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Evaluating the Effectiveness of the Pickering Nuclear Generating Station Fish Diversion System Barrier Net

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ARTICLE

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Abstract

Barrier nets can be an effective alternative for reducing impingement mortality of fish at power plant intakes. In 2010, a paired, split-beam hydroacoustic method was used as the primary assessment tool for comparing relative fish density between the lake (“outside”) and station (“inside”) side of the Pickering Nuclear Generating Station fish diversion system (FDS) barrier net while it was in place. Behavioral information was also collected using a DIDSON acoustic camera and underwater video camera to determine fish responses to the FDS. Verification monitoring was completed using conventional gill netting. The DIDSON provided useful and valuable information on relative fish densities, relative school sizes, and behavior of fish as individuals, small groups, or schools on both the outside and inside of the FDS, as well as general behavior of fish approaching the FDS. There was no evidence of passage through the net based on DIDSON evaluation; however, fish passage occurred when the FDS net was considered to be in a degraded condition (from biofouling or storm events, or both) and passage occurred over the net, not through it. Analysis of the hydroacoustic data based on the weighted average biomass indicated that FDS effectiveness was 75, 98, and 100% for the spring, summer, and fall periods, respectively, and 98% for the three seasons combined. The summer and fall estimates were based on net performance under optimal net-deployment conditions and if the net degrades, effectiveness is reduced significantly as observed in the spring data. Our study results were supported by impingement monitoring at the station whereby impingement biomass was reduced by greater than 80% for each of the first 3 years after installation compared with before installation of the barrier net. Overall, the FDS was demonstrated to offer significant fish protection from potential impingement at the Pickering Nuclear Generating Station.

There has been a renewed interest in the use of fish protection systems to reduce fish impingement at power plants. A wide range of technologies are available ranging from screening technologies to diversion schemes as well as behavioral systems (Allen et al. 2012). Behavioral systems tend to be more cost effective than screening technologies, but application of any technology can be very site-specific (Noatch and Suski 2012). Barrier nets can be an effective alternative for reducing fish impingement mortality at power plant intakes. As such, they have the potential to meet the Clean Water Act, section316(b) fish impingement performance standard (for impingement mortality) under several of the U.S. Environmental Protection Agency’s compliance alternatives (EPRI 2006).

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In 2009, a fish diversion system (FDS) barrier net of 0.5-in (1.27 cm) mesh was installed around the intake structure at Pickering Nuclear Generating Station (PNGS) on Lake Ontario. The goal of the FDS was to reduce fish impingement at the intake and not to completely exclude all fish. Approximately 41 different fish species have previously been found impinged at the station. In recent monitoring, impinged fish consisted primarily of pelagic species such as Alewife *Alosa pseudoharengus*, Rainbow Smelt *Osmerus mordax*, Emerald Shiner *Notropis atherinoides*, Gizzard Shad *Dorosoma cepedianum*, and the benthic Round Goby *Neogobius melanostomus*, an invasive species. The FDS was not designed to exclude entrainable organisms such as fish eggs and larvae, which would pass though the net.

The objective of this work was to quantify the overall performance of the FDS in reducing fish impingement. There are many other examples where barrier nets have been shown to effectively reduce impingement, but actual estimates of effectiveness were either not estimated or were based on pre- and postnet deployment impingement mortality assessments (EPRI 2006). This study involved assessing the effectiveness of the FDS in preventing fish passage and subsequent impingement at the intake by monitoring both the station side (i.e., "inside") and lake side (i.e., "outside") of the FDS on each net aspect. A hydroacoustic method that employed a paired, split-beam echo sounder (Simrad EK60, Kongsberg Maritime, Halifax, Nova Scotia) was used as the primary assessment tool for comparing relative fish density between the lake and station side of the FDS while it was being installed in place. Behavioral information was also collected using DIDSON imaging sonar (Sound Metrics, Bellevue, Washington) to determine fish responses to the FDS. Results were compared with verification monitoring results involving conventional netting for both fish species verification and effectiveness assessment. Underwater video data were also collected during the 2010 monitoring period for further effectiveness and behavioral evaluation. Impingement monitoring at the station was also conducted throughout the study period, and the additional data collected were available for comparison as required. Work was conducted in the spring, summer, and fall of 2010.

METHODS

Study site.—The PNGS is located in southern Ontario on Lake Ontario. The FDS net system consists of a series of interconnected net panels with a total length of 600 m. It is composed of three distinct sides or aspects (i.e., east, south, and west) that enclose the surface water intake of the plant. The top of the net is connected to a float line and the bottom of the net is connected to an anchoring system to provide coverage of the entire water column. The net is made of #18 Dyneema twine, which is very robust and rated stronger than both steel and Kevlar (tensile). The net is in place only during the ice free period (April to November).

The net is designed to a height of 110% of the high water level to accommodate changes in water levels. The design of the FDS also incorporates a top skirt section of netting held afloat by a secondary float line that provides additional coverage of the water column during higher intensity lake hydraulic conditions. The FDS is also designed to partially submerge (degraded condition) when it becomes highly clogged with attached algae in order to maintain adequate station flows. Monitoring of the FDS using gill netting, underwater video, split-beam hydroacoustic (Simrad EK60), and DIDSON occurred at all three aspects (i.e., south, east, and west) of the FDS (Figure 1).

Gill netting.—The purpose of netting was to verify fish composition in the area and relative abundance and be used to complement the DIDSON and hydroacoustic assessments. Gill-netting events that included sampling at all FDS aspects (i.e., east, south, and west) occurred during both the spring (four events) and summer (three events) verification sampling periods (May 29–July 5, 2010; August 11–September 27, 2010). For each event at an aspect, four gill nets (two inside and two outside) were set perpendicular to the FDS (Figure 1) for approximately 22 h. Nets having either large monofilament mesh (mesh sizes: 1.50, 2.00, 2.50, 3.00, 3.50, 4.00, 4.50, and 5.00 in [38, 51, 64, 76, 86, 102, 114, and127 mm]) or small mesh (mesh sizes: 0.50, 0.75, 1.00, 1.25, and 1.50 in [13, 19, 25, 32, and 38 mm]) were both used, and mesh sizes were randomly distributed across the 1.8-m high panel. Nets were initially set on the bottom during the spring period and were later suspended within the middle of the water column for the summer monitoring period so that they were representative of the water column being ensonified. Fish species, FL (cm), and weight (g) data were collected.

An ANOVA was used to determine whether there were differences between fish collected inside and outside of the FDS for each of the spring and summer periods. The variables, FL and weight, were assessed. In instances where assumptions of homogeneity of variances could not be met, data were log transformed to meet these assumptions. For the spring period, comparisons were made separately for each aspect (i.e., south, east, and west). However, for summer, comparisons were made by combining the data from each aspect to increase sample size since the numbers of fish caught were low; although this was not a preferred method, it allowed for evaluation with increased statistical power.

The effectiveness of the FDS based on fish biomass was measured for both the spring and summer periods. For each of the seasons, the weights of all fish collected at all aspects (i.e., south, east, and west) on the inside of the FDS were summed. Similarly, the weights of all fish collected at all aspects on the outside of the FDS were summed. The percent effectiveness of the FDS for each season was then calculated as follows:

$$\% \text{ Effectiveness} = \{100 - [X_{in}/(X_{in} + X_{out})] \times 100\},$$

where X_{in} is the total weight (g) of fish collected on the inside and X_{out} is the total weight (g) of fish collected on the outside of the FDS.

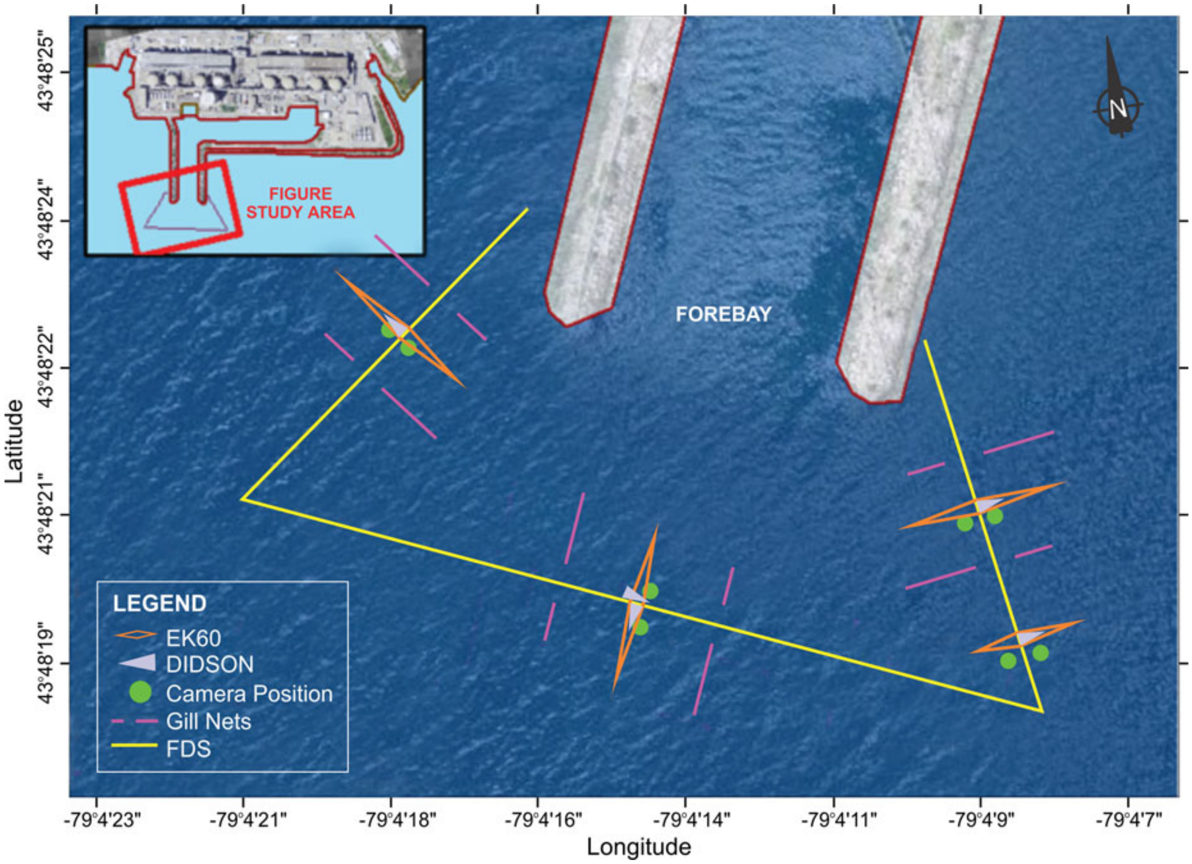

FIGURE 1. Approximate sampling locations and placements (not to scale) of the Simrad EK60 echo sounder, DIDSON imaging sonar, gill netting, and underwater video cameras used at all aspects (south, east, and west) for the Pickering Nuclear Generating Station (PNGS) Fish Diversion System (FDS) barrier net effectiveness study, 2010.

Video data collection.—Four underwater video cameras were installed, two inside the FDS and two outside the FDS at each aspect (south, east, and west) (Figure 1). Of the two installed on the outside of the FDS, one was facing the net (lower one-third) while the other was aimed at the bottom of the net. The underwater videos operated on a continual basis (24 h per day) for the spring, summer, and fall periods and were used to confirm whether fish passage occurred through or under the FDS.

Quantitative echo sounder data collection.—Acoustic monitoring of the FDS was completed using a Simrad EK60 split-beam echo sounder system. Two 120-kHz elliptical transducers (Simrad ES120-4 × 10; beamwidth: 4.4° vertical, 9° horizontal), affixed to remote-controlled pan-tilt rotators (model OE10-102, Kongsberg Maritime), were multiplexed to horizontally sample in a near-simultaneous manner a fixed volume of water adjacent to the FDS net face. For each aspect (south, east, and west), the transducers were placed either 30 m (spring) or 20 m (summer and fall) from the inside and outside of the FDS (Figure 1). This allowed for paired data collection. A total of 1,034 h of acoustic monitoring data were analyzed (spring: 284 h, summer: 421 h, fall: 329 h), with 576 of these hours being used for paired comparisons (Table 1). The transducers were mounted to

TABLE 1. Summary of the split-beam echo sounder data collection for the Pickering Nuclear Generating Station Fish Diversion System (FDS) barrier net-effectiveness study, 2010.

FDS monitoring period	FDS monitoring dates (2010)	Transducer distance from FDS (m)	Hours of “paired comparison” data analyzed
Pre-analysis equipment testing	May 25–May 29	30	
Spring	May 29–Jul 5	30	79
Summer	Aug 11–Sep 27	20	224
Fall	Oct 13–Nov 15	20	273

vertical poles that were anchored to the lake bottom using large concrete blocks, and the pan-tilt rotators were adjusted to face the transducers towards the FDS and to minimize interference from the water-surface and lake-bottom boundaries.

The transducers were moved closer to the FDS during the summer and fall periods to reduce acoustic reverberation from algae and air bubbles that were observed near the top of the FDS float line during the spring monitoring period. Additionally, the EK60 echo-sounder transducers, DIDSON sonar, and camera positions on the east FDS were also relocated from the midnet position to one much closer to the south corner to minimize interference by net movement, flow, and algae transportation.

The percent reduction in the 6-dB two-way beam volume from moving the EK60 transducers from 30 to 20 m to the net face was approximated using the equation

$$V_p = \frac{\psi}{3} \sum_{i=0}^{n-1} \delta_i \left(R_{i+1}^3 - R_i^3\right),$$

where ψ = the equivalent two-way beam angle (steradians), R = the range from the transducer (m), δ = a generalized function that can be defined as the limit of a class of delta sequences (i.e., "Dirac delta function"), and $R_i = 1$ m.

At 30 m from the FDS face, the estimated beam volume of a transducer with a one-way 3-dB beam width of 4.3° and 8.5° was 56.9 m^3. Moving the transducer to 20 m from the FDS face decreased the estimated beam volume to 16.9 m^3, a reduction of approximately 70%. However, it is important to note that fish activity tended to be greatest within 5 m of the FDS. Given this observation, the beam volume within this active region in front of the FDS was reduced by only 59%.

Hydroacoustic beam mapping and calibration.— Calibration of the EK60 split-beam echo sounder transducer and beam mapping was conducted using the pan and tilt motors on the assembly on both the inside and outside transducers. Divers deployed a 23-mm-diameter copper calibration sphere at approximately 10 m from the transducer face using a surveyor's measuring tape. The estimated compensated target strength of the sphere was −40.4 dB (at 14°C). The EK60 split-beam transducers were calibrated using survey parameters (pulse length = 256 μs, output power = 500 W, estimated speed of sound = 1463.88 m/s, and estimated sound absorption coefficient = 0.00381126 dB/m: Parker-Stetter et al. 2009).

The Simrad EK60 scientific echo sounder calibration software (version 2.2.1) was used to record single target detection points throughout the beam. The pan-tilt motors were used to conceivably "move" the calibration sphere throughout the entire beam at the 10-m range.

TidBit(r) temperature loggers (Onset Computer Corporation, Bourne, Massachusetts) were deployed on the south face of the FDS to record water temperature at 10-min intervals from three depths (FDS main float line, midnet, and chain line) for all echo sounder calibration calculations.

Near-net dead zone estimates.—The likelihood of detecting a fish traveling close to the FDS net face may be reduced at the distance where the transmitted acoustic pulse first strikes the net material. The netting material, in combination with photosynthetic algae, air bubbles, and detritus on the net, will generate an echo that is much stronger than any individual fish. As the attack angle of the acoustic axis increases from perpendicular, the dead zone distances and sample volumes will change significantly. We used the Ona and Mitson (1996) equation to estimate the dead zone range above the bottom (or in front of the net).

To empirically estimate the dead zone region of the net, divers deployed a 23-mm-diameter copper calibration sphere at various ranges (i.e., 4, 2, 1.5, 1.0, 0.75, 0.5, and <0.25 m) from the FDS net until the sphere was no longer visible within the echogram. The dead zone range was estimated as 0.26 m for the transducer on the inside of the FDS and 0.07 m for the transducer on the outside of the FDS.

Background noise estimates and removal.—The returning echo from fish targets must be higher than the noise level to be detected and to provide interpretable data (Parker-Stetter et al. 2009). The proportion of backscatter from the biological target of interest to background noise is known as the signal-to-noise ratio (SNR). The SNR decreases with depth (range) due to signal attenuation and spreading. Therefore, detection of the smallest target of interest is ultimately limited by the target's range from the transducer. Simmonds and MacLennan (2005) suggested a SNR of 10 dB; however, the Great Lakes Standard Operating Procedure (Parker-Stetter et al. 2009) suggested that an SNR of 3 dB would be sufficient. Background acoustic and electronic noise levels were estimated and results indicated that the echo sounder system had been adequately isolated from extraneous electrical and acoustical noise. Data were also reviewed and adjusted for ray-tracing and bending (Urick 1975; Medwin and Clay 1998; Simmonds and MacLennan 2005; Parker-Stetter et al. 2009).

Quantitative echo sounder data processing.—Echoview acoustic processing software was used to calculate the echo integral (E_i) or the integrated volumetric backscattering strength (S_v) across contiguous 15-min observations or elementary time sampling units (ETSUs). The ETSU (modified from the elementary distance sampling unit concept introduced by Simmonds and MacLennan 2005) is the period of time in which measures of backscattered energy are integrated to provide one sample. Given the patchiness of the observed fish density, 15 min was selected as an appropriate ETSU, or temporal survey bin, for all analyses.

To provide a measure of FDS effectiveness for all schooling and nonschooling fish, the average acoustic backscatter for each ETSU was calculated. The total acoustic backscatter makes no assumptions of fish size or density and provides a standardized surrogate for fish biomass.

The integrated average volumetric backscattering strength (S_v) of each ETSU was expressed as a volume backscattering

TABLE 2. Summary of DIDSON imaging sonar data collected and analyzed for the PNGS FDS barrier net effectiveness study, 2010.

Season	DIDSON monitoring dates (2010)	DIDSON orientation	Number of hours analyzed
Spring	May 31–Jun 30	On outside perpendicular to FDS.	12
Summer (late)	Aug 11–Sep 27	Aug 11–Sep 3 and Sep 24–27: on outside perpendicular to FDS; Sep 3–7: on inside parallel to FDS.	21
Fall	Oct 13–Nov 15	On outside perpendicular to FDS.	18

coefficient (s_v in units m^2/m^3) using the equations

$$s_v = \left(10^{\left(\frac{S_v}{10}\right)}\right),$$

where S_v = the mean volumetric backscattering strength (dB re: 1 m^{-1}) and s_v = the volume backscattering coefficient (m^2/m^3).

A minimum time-varied uncompensated target strength (TS_u) threshold of −55 dB was applied to all volumetric backscatter (S_v) data as an attempt to reduce the effect of reverberation from detritus, algae, and air bubbles. On some occasions we observed acoustic reverberation or side-lobe effects that were confined to a fixed-range layer (usually 5–7 m) in front of the FDS barrier. These layers were often associated with storm and wind events that increased incidences of acoustic reverberation and thus decreased the signal to noise within the data. A range- or region-specific threshold filter was identified as an appropriate method for further reducing the acoustic reverberation. Estimates of fish biomass (g/m^3) were scaled from the average volume backscattering coefficient (m^2/m^3) using seasonal conversion coefficient estimates (Frouzová et al. 2005; SENES and Milne 2011).

Data that were collected but determined to have excessive interference and reverberation caused by algal influx (large mats of *Cladophora*), air bubbles, storm events, and diver net-cleaning operations were excluded from analyses; these were the ETSUs that contained greater than 25% "bad data" (i.e., the proportion of the total number of acoustic data samples due to algae or air bubble reverberation exceeded 25%) or "no data" samples. Statistical confidence intervals around the average acoustic backscatter estimates were generated using the iterative bootstrapping method within the open source statistical software package R (http://cran.stat.sfu.ca/).

For each season, the average acoustic backscatter (s_v; volume backscattering coefficient m^2/m^3) and biomass (g/m^3) were calculated by FDS aspect (inside or outside) and diel period (day or night). The FDS net-effectiveness calculations were computed using the same equation as the gill-netting effectiveness calculations. In this case, however, X_{in} was the average (arithmetic mean) volume backscattering coefficient (s_v in m^2/m^3) or average (arithmetic mean) biomass (g/m^3) inside the FDS, and X_{out} was the average volume backscattering coefficient or average biomass outside the FDS.

We also determined FDS effectiveness based on the weighted average (i.e., weighted arithmetic mean) biomass from the FDS inside and outside. The weighting factor is the sum of the biomass on the inside and outside for each 15-min ETSU. The weighted average biomass for each season for the inside FDS and outside FDS was calculated by dividing the sum of products [biomass inside × (biomass inside + biomass outside)] for each 15-min ETSU by the weighting factor. The FDS net-effectiveness estimates were then calculated using the same equation as that used to calculate FDS effectiveness based on gill netting. In this case, X_{in} was the weighted average biomass inside and X_{out} was the weighted average biomass outside the FDS. The weighted average statistic asserts greater importance to those time periods when estimates of the integrated acoustic backscatter is high.

DIDSON imaging sonar data collection and processing.—The DIDSON imaging sonar was placed either outside or inside of the FDS net and "in-line" with the EK60 echo sounder beam sample volume (i.e., some degree of overlap) (Figure 1), approximately 10 m from the main frame line to achieve the highest image resolution. The imaging sonar data were processed using Echoview and Sound Metrics Corporation software. A total of 51 h of video data files were analyzed (Table 2) over the monitoring period and were assumed to be representative of a sample of day, night, and expected crepuscular periods to capture differences in fish behavior at different times. Each 1-h video file (consisting of four 15-min segments) was observed for various behavioral responses to the FDS. Fish that were recorded by the DIDSON imaging sonar were identified as individuals, small aggregations or groups (<20 individuals), or schools (>20 individuals). Schools consisted of a single species and were occasionally very large (>500 individuals).

During the spring and summer monitoring periods, the DIDSON imaging sonar was mounted outside the FDS 10 m away and aimed towards it. However, since Alewives were observed schooling on the inside of the FDS following passage when the FDS was degraded, it was felt that additional behavioral data were required on the inside of the FDS to aid in interpreting results. Thus, on September 3–7, 2010, at the south aspect, the imaging sonar was placed on the inside and aimed parallel to the FDS. Similar to the spring period, the imaging sonar was mounted on the outside of the FDS, 10 m away during most of the fall collection periods from October 13 to November 15, 2010.

Impingement monitoring.—Baseline impingement monitoring at PNGS was conducted from September 2003 to September 2004 prior to the installment of the FDS. Bins were used

TABLE 3. Impingement monitoring effort at the Pickering Nuclear Generating Station for sampling years 2003–2004, 2010, 2011, and 2012. The percent of service time is based on a full year of service for each bin.

Sample period	Number of bins sampled	In-service hours	Percent of service time (%)
Sep 2003–Sep 2004	574	32,236	46
Feb 2010–Jan 2011	1,505	37,904	54
Jan 2011–Dec 2011	1,456	38,541	55
Jan 2012–Dec 2012	1,181	29,415	42

to collect 24-h samples. Sampling was carried out a minimum of 1 d per week. Impingement monitoring at PNGS was also conducted in 2010 (February 2010 to January 2011), 2011 (January to December), and 2012 (January to December); for these years, the FDS was in place during the ice-free period. Sampling was carried out a minimum of 3 d per week and 24-h samples were also collected in bins. The effort expended in screen house bin-impingement monitoring was generally similar for all years (Table 3). The following data was collected for the fish species impinged in all years: species identification, numbers impinged, fish length, and fish biomass. Estimates of impingement reduction with the FDS in place (April to November for years 2010–2012) relative to baseline conditions (i.e., April to November from the 2003–2004 data) were calculated using annualized impinged biomass that was extrapolated from debris-bin screen house monitoring and expressed as biomass per unit condenser cooling water flow (mg/m^3).

RESULTS

Gill Netting

During the spring sampling period, 1,750 fish were collected with gill nets. A total of 301 fish were collected inside the FDS; these consisted entirely of two species, Round Goby (79%) and Alewife (21%). In contrast, 1,449 fish were collected outside the FDS, the majority of which were Round Gobies (60%) and Alewives (39%). Other fish species caught were Yellow Perch *Perca flavescens*, Rainbow Smelt, White Sucker *Catostomus commersonii*, Brown Trout *Salmo trutta*, and Common Carp *Cyprinus carpio*.

The sizes and weights of Alewives caught from both inside and outside the FDS during spring sampling were not significantly different statistically at the south aspect (ANOVA: $\alpha = 0.05$); however, at the west aspect, Alewives collected on the outside were significantly larger and heavier than those collected on the inside (ANOVA: $\alpha < 0.05$) (Table 4). Alewives were not collected at the east aspect during sampling. Results from the ANOVA indicated that the sizes and weights of Round Gobies caught during spring sampling from both inside and outside the FDS were not significantly different ($\alpha = 0.05$) except at the east aspect where those collected on the inside were significantly larger and heavier than those collected on the outside ($\alpha < 0.05$) (Table 4).

During the summer sampling period, 55 fish were collected. Thirteen fish were collected inside the FDS: 12 Round Gobies and 1 Rainbow Trout *Oncorhynchus mykiss*. Alewives were not collected inside the FDS. In contrast, 42 fish were collected outside the FDS, the majority of which were Alewives (72%), followed by Round Gobies (26%) and Brown Trout (2%).

TABLE 4. Summary statistics for Alewives and Round Gobies collected on the inside and outside face of the fish diversion system (FDS) barrier net during spring gill netting at the Pickering Nuclear Generating Station. Gill netting occurred at the south, west, and east aspects. An ANOVA was used to compare mean lengths and weights from fish collected on the inside and outside for each aspect. Differences between the inside and outside FDS for each aspect were considered significant at $P < 0.05$. Alewives were not collected at the east aspect during spring gill netting. The number of fish measured (*n*) and SD are also shown.

Aspect	FDS face	*n*	Mean FL (cm)	SD FL (cm)	FL difference inside and outside for aspect (*P*-value)	*n*	Mean weight (g)	SD weight (g)	Weight difference inside and outside for aspect (*P*-value)
					Alewife				
South	Inside	13	14.9	0.7	$P > 0.05$	13	35.7	4.5	$P > 0.05$
	Outside	115	15.1	0.8		115	37.5	7.1	
West	Inside	7	12.7	3.7	$P < 0.05$	7	26.3	14.6	$P < 0.05$
	Outside	23	15	0.9		23	39.3	6.2	
					Round Goby				
South	Inside	75	9.6	2	$P > 0.05$	75	14.3	9.4	$P > 0.05$
	Outside	226	10	2.2		226	15.4	9.3	
East	Inside	14	9.9	2	$P > 0.05$	14	15.8	10.6	$P > 0.05$
	Outside	27	6.9	1.9		27	5.3	5.3	
West	Inside	9	9.8	3.5	$P < 0.05$	9	18.1	18.7	$P < 0.05$
	Outside	88	9.1	2.1		87	12.5	10.4	

Results from the ANOVA showed that both mean lengths and weights of Round Gobies collected during summer sampling were significantly different ($\alpha < 0.05$), with the inside of the FDS having larger and heavier fish. The mean Round Goby size was 10.6 cm ($n = 12$) inside the FDS and 6.8 cm ($n = 11$) outside the FDS. The mean weight of Round Gobies was 23.1 g ($n = 12$) and 4.9 g ($n = 11$) for inside and outside the FDS, respectively.

An estimate of FDS net effectiveness (outside versus inside) was also determined based on gill-netting data for Alewife, Round Goby, and all species combined over the spring and summer periods. Based on biomass, effectiveness was estimated to be 90% and 91%, respectively, for spring and summer.

Underwater Video Results

Fish activity, defined as fish present in the video over time, was higher outside the FDS than inside the FDS, with high numbers likely being Alewife schools passing by. This was observed for both cameras positioned near the bottom as well as at the net face. There was no evidence of fish passage though the FDS. These observations were strictly qualitative since individual fish or schools cannot be distinguished from others.

Acoustic Monitoring with the Simrad EK60 Echo Sounder

A total of 576.3 h (spring: 78.6 h, summer: 224.3 h, fall: 273.4 h) were analyzed for paired comparisons (inside versus outside). More data were collected but were not used because of excessive interference caused by algal influx (large mats of *Cladophora*), air bubble interference, reverberation, storm events, and diver net-cleaning operations. Still, we felt that there was sufficient reliable data to assess performance of the FDS barrier net in fish exclusion. However, we emphasize that evaluations in the summer and fall were done primarily when the net was optimally employed (i.e., not degraded). The net was degraded during the spring assessment (which was supported by field staff observations).

Results from the echo sounder data indicate that those ETSUs with the highest observed integrated acoustic backscattering strength (and likely biomass) occurred during the day where the presence of schooling fish were obvious (likely Alewife schools). There was synchronization and correlation of echogram data collected simultaneously by both the DIDSON imaging sonar and the EK60 echo sounder systems (both outside and inside the FDS) (Figure 2). The large schools seen by the DIDSON imaging sonar also occurred on the EK60 echo sounder (outside transducer only).

Overall, most fish activity observed was within approximately a 10-m range of the net during the day. However, at night, single target detections were observed throughout the full range of the beam (30 m or 20 m). This observation could also partly be a function of an increasing beam sample volume with range from the transducer.

For each of the spring, summer, and fall monitoring periods, the average acoustic backscatter (s_v; volume backscattering

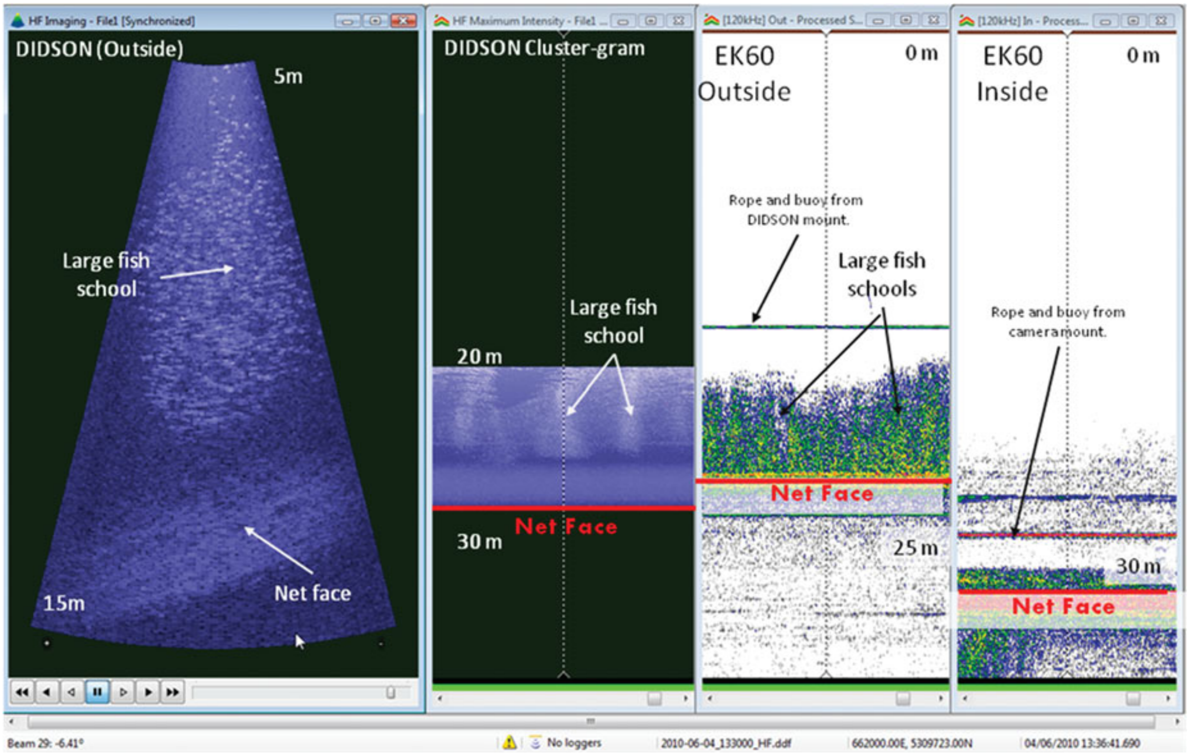

FIGURE 2. Schooling fish observed from both the DIDSON imaging sonar and Simrad EK60 echo sounder using Echoview software. The data show synchronization and correlation of echogram data collected simultaneously by both the DIDSON and EK60 systems (both inside and outside the FDS). Large schools of fish seen by the DIDSON also occurred on the EK60 (outside transducer only).

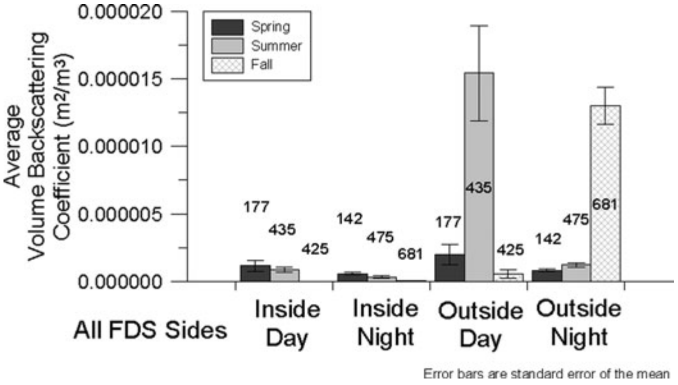

FIGURE 3. Average acoustic backscatter (s_v; volume backscattering coefficient, m^2/m^3) from all sampling seasons by FDS aspect (inside and outside) and diel period (day and night) for the PNGS FDS barrier net-effectiveness study, 2010. Average s_v was calculated from all the 15-min EK60 echogram segments across all FDS aspects (i.e., south, west, and east). Error bars denote SE of the mean. Values shown are the total number of 15-min elementary time sampling units (ETSUs).

coefficient m^2/m^3) was calculated by FDS aspect (inside or outside) and diel period (day or night) (Figure 3). Given the prevalence of a single schooling species within the gill-net catches, it was assumed that Alewives contributed the majority of the integrated acoustic backscatter.

The average acoustic backscatter was estimated from the inside and outside of the FDS by FDS face for all sampling seasons. Estimates for the spring, summer, and fall monitoring periods based on the mean volume backscattering and biomass showed the FDS to be 62, 93, and 99% effective, respectively, in keeping out fish (Table 5).

Effectiveness of the FDS based on the weighted average (i.e., weighted arithmetic mean) biomass from the FDS inside and outside was also determined. Average fish biomass, weighted on the sum of biomass from the FDS inside and outside, improved the estimated FDS effectiveness to 75, 98, and 100% for the spring, summer, and fall sampling periods, respectively (Table 6). The overall weighted arithmetic mean of the three seasons combined (spring, summer, and fall) estimated the FDS to be 98% effective. Fewer high fish density data were available during the spring period for analysis.

Behavioral Observations with DIDSON Imaging Sonar

Data collected by the DIDSON imaging sonar showed synchronization and correlation with the EK60 echo sounder data collected simultaneously (Figure 2). Five different fish behavioral patterns for Alewives and large predators were observed during the spring and summer periods with the imaging sonar oriented facing the outside and perpendicular to the FDS; these were:

1. Parallel movement behavior to the FDS
2. Fish movement towards the FDS
3. V-shaped response to the FDS
4. Reversal of direction (parallel to the FDS)
5. Reversal of direction (perpendicular to the FDS)

During the spring period, fish behavior in response to the FDS was primarily schools moving parallel to the net (Figure 4), which for the south aspect involved movements either east to west or west or east, as well as reversal of directions. Similar patterns were evident at all the other placements of the DIDSON imaging sonar (e.g., east and west aspects). In all instances, Alewife school cohesiveness and fish position were evident. Reversal-of-direction behavior often involved an avoidance response to a predator such as a salmonid that was "chasing" the Alewife school. The only other noticeable behavioral response observed was a V-shaped response that involved a school of fish approaching the FDS from a specific direction and displaying a noticeable avoidance response characterized by a "V"-shape movement.

TABLE 5. Average acoustic backscatter (s_v; m^2/m^3) and fish biomass (g/m^3) estimated from the inside and outside of the FDS by FDS aspect (south, east, or west) and net effectiveness (%) for the PNGS FDS barrier net-effectiveness study, 2010. Calculations are described in the Methods; CI = the bootstrap estimated 5% and 95% CIs, n (ETSUs) = the total number of 15-min elementary time sampling units (ETSU) included in the calculation. Those ETSUs with greater than 25% no data or bad data samples were excluded.

			Inside				Outside					
Season	FDS aspect	Diel period	Average	SD	CI (5.0%)	CI (95.0%)	Average	SD	CI (5.0%)	CI (95.0%)	n (ETSUs)	FDS net effectiveness (%)
Volume backscattering coefficient, s_v (m^2/m^3) × 10^{-6}												
Spring	All	All	0.941	4.049	0.666	1.494	1.520	7.418	0.999	2.443	319	62
Summer	All	All	0.619	2.575	0.506	0.796	8.039	51.295	5.920	12.072	910	93
Fall	All	All	0.051	0.129	0.045	0.058	8.237	29.065	6.844	9.736	1,106	99
Estimated fish biomass (g/m^3)												
Spring	All	All	0.097	0.417	0.069	0.154	0.157	0.764	0.103	0.252	319	62
Summer	All	All	0.058	0.241	0.047	0.074	0.751	4.792	0.553	1.128	910	93
Fall	All	All	0.004	0.009	0.003	0.004	0.587	2.070	0.487	0.693	1,106	99

TABLE 6. Estimated weighted average biomass (g/m^3) from the FDS inside and outside and FDS net-effectiveness estimates (%) for the PNGS FDS barrier net-effectiveness study, 2010. The weighting factor is the sum of the biomass on the inside and outside FDS for each 15-min ETSU. Calculations are described in the Methods. The weighted arithmetic mean statistic asserts greater importance to those time periods when a large number of fish were observed.

				Inside		Outside			
Season	FDS aspect	Diel period	Weighting factor	Sum of products	Weighted average biomass	Sum of products	Weighted average biomass	*n* (ETSUs)	FDS net effectiveness (%)
Spring	All	All	80.8	68.2	0.84	203.4	2.52	319	75
Summer	All	All	736.1	447.4	0.61	21,782.6	29.59	910	98
Fall	All	All	652.9	2.1	0.00	5,118.0	7.84	1,106	100
All seasons			1,469.8	517.8	0.40	27,104.0	18.40	2,335	98

Diurnal differences were observed in fish schooling behavior (Figure 5). No large schooling aggregations were observed in the vicinity of the FDS late at night or early morning (e.g., time periods of 2200–2300, 0300–0400, and 0500–0600 hours) as fish were either dispersed individually (in large numbers) or in small groups or aggregations. Fish schooling behavior in the spring was primarily during daytime periods.

Overall, there was no evidence of fish passage through the small mesh of the FDS based on DIDSON imaging sonar review of data collected diurnally over the spring and summer monitoring periods, thus suggesting that the FDS is an effective barrier against intake impingement. However, there were instances where fish passage was observed over the FDS when it was degraded in the water column due to large mats of algae. For example, fish behavioral observations were made with the imaging sonar on the inside of the FDS from September 3 to 7, 2010, when net degradation occurred. On September 3–4, 2010, the FDS was degraded up to 1 m. During this period, large Alewife schools were observed in the vicinity of the FDS (on the inside), and these fish tended to maintain position

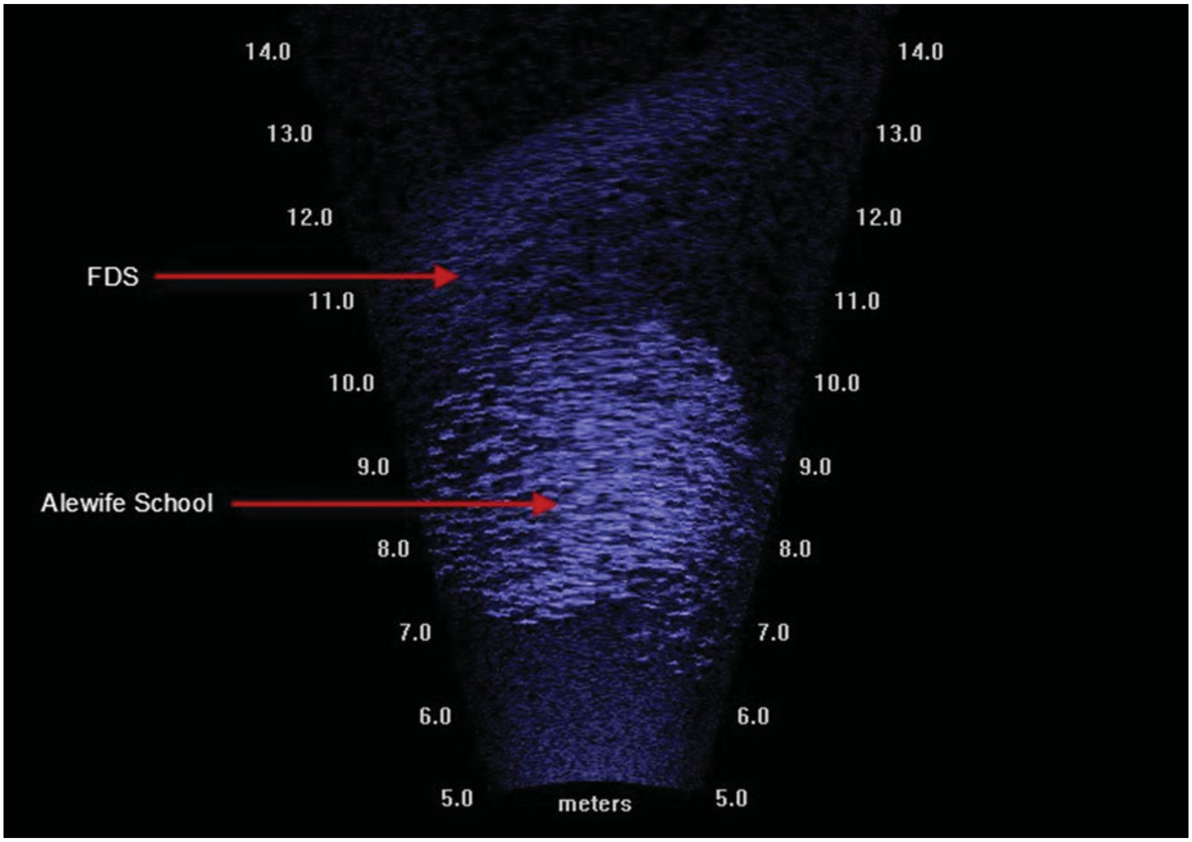

FIGURE 4. Image from DIDSON imaging sonar showing a school of Alewives traveling parallel to the FDS (May 31; 1550 hours, 27 s). The DIDSON beam covers a distance of approximately 12–14 m from the FDS.

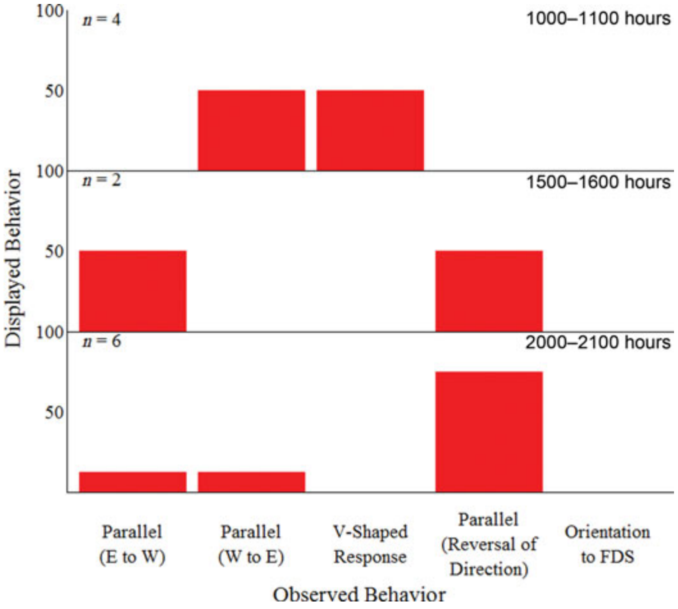

FIGURE 5. Fish behavioral patterns in response to the FDS based on DIDSON imaging sonar observations (May 31 to June 1, 2010). The percent displayed behavior (*y*-axis) is based on the percentage of observations and not the percentage of time observed. Data are not shown for the time periods of 2200–2300, 0300–0400, and 0500–0600 hours since no schooling behavior was observed.

immediately behind the FDS (although the schooling was less cohesive over the 2000–2100-hour period). The estimated size of each school was in excess of 1,000 individuals. No fish schools were observed after 2300 hours on September 4, 2010, through to the early morning on September 7, 2010 (0300–0400 hours). The data suggested that Alewife schools might only have stayed in the area immediately behind the FDS (on the inside) for less than 10 h.

Predatory fish activity (assumed to be salmonids) was observed and expressed as fish activity (the number of fish observed over time) as they were chasing Alewives on the inside of the FDS (Figure 6). These results may be biased since this activity index may incorporate some resampling of fish congregating inside the FDS. Activity was highest on September 5, 2010, when the FDS was further degraded to 1–2 m below the surface (submergence of both float lines). On September 6–7, 2010, the FDS was no longer degraded and net flotation was at the surface.

Analysis of DIDSON imaging sonar indicated a wide size range of fish being recorded on both inside (at the south aspect) and outside (at the east aspect) of the FDS during the summer period. The size distribution of fish targets detected by the DIDSON sonar over a 24-h period on the inside (at the south aspect) of the FDS is shown in Figure 7. The smaller fish were assumed to be Alewives based on size, body shape, and shoaling behavior. Using similar criteria, larger fish, some estimated to be up to 115 cm TL, were assumed to be salmonid species.

Impingement Monitoring Results

Fish species that were most frequently impinged comprised a biomass of 18,214 kg in 2003–2004 before the FDS installation to less than 5,000 kg for each of the years 2010, 2011, and 2012 when the FDS was installed during the ice-free period (Table 7). These most frequently impinged species consisted of dominant species impinged by biomass in 2003–2004 and species found in 2010 and 2011 that had more than 10 kg of biomass impinged. The impingement biomass reduction with the FDS in place relative to the 2003–2004 baseline conditions was estimated at 80.9, 84.8, and 98.0% for the years 2010, 2011, and 2012, respectively. These results are conservative since the data used to measure impingement reductions during FDS installation were based on the April 1–November 30 period, but the actual time frame for FDS installation in 2010, 2011, and 2012 differed slightly. The improved impingement reduction in 2012 while the FDS was installed was attributed to further improvements to the FDS such as the addition of a second skirt and crown floats that prevented some fish passage over the net, which was observed in our 2010 sampling (see above results for DIDSON imaging sonar). In 2010, the year of our FDS effectiveness study, Alewife was the most abundant species impinged based on biomass; for the months coinciding with our FDS effectiveness study (i.e., May to September), Alewives comprised more than 75% of the biomass impinged. For September 9–10, 2010, a few days after the September 3–7 imaging sonar observations of Alewife passage over the degraded FDS, Alewife impingement at the station were in the thousands of individuals (raw data) per sampling event. In contrast, for the month leading up to this event, Alewife impingement during a sampling event was a maximum of a few hundred individuals (raw data). Large salmonids were also impinged (e.g., a single Chinook Salmon *O. tshawytscha* 96.9 cm in length and weighing 11 kg), including during periods of our effectiveness assessments. Some other notable fish species impinged in 2010 were schooling fish Gizzard Shad and Rainbow Smelt, as well as Round Goby, an invasive species that was not present during baseline sampling in 2003–2004.

DISCUSSION

Based on the results of the Simrad EK60 echo sounder and supporting results from gill netting, DIDSON imaging sonar, underwater video, and station impingement sampling, the FDS is effective at preventing fish from entering the PNGS intake and becoming impinged. The prevalence of a schooling species (i.e., Alewife) in the gill-net collections and DIDSON sonar results allowed us to assume that Alewives contributed the majority of the integrated acoustic backscatter for the EK60 analysis. The gill-netting results and underwater video observations also supported the data collected by the EK60 echo sounder, which showed more fish on the FDS outside than inside. The DIDSON sonar results revealed that when fish encounter the FDS from the outside, they exhibit any or a combination of five different

TABLE 7. Total biomass impinged (annually) and percent reductions comparing 2003–2004 baseline data to years 2010, 2011, and 2012 for the period when the fish diversion system (FDS) barrier net was in place at the Pickering Nuclear Generating Station. Only results for the most frequently impinged species are shown, which are based on the dominant species impinged by biomass in 2003–2004 and species collected in 2010 and 2011 when greater than 10 kg biomass was impinged. The percent impingement reductions are conservative since the data represents a time period from April 1 to November 30, but the actual time frame for FDS installation in 2010, 2011, and 2012 differed. NA = not applicable. Round Goby is an invasive species that was not reported during 2003–2004 baseline sampling but has become common in recent impingement sampling. Added numbers may not match due to rounding.

Fish species	Total biomass (kg) (2003–2004)	Total biomass (kg) (2010)	Total biomass (kg) (2011)	Total biomass (kg) (2012)	Percent (%) impingement reduction (2010)	Percent (%) impingement reduction (2011)	Percent (%) impingement reduction (2012)
Freshwater Drum *Aplodinotus grunniens*	4,803.4	128.9	204.1	95.1	99.4	98.4	99.6
Brown Bullhead *Ameiurus nebulosus*	3,287.2	48.7	46.0	11.4	99.4	99.3	99.9
Alewife *Alosa pseudoharengus*	3,134.6	2,591.9	1,912.1	165.3	19.4	47.7	95.3
Common Carp *Cyprinus carpio*	2,621.7	347.3	462.5	263	94.1	94.1	98.8
Gizzard Shad *Dorosoma cepedianum*	1,702.0	393.1	327.2	528.2	78.1	76.6	98.6
Salmonids, family Salmonidae	717.8	260.5	237.4	155.3	71.9	36.3	90.6
Walleye *Sander vitreus*	617.8	27.8	0.0	3.5	98.9	100.0	99.4
White Sucker *Catostomus commersonii*	608.3	77.9	94.9	33.5	86.2	90.7	97.3
Threespine Stickleback *Gasterosteus aculeatus*	279.0	0.6	0.3	0.2	100.0	100.0	100.0
Emerald Shiner *Notropis atherinoides*	136.0	23.7	4.1	7.5	79.5	96.4	96.1
Smallmouth Bass *Micropterus dolomieu*	84.2	11.2	17.8	8.9	96.7	93.0	96.7
Northern Pike *Esox lucius*	66.9	51.2	120.4	132.9	100	38.3	66.4
Rainbow Smelt *Osmerus mordax*	41.7	124.5	132.5	4.7	−153.7	−141.6	98.1
American Eel *Anguilla rostrata*	38.5	0.51	12.3	53.6	98.7	90.3	72.6
Yellow Perch *Perca flavescens*	16.6	15.3	18.1	23.2	16.3	28.3	79.6
Sea Lamprey *Petromyzon marinus*	4.4	36.1	14.7	7.2	−651.1	−216.0	67.4
Round Goby *Neogobius melanostomus*	0.0	287.5	155.6	120.8	NA	NA	NA
Total biomass impinged (kg) and percent reduction (%)	18,214.0	4,616.5	3,782.0	1,706.0	77.8	82.8	97.6
Flow corrected impingement rate (mg/m^3 CCW flow) and reduction (%)	4.35	0.95	0.79	0.35	80.9	84.8	98.0

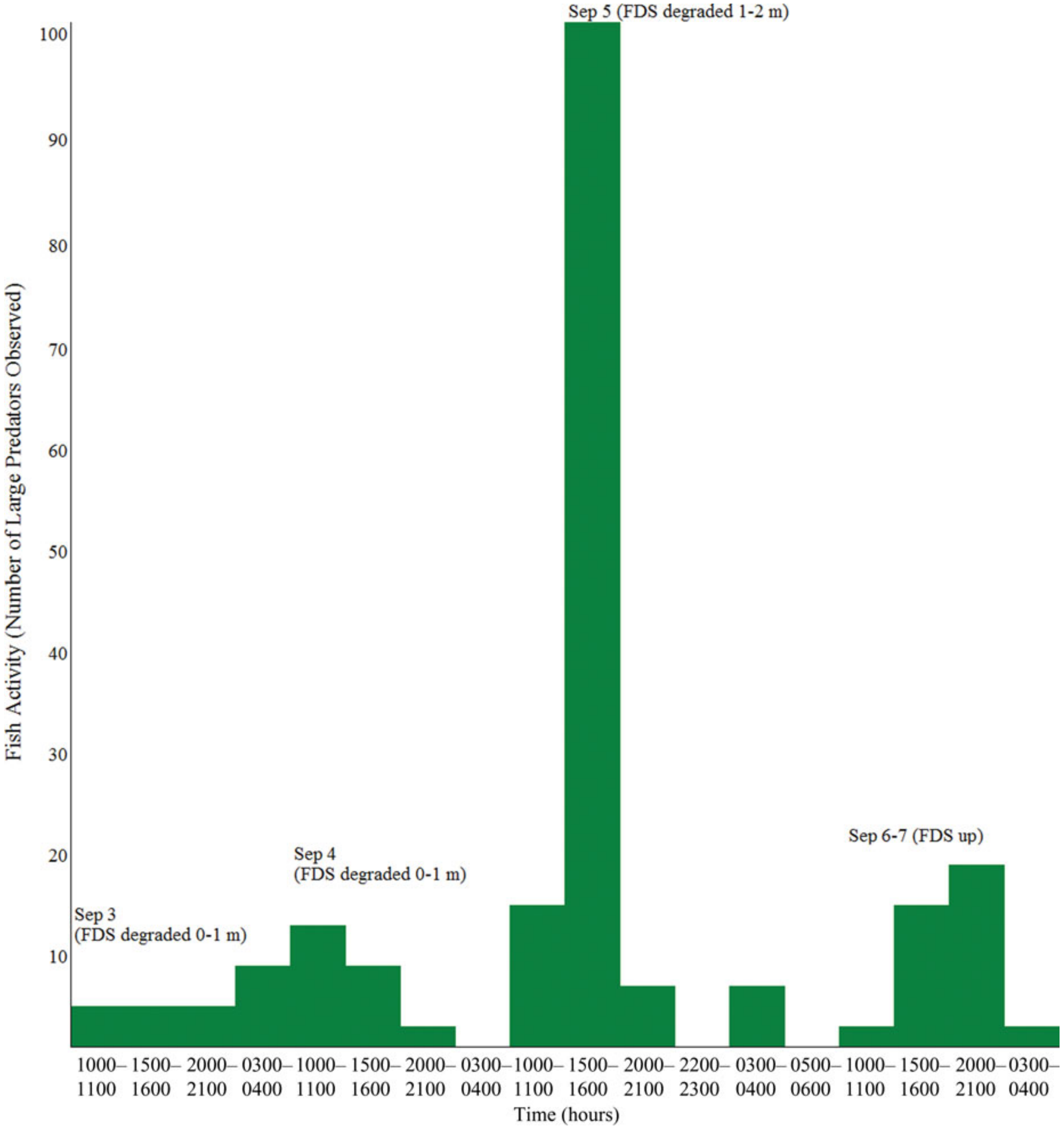

FIGURE 6. Predatory fish activity in the FDS inside expressed as numbers observed using DIDSON imaging sonar, September 3–7, 2010.

behavior patterns and that fish passage does not occur through the net, thus supporting our conclusion that the FDS is effective. However, there were some instances where the FDS was degraded based on observations of the float lines, which resulted in fish passage over the FDS net. For Alewives, an increase in number of individuals impinged at the station was seen during the days following net degradation. The significant reductions (greater than 80%) in fish biomass impinged at the intake following installation of the FDS also support our conclusions that the FDS net is an effective technology for reducing impingement at PNGS.

Similar to the results of the EK60 echo sounder, the gill-netting results suggested high FDS effectiveness. However, the gill-netting results might not have been entirely representative of fish in the vicinity of and being impinged at PNGS. During the spring, the gill nets were bottom sets, which likely resulted in Round Goby, a benthic species, being more abundant than Alewife, a pelagic species, despite Alewives comprising the majority of fish being impinged at the station during this time. At the west aspect, the finding of significantly smaller and lighter Alewives inside the FDS compared with those outside suggests that smaller Alewives pass over the FDS when it is degraded.

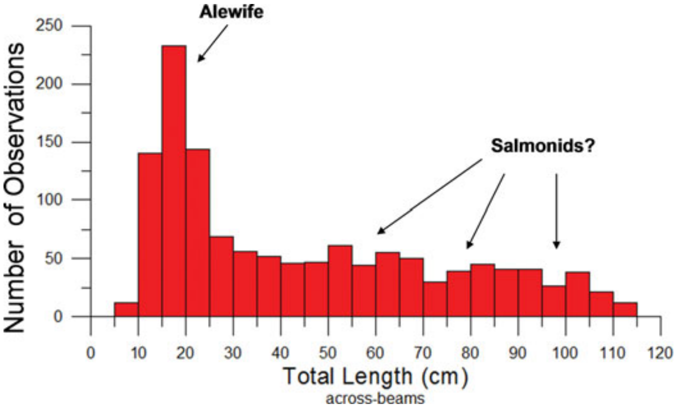

FIGURE 7. Size range (TL, cm) of nonschooling fish (>8.0 cm) estimated from DIDSON imaging sonar fish target detections using the Echoview 3D sonar module (September 5, 2010; south aspect of FDS barrier net).

During the summer, the gill nets were moved off the bottom. The prevalence of Alewives was consistent with DIDSON sonar observations, but the larger fish observed by the DIDSON sonar (up to 115 cm) and collected during impingement monitoring at the station were not seen in gill-net catches. Round Gobies collected during spring and summer gill netting were significantly larger and heavier inside the FDS than they were outside suggesting that they are living in the forebay of the PNGS.

The DIDSON imaging sonar observations of Alewives maintaining position in the immediate vicinity of the FDS following passage over the net (September 3–4, 2010) and then disappearing (late September 4–7, 2010) suggested that these fish left the area and continued down the intake channel towards the plant water intake where they would eventually become impinged. This is supported by the high Alewife impingement observed at the station on September 9–10, 2010. The DIDSON data suggested that Alewife schools may not spend significant time in the vicinity of the FDS on the inside (i.e., less than 10 h). This may be related to their swimming capability since movement towards the FDS would be against water velocities and flows; water velocities were typically at or below 15 cm/s in the vicinity of the FDS. This behavior may also be related to other environmental changes such as upwellings, which occurred regularly during the monitoring. In contrast, larger fish (believed to be salmonids) were observed on the inside of the FDS for several consecutive days.

Calculations for FDS effectiveness using the Simrad EK60 data were performed based on mean volume backscattering and biomass as well as on weighted average biomass. Effectiveness values based on weighted average biomass were greater than those from mean volume backscattering and biomass. The weighted average statistic asserted greater importance to those time periods when estimates of the integrated acoustic backscatter was high. Schooling species represented the primary species impinged at PNGS; therefore, this statistic would likely be a more accurate representation of overall FDS effectiveness.

The impingement monitoring results before and after deployment of the FDS barrier net indicated that the FDS is effective at reducing impingement at PNGS. However, there are annual variations in the lake's fish populations, and these estimates of impingement relative to baseline conditions are only approximate given that baseline conditions were only based on 1 year of data. Nevertheless, FDS reductions in impingement exceeding 80% in 3 years of continuous impingement sampling with the FDS in place relative to baseline conditions provides some validation of the 98% reduction measured from our hydroacoustic evaluation.

There are few quantitative assessments of barrier net effectiveness using a combination of technologies such as hydroacoustics, DIDSON imaging sonar, and netting during the actual deployment of the barrier. Most barrier net studies have used paired gill netting or pre- and postimpingement monitoring (EPRI 2006). For example, at the Ludington Pumped Storage Hydroelectric Plant, Michigan, on Lake Michigan, barrier net effectiveness was measured using paired gill-net catches inside and outside the barrier net (Consumers Energy 2010). Similar to the PNGS FDS net, the bar mesh of the Ludington barrier net was 0.5 in (1.27 cm), but at 3,917 m the net was more than six times longer than the PNGS FDS net. The Ludington barrier net has been in operation since 1989 (EPRI 2006; Consumers Energy 2010). In 2010, a study was conducted to determine the effectiveness of the net. Paired gill-net catch data from eight stations (four inside and four outside the barrier net) were used for the assessment. A total of 272 gill nets were set, which can be a consumptive approach. The overall effectiveness of the barrier net for the target species based on cumulative measurements was 89.3% and was consistent with other annual estimates since 1991. For large Alewives (>12.7 cm), the effectiveness was 94.5% while for small Alewives (10.2–12.7 cm), the effectiveness was 82.0%. For salmonids $\geq$ 12.7 cm, effectiveness was 77.4%; however, the net was compromised for 1 week, which resulted in slightly lower effectiveness estimates than expected (Consumers Energy 2010). Other power plants that have reported positive results with barrier nets include Bowline Point Station, New York, on the Hudson River and Chalk Point Station, Maryland, on the Patuxent River; in these cases, reductions in impingement were seen following barrier net deployment (EPRI 2006).

A barrier net can be a relatively inexpensive alternative compared with other intake screening-technology compliance options. While barrier net technologies have been effective in reducing fish passage and subsequent impingement at PNGS and the Ludington plant, they may not be applicable for use at all intakes. The barrier net requires continual maintenance, such as the removal of algae, and net repair to ensure that the net is not degraded or compromised. Thus, the potential use and effectiveness of a barrier net may be determined by site-specific conditions (EPRI 2006). Despite the maintenance required to remove algae and prevent net degradation, the ability of the net to partially degrade or submerge when clogged with attached algae is a beneficial safety feature allowing for the maintenance of sufficient station flows.

Overall, the FDS was demonstrated to offer significant fish protection at PNGS based primarily on Simrad EK60 echo sounder results and supported by data from gill netting, DIDSON imaging sonar behavioral observations, underwater video, and station impingement monitoring. This barrier net technology has now been accepted by industry as a successful system for reducing fish impingement at the plant. The advantages of the hydroacoustic and imaging sonar methodologies are that they are not consumptive and have the ability to collect continuous diurnal data on fish abundance, size, and behavior, but they do require calibration. Paired inside-versus-outside analysis to measure barrier net performance circumvents the need to compare data with a baseline collected from a different year, which can be problematic since there are annual variations in fish abundance. The methodological approach used by PNGS can be adopted by existing and future facilities that operate barrier nets as a nonconsumptive and effective means to evaluate net performance.

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