herring passage regardless of direction of travel versus run size (the number of upstream migrants less the number of downstream migrants) at study site 1 by time of day (twilight = the period 15 min before and 15 min after sunset and sunrise).

TABLE 1. DIDSON file processing times and fish counts by method for study site 1. The counting methods employed were manual tallying in fast replay (tally), manual marking and measuring of each fish (measure), and use of the automatic counting function (auto). Note that the automatic method did not discern species or estimate run size.

Counting method	Tally	Measure	Auto
Data processing time (h)	19.5	33	11
Hours of data analyzed	42	42	38
Labor per 10-min file (min)	4.5	8	3.5
River herring (upstream)	3,055	3,089	
River herring (downstream)	1,079	1,030	
River herring (run size)	1,976	2,059	
American eel (upstream)	16	18	
American eel (downstream)	11	11	
Other species (upstream)	82	87	
Other species (downstream)	69	75	
Total fish count	4,312	4,310	2,393

TABLE 2. Quality of DIDSON images (see text for details) and total length by species.

Variable	River herring	American eel	Other species
Total images with quality $\geq 3$	1,519	25	123
Total images with quality $< 3$	2,600	4	39
Average total length (cm)	27	27	33
Range of total length (cm)	19–33	14–75	5–67

total length of other species averaged 33 cm, ranging from 5 to 67 cm (Table 2).

Upstream-migrating river herring preferred to migrate near sunset, which occurred about 1925 hours during this study, with the period from 1800 to 1900 hours having the highest passage rates (Figure 7). The next highest period of upstream migration was at night between approximately 1940 hours and 0540 hours, with 63 river herring passing upstream per hour on average (though the number averaged almost 200 per hour at 0100 and 0200 hours) (Figure 7). By contrast, only 32 river herring passed the site each hour during the day between 0610 and 1910 hours (Figure 7). There was no significant difference between the mean total length of river herring moving during the day, at night, or at twilight ( $F = 2.00$ ,  $P = 0.13$ ).

The automatic method took 11 h to process the 38 h of raw data collected at site 1. The automatic count was 2,393 fish; unfortunately, run size could not be estimated with this method due to the inability to factor in reliable migration direction or species (Table 1). Missing time was due to moving and adjusting the DIDSON during a data file. Fish counts ranged from 0 to

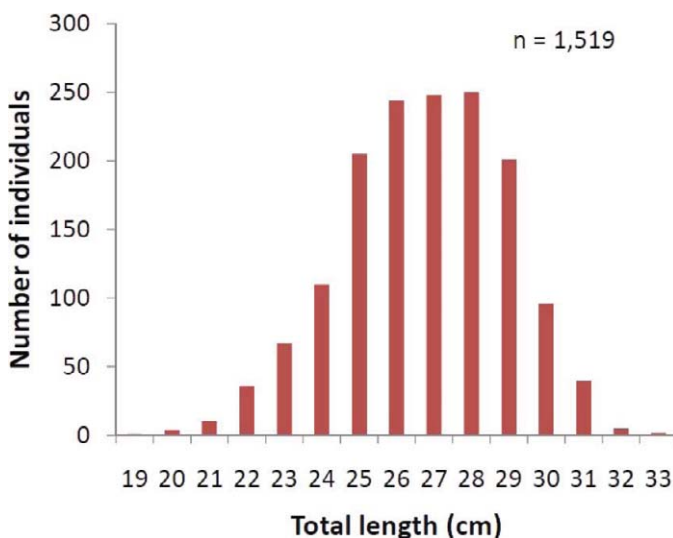


FIGURE 6. Length frequency distribution for river herring collected at study site 1. All measurements were made with the DIDSON measuring tool. Only fish images with a quality score of 3 or higher were used to construct this distribution.

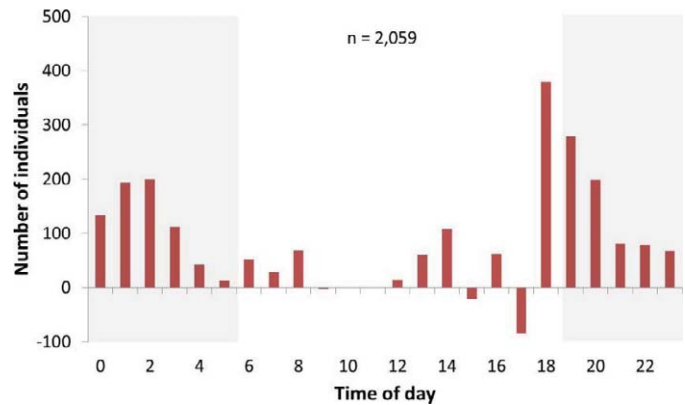


FIGURE 7. River herring run size estimates at study site 1 averaged by hour of day from 1200 hours on April 19, 2011, to 0730 hours on April 21, 2011. The shaded areas indicate the periods before sunrise (0600 hours) and after sunset (1925 hours).

130 fish per 10-min file; average file processing time was about 3.5 min per 10-min file.

The data collected at site 2 were processed by a single observer using the fast-replay tally count method and the manual mark-and-measure method. The processing time with both methods was 1.5 h, or about 2.5 min per 10-min file. Only one fish passed upstream through the fishway at Hinckleys Pond during this period (at 2050 hours; Video 5). This fish was measured using the DIDSON measuring tool and found to be 14.5 cm in total length. It was classified as an other species because it was smaller than the river herring measured at site 1 and did not display behavior typical of the herring at that site. Many resident species, likely white suckers, were seen schooling around the opening of the fishway and within the beam of the DIDSON from 2000 to 2120 hours (Video 6). Some of these fish were measured using the DIDSON measuring tool and found to have an average total length of 38 cm; thus, they were clearly not river herring.

## DISCUSSION

This pilot study shows that river herring can be imaged and counted using a DIDSON in a small coastal stream. There are many advantages to using a DIDSON for this purpose. For one, it is a technique that can collect valuable data, like fish size, shape, number and behavior, without the risk of incidentally harming the fish one is trying to monitor through handling. In addition, the DIDSON collects data continuously and the picture-like images are relatively easy to interpret whether they are recorded during the day or at night. Also, interest in using DIDSON for counting diadromous fish is increasing, and much effort is being made to automate the process as much as possible (Boswell et al. 2008; Mueller et al. 2008).

River herring are considered to be hearing specialists, readily detecting sounds with a frequency range of 0.02–1.2 kHz (Mitson 1995) while responding to ultrasound to 200 kHz (Nestler et al. 1992; Mann et al. 2001). The operating frequency

of DIDSON is 1.8 MHz, and this is believed to be above the threshold detected by river herring. In a study using pulsed ultrasound techniques with a related species, twaite shad *Alosa fallax fallax*, it was found that 200-kHz sound created an avoidance behavior while at 420 kHz this behavior subsided (Gregory and Claburn 2003). Although river herring hesitated to pass the study site in the current study, they eventually did (often multiple times), so no lasting obstruction to upstream migration was observed. The two weirs blocking about two-thirds of the channel cross section (Figure 3) may also have accounted for some of the hesitation behavior in the herring. Avoidance behavior has been observed among American shad *Alosa sapidissima* in relation to visual and flow disturbances created by bypass weirs (Haro et al. 1998). This hesitation behavior was not anticipated, and due to the limited experimental design we were unable to determine whether this behavior was due to the study site, the DIDSON, the weirs, or a combination thereof.

Currently, river herring estimates in Massachusetts are based on daytime counts (between 0700 and 1900 hours) and data are collected by dedicated volunteers (Nelson 2006). The 12-h daytime sampling window is largely based on a study by Rideout et al. (1979), in which estimates of alewife run size were based on hourly visual counts of upstream-migrating alewives in a fishway in the Parker River, Massachusetts. Rideout et al. (1979) noted that alewives failed to migrate after 2200 hours, and it was similarly observed that alewife activity was largely daytime oriented (Richkus 1974; Richkus and Winn 1979), with night migration reports being much less common. In our study, nighttime was a period of high upstream movement for fish, many of which were classified as river herring based on their total length, shape, and behavior. Although this study covers an extremely short period, we observed a definite pattern of river herring migration. During the daylight hours on April 19, 2011, about 100 herring were observed milling around the study site for most of the day; upstream migration started at about 1900 hours and continued until 0800 hours on April 20, 2011. Only 15 river herring were observed during the daytime on April 20. Again, river herring started migrating upstream late in the day (at about 2000 hours) and continued until about 0630 hours on April 21. If we had used the 12-h daytime sampling method, we would have missed 1,449 migrants, or about 70% of all upstream-migrating river herring (Figure 7).

The results of this pilot study thus suggest that daytime counts would miss a substantial fraction of the population of migrating river herring. However, the pattern of nighttime migration that we observed could be site specific due to the extremely shallow water (average depth, ~0.35 m) located in the section of the river just upstream of study site 1 (Figure 2). In addition, the river is completely exposed in this stretch due to the lack of tall riparian vegetation and avian predation on river herring was also observed (Figure 2). At about 1630 hours on April 20, a group of three river herring were recorded migrating upstream by the DIDSON; about 10 s later an osprey *Pandion haliaetus* was observed catching a river herring just upstream of the DIDSON,

and seconds later two fast-moving river herring swam downstream past the DIDSON. It appeared that these fish were aware of the potential hazards upstream and waited until nighttime to navigate this section of the Herring River.

We do not recommend using site 1 to conduct future river herring counting due to the amount of fish seen milling during the day (Figure 5). These fish were likely waiting for the cover of darkness to safely navigate the shallows. Since the DIDSON was located just above the deepest and most protected water in this stretch of the Herring River, the area seemed to provide a safe holding area for the migrating river herring. Milling fish made fish counting more difficult and time-consuming and compromised the accuracy of the run size estimate because some images of milling fish were so poor that they were difficult to count. DIDSON images were found to degrade in some instances for two main reasons. First, some fish passed in the far ranges of the acoustic beam where it contacted the opposite riverbank hard, creating a very bright return and thus an area in which it was difficult to detect fish movement. This could be fixed by adjusting the position and aim of the DIDSON, adjusting weir placement, or changing sites. Second, the position of a fish relative to the sonar beam axis (i.e., the line that originates at the midpoint of the transducer face and extends downrange to the leading edge of the acoustic beam) can cause poor image quality because it plays a large role in determining how large an acoustic target the fish represents. Fish that are perpendicular to the sonar beam axis have a better chance of being detected because their entire side is available to reflect acoustic energy back to the sonar; fish that are at an angle to the sonar beam axis present a smaller acoustic target, and those that are parallel to it present a very small acoustic target (Love 1977). In this study, many downstream-moving schools of milling river herring would enter the acoustic beam tail first, drift toward the middle of the beam, turn, and then scatter quickly at all angles (relative to the sonar beam axis), making for poor images and inaccurate counts. Since this was the beginning of the herring run, downstream-moving fish were not simply emigrating, and accurate counts for fish moving in both directions were needed. This problem could likely be solved by finding an alternative site where river herring are actively migrating upstream with minimal milling activity.

The effect that acoustic shadows had on our ability to accurately count river herring is unknown. Acoustic shadows can occur as a fish swims through the acoustic beam, reflecting the majority of the sound energy back to the sonar, creating a dark shadow that can be seen downrange (Video 1). The shadowed area beyond the fish can become an area of low detection for other fish if they are completely masked by the shadow. As river herring are a relatively small fish known to swim in tight schools, acoustic shadows can be a concern when trying to count individual fish with a DIDSON. In a study by Maxwell and Gove (2007), high agreement between DIDSON counts and visual counts of upstream-migrating sockeye salmon *Oncorhynchus nerka* show that acoustic shadows did not affect the DIDSON's



ability to accurately count upstream migrants at passage rates up to 6,000 fish/h. In our study, average fish passage rates did not exceed 400 fish/h, though visual counts were not made for comparison because the majority of fish migrated at night. However, since the Herring River is narrow (<10 m wide) and our weirs constricted the width of the river channel to about 2 m, river herring schools were not very wide, making acoustic shadows less of a concern. Furthermore, the majority of river herring, which averaged 27 cm in total length, passed at a range of 2 m from the DIDSON; at this range the composite beam width is about 100 cm (Sound Metrics Support 2010), which means that a river herring occupies a fraction of the beam, allowing more than one fish to be detected by the DIDSON simultaneously.

Site 2, the opening of the fishway at the outlet of Hinckleys Pond, was chosen because it was thought that migrating river herring would swim upstream through the fishway and enter the pond without milling. However, no river herring passed through the fishway during the study period at this site. About 4 h before setting up at site 2, visual observations were attempted by hiking approximately one-quarter mile of the Herring River downstream of the Hinckleys Pond fishway, but no fish were observed. However, this would be a good site to repeat this study when river herring are migrating through the fishway consistently, as the DIDSON was able to effectively image other fish species at this site and there are comparable sites in a number of other streams in the region.

In comparing the methods of enumerating fish species by means of the DIDSON data, we found that the manual tally counting and mark-and-measure methods with a single observer produced very similar, but not identical numbers in terms of river herring run size and the numbers of other species migrating up- and downstream (Table 1). The difference in herring run size between the two methods was 83 fish, with a mean of 2,018 and a CV of 2.9%. This variation is likely due to simple error in reader interpretation of the DIDSON files, as fish may be missed, counted twice, or mislabeled as to species, especially when image quality is poor or many fish are moving together.

Similarly, when the counts of three separate individuals were compared for randomly chosen files with passing river herring, differences in interpretations led to some variation in results. The variation between observers is somewhat higher than but similar to that in published results with larger Pacific salmon (Holmes et al. 2006), though the authors of that report recognize that when the numbers of passing fish were low (<50 fish per event) the variation levels increased rapidly because small differences in the observations had large impacts on the variation. Although river herring passage was relatively low during the period of this study, inter- and intrareader variation were not very different from that for other DIDSON results. DIDSON may be expected to produce fairly accurate counts both during the day and at night if careful attention is paid to site selection and setup so that milling behavior and downstream movement are limited.

It should be noted that since every fish was individually marked and measured by an observer in the mark-and-measure

method the average processing time was about twice that of the other two methods. However, additional information can be collected with this method, including the length and shape of the fish and other observations about them. The mark-and-measure method would likely be recommended to obtain the most accurate information about fish migrating past a DIDSON, though the tally count method provides a very similar count overall and in much less time. For future studies, including ones with larger data sets, it may be beneficial to use the tally count method with randomized subsampling with the mark-and-measure method to obtain the benefits of both methods.

The automatic method of counting fish, while faster than the tally and mark-and-measure methods, was not viable in the current study because it was not able to differentiate species or provide a reliable direction of migration and produced estimates of total fish passage that were far lower than those of the manual methods (Table 1). This result is similar to those of other evaluations of DIDSON technology in fish migration studies (Baumgartner et al. 2006). If a site could be found in which fish passage was ultimately in only one direction with little back and forth movement, the autocounting method may prove more effective. However, because the fish milling behavior encountered in this project was so prevalent and no river herring were detected at the outlet of Hinckleys Pond, this was not pursued in the current study.

The amount of information contained in DIDSON fish images is largely a function of the distance from the face of the DIDSON to the fish (range) and the size of the fish. The cross-range resolution of our DIDSON images can be calculated as  $R/2/96$ , where  $R$  is the range of the fish and 96 is the number of acoustic beams used (this value can vary, but it is 96 in our case because we used the high-frequency mode (Sound Metrics, Bellevue, Washington; <http://www.didson.com/SONAR101/resolution.html>). The cross-range resolution in this study ranged from about 0.5 cm for fish with a range of 1 m to 2.6 cm for fish with a range of 5 m. Since adult river herring in Massachusetts have an average total length of about 26 cm (Hartel et al. 2002), their DIDSON images contain information about size, body shape, and swimming behavior.

Future study of using DIDSON to count river herring is recommended, as the ability of the DIDSON to image river herring was apparent but testing of effective sites for monitoring was limited due to the timing of the herring run. We encountered river herring passage rates as high as 300 individuals per 10-min file. Further study is warranted to validate the DIDSON counts, comparing them with visual counts at higher passage rates. Many fish were imaged during the overnight period and were classified as river herring based on their size and swimming behavior. The next study should include biological sampling to confirm species identification and should include a site at which the fish migrate through with less milling.

In summary, DIDSON is an effective type of sonar with which to count river herring in a small coastal stream, as is

evident by the many clear images of river herring that we collected both during the day and at night. High-quality images of American eels were also collected, indicating that this species could be monitored concurrently. The ability to monitor a fish run 24 h a day, 7 d a week using DIDSON technology should allow fishery managers to obtain accurate population estimates and would be helpful in evaluating river herring restoration efforts in Massachusetts.

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