# Assessing seasonal changes in pelagic fish density and biomass using hydroacoustics in Hamilton Harbour, Lake Ontario in 2016 

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# ASSESSING SEASONAL CHANGES IN PELAGIC FISH DENSITY AND BIOMASS USING <br> HYDROACOUSTICS IN HAMILTON HARBOUR, LAKE ONTARIO IN 2016 

by<br>Jonathan D. Midwood ${ }^{1}$, Kathy E. Leisti ${ }^{1}$, Scott W. Milne ${ }^{2}$, and Susan E. Doka ${ }^{1}$

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#### Abstract

Midwood, J.D., Leisti, K.E., Milne, S.W., Doka, S.E. 2019. Assessing seasonal changes in pelagic fish density and biomass using hydroacoustics in Hamilton Harbour, Lake Ontario in 2016. Can. Tech. Rep. Fish. Aquat. Sci. 3299: x +63 pp.

In the Hamilton Harbour Area of Concern (AOC) one of the delisting targets for the assessment of Beneficial Use Impairment \#3 (Degradation of fish and wildlife populations) is to support a shift in community and trophic structure such that top predators are better represented. Since many of these species are not solely reliant on littoral habitats for their life history and exhibit a range of foraging behaviour that link littoral and pelagic habitats, an assessment of forage fishes outside of the littoral zone is warranted. Fish hydroacoustic and mid-water trawl surveys were therefore undertaken in 2016 over three seasons (spring, summer, and fall). The primary objective of these surveys was to assess the density, biomass, spatial variability, and depth distribution of the pelagic fish community in the AOC. Results from the present study suggest that the majority of pelagic fish density and biomass is concentrated in the western part of the harbour (non-random distribution). There was also a clear influence of anoxia on the depth distribution of fish, with the majority of fish restricted to the top 9.0 m of water during the summer; the deepening of the thermocline expanded this zone, but there was still limited use of water below $14.0-18.0 \mathrm{~m}$ in the fall. The latter finding has implications for additional long-term goals in the harbour of seeing the return of fall spawning Coregonids. Seasonally, both density and biomass were generally higher in the fall, but had an overall peak in the western portion of the harbour in the summer. Collectively, these results emphasize the need to address eutrophication issues in the harbour as well as unequal distributions of productivity that are presumed to be the main driver of unequal pelagic fish distributions.


## RÉSUMÉ

Midwood, J.D., Leisti, K.E., Milne, S.W., Doka, S.E. 2019. Assessing seasonal changes in pelagic fish density and biomass using hydroacoustics in Hamilton Harbour, Lake Ontario in 2016. Can. Tech. Rep. Fish. Aquat. Sci. 3299: x + 63 pp.

Dans le secteur préoccupant (SP) du port d'Hamilton, une des cibles à atteindre en vue de la radiation de la mention «évaluation bénéfique diminuée $\mathrm{n}^{\circ} 3$ » (dégradation des populations de poissons et d'autres espèces sauvages) est le soutien à une modification des communautés et des structures trophiques visant à rehausser la représentation des superprédateurs. Comme bon nombre des espèces concernées ne dépendent pas seulement des habitats littoraux pour leur cycle vital et présentent un éventail de comportements de recherche de nourriture reliant les habitats littoraux et pélagiques, l'évaluation des poissons-fourrages hors de la zone littorale est justifiée. Des relevés hydroacoustiques et par chalut pélagique des poissons ont donc été effectués pendant trois saisons (printemps, été et automne) en 2016. Ils visaient principalement à évaluer la densité, la biomasse, la variabilité dans l'espace et la répartition en profondeur de la population de poissons pélagiques dans le SP. Les résultats de la présente étude laissent à penser que la plus forte densité et la plus grande proportion de la biomasse des poissons pélagiques se trouvent dans la partie ouest du port (répartition non aléatoire). L'anoxie influe aussi de façon claire sur la répartition en profondeur des poissons qui vivent principalement en deçà de 9 m de la surface, en été. L'abaissement de la thermocline agrandit la zone de répartition, mais l'eau demeure peu occupée à une profondeur de 14 à 18 m en automne, ce qui se répercute sur un autre objectif à long terme pour le port, soit le retour des corégonidés pour le frai d'automne. De façon saisonnière, tant la densité que la biomasse étaient généralement plus élevées en automne, mais atteignaient un sommet global dans la partie ouest du port en été. Ensemble, les résultats mettent en lumière la nécessité de s'attaquer aux problèmes d'eutrophisation dans le port et de répartition inégale de la productivité, lesquels constitueraient la principale cause de la répartition inégale des poissons pélagiques.

### 1.0 INTRODUCTION

Hamilton Harbour, Lake Ontario was designated as an Area of Concern (AOC) in 1987 due to a legacy of anthropogenic development and industry including substantial industrialization in surrounding watersheds that led to alterations to fish and wildlife habitat and populations, polluted waters, and contaminated sediments. To support the delisting of this AOC, the Hamilton Harbour Remedial Action Plan (HHRAP) identified a series of Beneficial Use Impairments (BUI) that needed to be addressed, outlining specific targets for each BUI. From a fisheries perspective, targets for the two most relevant BUls (Degradation of fish and wildlife populations and Loss of fish and wildlife habitat) are largely focused on the littoral zone, which has been defined as underwater areas less than 2 m in depth that can support aquatic vegetation (HHRAP 2004). Within the harbour this type of habitat primarily occurs along the western, northern, and southeastern margins, with more substantive areas in Cootes Paradise (situated at the western end of the harbour). Due to this restricted distribution, the littoral zone represents only a small fraction of the available habitat within the harbour (8.9\% by surface area and $14.8 \%$ by volume, at a water level of 74.8 m above sea level), with the remainder classified as pelagic and benthic habitats. An expanded assessment of conditions throughout the harbour is needed to determine the status of fish productivity in areas outside of the littoral zone.

This expansive assessment is important given the well-established interconnected nature of the benthic, pelagic, and littoral zones (Schindler et al. 1996; Vander Zanden and Vadeboncoeur 2002). There is considerable evidence of diel horizontal migrations by invertebrates (Van de Meutter et al. 2004) and fishes (Muška et al. 2013) between littoral and open waters. One of the delisting targets for the HHRAP is to see a shift in fish community structure away from one indicative of a eutrophic environment (e.g., White Perch [Morone americana], Bullhead [Ameiurus spp.], Common Carp [Cyprinus carpio]) to a more balanced trophic structure that is indicative of a mesotrophic environment (e.g., Northern Pike [Esox lucius], Largemouth Bass [Micropterus salmoides], Walleye [Sander vitreus]; HH RAP 2012). Some of these RAP target species (i.e., Northern Pike , Walleye) are not solely reliant on littoral habitats for their life history and exhibit a range of foraging behaviour that link littoral and pelagic habitats (Kobler et al. 2008). Efforts to facilitate their potential recovery would therefore be supported through an evaluation of the spatial distribution, abundance, and biomass of pelagic fishes in the harbour. Incorporating a seasonal component into this survey allows for an evaluation of the productive potential of different regions of the harbour, and allows for an exploration of how summer anoxia affects pelagic fishes. In addition, a long-term target for the harbour is to recover the formally robust population of Coregonids to the harbour (Bowlby et al. 2016), and ensuring a sufficient forage base for these species' is one of many components to their recovery.

The littoral zone can be sampled using traditional active (i.e., electrofishing) and passive (i.e., trap or fyke nets) gear; however, pelagic waters can be more challenging to sample due to the larger volume of water and lower density of fish. Since their development in the late 1940's, hydroacoustics have become a common technique for surveying pelagic fishes (Simmonds and MacLennan 2005) and have been found to be more accurate at providing estimates of fish populations than traditional trawl surveys (Argyle 1992). Furthermore, hydroacoustics have the advantage of being able to cover large areas relatively quickly and with a nearly complete snapshot of the water column (Godø 2009 in Trenkel et al. 2011). Pairing hydroacoustic surveys with trawling allows for an estimation of species composition and their size based on target signature, which in turn can be used to estimate fish density and biomass in the survey region.

In support of the Hamilton Harbour RAP, hydroacoustic and trawling surveys were completed in the spring, summer, and fall of 2016. The primary objective of these surveys was to assess the
pelagic fish community in the Harbour, with emphasis on their density, biomass, spatial variability, and depth distribution. A secondary objective was to document seasonal changes in available pelagic habitat (i.e. water temperature, potential hypoxia, etc.) and its effect on the distribution of pelagic fishes. The hydroacoustic and trawling data were analyzed by Milne Technologies Inc. who prepared a detailed report on the methodology and a summary of the results (Milne 2017). Here we summarize and interpret the main findings from this report and expand to address areas of particular interest, with particular focus on how the results relate to the RAP objectives outlined above.

### 2.0 METHODS

### 2.1 STUDY SITE

Hamilton Harbour is an embayment located at the western end of Lake Ontario (Figure 1) and is bounded by the Burlington shipping canal under the Skyway Bridge to the east and Cootes Paradise to the west. The south shore of Hamilton Harbour is heavily industrialized and includes two large steel processing factories (although U.S. Steel Canada). Although the total surface area of the bay is large (2150 ha), much of Hamilton Harbour is shallow with a mean and maximum depth of 13.7 m and 27.0 m , respectively.

For the purposes of this study, the survey area was defined as the entire area of Hamilton Harbour excluding shallow areas ( $<5 \mathrm{~m}$ ) that are primarily found along the north and east shores and western portion of the harbour (Figure 1). After excluding these areas, the remaining potential survey area had a surface area of $1.99 \times 10^{7} \mathrm{~m}^{2},(85 \%$ of that harbour by area) and total volume of $1.76 \times 10^{8} \mathrm{~m}^{3}$ ( $65 \%$ of the harbour by volume). To allow for a spatial comparison of fish abundance and biomass, the survey region was partitioned into four analysis sector regions (herein referred to as analysis sectors) based on several habitat criteria including depth, bottom complexity, and basin isolation. These sectors were defined during previous surveys (see Milne 2009) and kept consistent for the present survey to allow for a comparison across years. Three sectors were in the northern portion of the harbour (north [N], north east [NE] and west [W]) and one represented the more industrialized south central portion (SC; Figure 2).

### 2.2 SURVEY DESIGN AND METHODOLOGY

Seasonal sampling for the 2016 survey occurred in spring (April 26 - 29), summer (August 15 20) and fall (September 27 - October 6). The priority for the survey was to complete a full set of nighttime, concurrent trawling ( $\mathrm{N}=19$ ) and hydroacoustic transects along a series of pre-defined paths that were partially based on similar surveys completed in 2006. Due to basin morphometry, the number of trawling transects was not consistent across the analysis sectors with three trawls in both the N and W , six in the NE and seven in SC. When time allowed, some transects were resampled and these were chosen based on weather conditions and potential issues with initial results from the first trawl and hydroacoustic transect. This resulted in variation in the level of effort across transects within and across the seasonal time periods. Additional day and crepuscular samples were also collected; however, for the present report only data collected at night were evaluated.

### 2.2.1 Temperature and dissolved oxygen profiles

At the start of each trawling transect, a YSI Sonde EXO multiprobe (YSI Inc., Yellow Springs, OH ) was lowered into the water and measurements of water temperature $\left({ }^{\circ} \mathrm{C}\right)$ and $\mathrm{DO}(\mathrm{mg} / \mathrm{L})$ were recorded at 1-m intervals until the bottom was reached. The main objective of these
profiles was to verify the presence of a thermocline and document its depth; these profiles also provide an indication of the depth of the hypoxic zone, particularly during the summer and fall surveys.

### 2.2.2 Mid-water trawling

A small-mesh, pelagic mid-water trawl was used for acoustic target verification and to collect information about the species and size composition of the Hamilton Harbour fish communities. Trawls were run concurrently with the acoustics, although in a few instances trawling and acoustics occurred independently due to rough water conditions. Some of the trawls were sampled close to the surface ( 1.0 to 2.5 m water depth) to determine if fishes were occupying areas where downward-looking acoustics are not as effective.

The mid-water trawl (built by CanTrawl Nets Ltd., BC) was fished from the same vessel (CCGS Kelso) that ran the acoustic surveys. The trawl headline was 7.2 m wide and had an overall length of 13.6 m . The design was modified from Emmrich et al. (2010) and was constructed from $38.0 \mathrm{~mm}(1.5 ")$ and $19.0 \mathrm{~mm}(0.75$ ") netting with a 9.5 mm (3/8") knotless nylon liner in the cod-end. Mid-water doors ( $0.5 \mathrm{~m} \times 1.0 \mathrm{~m}$ ) were constructed from rolled aluminum and door spread was estimated from the observed distance between surface floats attached to the upper wing tips. The trawl was deployed using a single warp line and trawl depth was estimated from a known relationship between warp length and vessel speed. Onset level-loggers were attached to the foot-rope and head-line of the trawl to provide an estimate of the trawl mouth height.

Trawling depths were chosen by the acoustic survey crew to sample specific areas and layers where targets of interest were observed. The total trawl sampling volume (and area) was estimated from the observed vessel track and trawl duration. Detailed summary information on each trawling event (i.e., distance, sampling depth, etc.) can be found in Milne (2017). Trawl data were summarized by sector and season and the catch-per-unit-effort (CPUE) for each species was determined as \#/trawl area swept $\left(\mathrm{m}^{2}\right)$.

All fishes caught in the trawls were identified to species and counted. Total length (mm) and wet mass ( g ) were recorded for twenty fish of each species per trawl. If there were more than 20 fish of a species in the trawl, the remainder were counted, bulk weighed and the largest and smallest fish total length was recorded.

### 2.2.3 Hydroacoustics

Hydroacoustic data were collected using the BioSonics (BioSonics Inc., Seattle, WA) DTX echosounder system multiplexed with two split beam transducers ( $6.9^{\circ} \times 6.9^{\circ} 200 \mathrm{kHz}$ and $7.7^{\circ} \mathrm{X}$ $7.7^{\circ} 120 \mathrm{kHz}$ ); however, only data from the 200 kHz transducer were processed and evaluated for the present report. The transducer was mounted on a custom designed "dead-weight" tow body and deployed along-side the vessel at mid-ship to avoid hull cavitation and prop-wash. The downward-looking transducer and tow body was deployed approximately 1.0 m below the surface. GPS data were provided to the acoustic system from an external Garmin GPS Map 78s (Garmin Ltd., Olathe, KS). Parameter settings for data acquisition and detailed calibration information can be found in Milne (2017).

The hydroacoustic data were processed by Milne Technologies using Echoview processing software (Echoview Software Pty. Ltd., Hobart, Tasmania). The Milne (2017) report describes in detail the process for estimating fish density and biomass from echo integration; however, sections of this report have been incorporated into Appendix 1 to provide some background on the data processing approach. Echo integration estimates were derived for the data and
partitioned into six fish size classes. These general fish size class categories were chosen to standardize the size-stratified fish density estimates with previous DFO acoustic surveys (i.e. 2006 Hamilton Harbour and 2009/2010 Toronto Harbour surveys). Love's (1971a, 1971b) target strength model was used to estimate the equivalent target strength of the class limits for each of the six fish size categories. A description of the size composition of each class as well as a summary of the target strength and equivalent total length limits of the classes are summarized in Table 1.

Within each of the analysis sectors, the backscatter energy was integrated over the cruise track in 50 m segments or Elementary Distance Sampling Units (EDSUs). The results were binned into 1 m bins ( 1 m depth strata bins from the surface to the bottom) and also summed throughout the water column. These EDSU served as replicates within each sector for further analysis of differences among sectors.

Inspection of the 2016 acoustic survey echograms revealed the presence of gas bubbles throughout the water column of several transects, particularly in the summer and fall (Appendix 2). The bubbles appear within the echograms either as single targets or as stacked columns of individual targets extending up from the acoustically detected bottom. Gas bubbles are problematic for acoustics as they often share the same acoustic properties as small fish targets and therefore fish density estimates can be biased (Ostrovsky 2009). Two methods were used to detect and remove the acoustic backscatter that was caused by these bubbles and they are described in greater detail in Appendix 2.

### 2.3 DATA ANALYSIS

All analyses and data preparation were completed in R Studio (RStudio, Inc., Boston, MA).To explore spatial differences in fish distributions, we compared the distribution of fish encounters within a sector and season to a null hypothesis that fish were equally distributed across the entire sampling region across all seasons. Given that fish are typically not randomly distributed, this null was not necessarily expected, rather it serves as a benchmark from which to assess differences in fish distributions in the harbour. To accomplish this, the proportion of EDSU where fish were present within each sector and season was compared to the regional proportion of EDSU where fish were present using a Fisher's Exact test ( $\alpha=0.05$ for all tests). Additionally, a Generalized Additive Model (GAM) was applied to visualize spatial patterns in fish density throughout the harbour in all three seasons (implemented using the mgcv package (Wood 2018) with the following structure, Density~s(Longitude,Latitude)). These maps were then visually interpreted to provide additional evidence for apparent differences in fish distributions in the harbour.

A two-way analysis of variance (ANOVA) was used to compare fish biomass ( $\mathrm{g} / \mathrm{m}^{3}$ ) and density (number $/ \mathrm{m}^{3}$ ) among analysis sectors and seasons for the water column stratum (sum of 1 m depth bins). If a significant interaction in the omnibus test was detected ( $\alpha=0.05$ for all tests), a post-hoc Tukey-HSD was used to determine which components were significantly different. If no interacting effect was detected, the main effects for season and sector were tested independently using a pairwise comparison. Raw data were log transformed to meet the assumptions of normality and residuals were plotted to validate the model assumptions.

A potential caveat to the use of ANOVA is that the data violate a core assumption of parametric statistics in that they are spatially autocorrelated and are therefore not true independent replicates. Since data within each sector are collected along transects and, as noted, fish are generally not randomly distributed, adjacent EDSU are more likely to be similar than more
dispersed EDSU. As a result of this issue, results from this test should be interpreted with caution, particularly for more marginal $p$-values.

### 3.0 RESULTS

### 3.1 TEMPERATURE AND DISSOLVED OXYGEN PROFILES

There were clear changes in the temperature and DO profiles of each transect across seasons. Profiles in the spring were uniformly isothermal (mean temperature $8.11 \pm 0.52^{\circ} \mathrm{C}$, range 7.75 ${ }^{\circ} \mathrm{C}-8.52{ }^{\circ} \mathrm{C}$ ) with relatively consistent water temperatures and DO levels (at or near saturation) throughout the Harbour (Figure 3). Profiles in the summer showed the presence of a strong thermocline (mean depth of 8.3 m ) below which DO was rapidly depleted (Figure 3). Several stations (i.e., T6, T7, T10, 17B, and 18Z; Appendix 3) showed a DO spike at approximately 7.0 m . Finally, in the fall, shallow areas were once again isothermal with DO levels at or near saturation; however, a thermocline was still evident at deeper sites sitting between approximately 13.0-20.0 m (mean thermocline depth of 17.7 m ) with rapidly declining DO levels below this transition point (Figure 3).

### 3.2 MID-WATER TRAWLING

Due to weather conditions, equipment issues and other factors, nighttime trawling effort was not consistent across seasons and ranged from a total of 20 trawls in the spring to 30 trawls in the fall (Table 2). All designated trawling transects were run at least once each season, with the exception of one transect in the N sector in the spring. When time allowed, some of the trawl transects were re-run to provide information on variability. This additional trawling, combined with differences in the number of designated trawls per analysis sector established in the sampling design, resulted in higher levels of areal sampling in the NE and SC sectors (Figure 4). The depths at which the mid-water trawl was deployed varied throughout the survey and ranged from 1.0 to 14.0 m , with the bulk of fishes generally caught in moderate depths ( 7.0 to 9.0 m ) in the spring and fall and at shallower depths ( 1.0 to 3.0 m ) in the summer (data not shown).

Just over $83 \%$ of the total catch ( $\mathrm{N}=3609$ ) occurred in the summer while the spring yielded under $2 \%$ of the total. These differences were still evident when overall catch was converted to CPUE, with the highest CPUE's recorded in the summer SC and NE sectors and the lowest in the spring N sector. A total of 16 species were caught during the survey with richness ranging from 5 in the spring to 12 in the summer and fall. Within each season, the largest number of species was consistently found in the SC sector, while the lowest number was found in the N sector, which could be related to sampling intensity in addition to other habitat factors (Table 2).

Alewife (Alosa pseudoharengus) had the highest rates of capture across all sectors in the summer and in the NE and SC sectors in the fall (Table 3; Figure 5). In the summer and fall, Brown Bullhead (Ameiurus nebulosus) contributed 24\% of the relative percentage of CPUE to the W sector while Round Goby (Neogobius melanostomus) contributed approximately 30\% in the N sector. While some of the Round Goby caught in Hamilton Harbour were a result of the mid-water trawl coming in close contact with the bottom, we also found pelagic juveniles in our trawls. In the spring, relative CPUE percentages were dominated by Emerald Shiner (Notropis atherinoides) and Rainbow Smelt (Osmerus mordax), although total catches were lower than the other seasons.

Aside from a 547 mm Walleye (Sander vitreus) captured in the N sector during the summer, all
other fishes were less than 200 mm total length (Table 3), which is consistent with previous findings of net avoidance by larger fishes (Binion et al. 2008). Based on TL, the fishes that were caught were generally either YOY or juveniles, although most Emerald Shiners caught over the three seasons were adults. There were few other adult fish captured but they included Alewife in the spring, White Perch in the summer and fall and Rainbow Smelt over all three seasons.

### 3.3 HYDROACOUSTICS

There was considerable variability in effort across seasons and among analysis sectors with a low of 51 EDSU in the W sector in the fall to a high of 372 in the NE sector, also in the fall (Table 4). Fish were detected in significantly more EDSU in SC in the fall and W in the summer and fewer EDSU in N and NE in the spring and NE in the fall compared to the regional frequency (Fisher's Exact, $p<0.05$; Table 4; Figure 6). Outside of these five cases, results suggest few differences in the distribution of fishes although there was a relatively high proportion of fish in EDSU in the W and N sectors in the fall ( 0.96 and 0.95 , respectively), which were not deemed to be significantly different from regional predictions.

ANOVA suggested that there were significant differences among seasons and sectors and their interaction both in terms of mean fish density (Season: $F_{(2)}=29.9, p<0.0001$; Sector: $F_{(3)}=84.2$, $p<0.0001$; Interaction: $F_{(6)}=9.6, p<0.0001$ ) and biomass (Season: $F_{(2)}=10.5, p<0.0001$; Sector: $F_{(3)}=81.5, p<0.0001$; Interaction: $F_{(6)}=14.6, p<0.0001$. A post-hoc Tukey HSD test found that mean fish density and biomass in the W sector in the summer and fall were significantly higher than all other sector and season combinations (Figures 7 and 8 ). While more subtle differences in density and biomass among sectors and seasons were also detected, given the caveats discussed previously for this statistical approach, these subtle differences are not discussed further.

When the data were broken down by size class, the majority of the density tended to be within size classes 1 and $2(<82 \mathrm{~mm}, \mathrm{TL})$ and to a lesser extent 3 and 4 ( $82-250 \mathrm{~mm}$, TL; Figure 9; Appendix 4 Table A4.1). In contrast, biomass tended to be dominated by fish in size group 4 or larger (> 130 mm , TL; Figure 10; Appendix 4 Table A4.2). There were as a result more seasonal changes apparent in the biomass data than the density data. Specifically, large fish (>500 mm, TL ) were not detected during the summer surveys and were also not detected in N and SC in the spring and $W$ in the fall. When these individuals were absent, most of the biomass was made up of size class 4 fishes and, to a lesser extent, size 5 fishes (Figure 10).

Seasonal and spatial differences in nighttime fish density and biomass through the whole water column were also apparent when the EDSU data were mapped (Figures 11 and 12). Areas of high density and biomass were evident in the W sector as well as along the border between the NE and SC sectors in the fall. Additionally, variability in density and biomass were also apparent within the analysis sectors. This was particularly evident in the W sector during the spring and summer when fish densities were notably lower in the eastern portion of the W sector (covers the deeper part of the sector) relative to the western portion of this sector (adjacent to shallower waters; Figure 11). A similar pattern was also evident in SC in the fall, with higher densities in the south-eastern portion of the sector (Figure 11). In terms of biomass, EDSU estimates greater than $5.0 \mathrm{~g} / \mathrm{m}^{3}$ were generally infrequent and were likely driven by rare detections of large fish (i.e., size class 6).

The vertical distribution of the average estimated nighttime fish density was strongly dependent on available dissolved oxygen. The highest average fish densities in the summer surveys, in all analysis sectors, were observed within the 4.0 to 8.0 m stratum and closely associated with the
mean estimated thermocline (Figure 13a-d). One notable exception to this pattern was found in the SC sector, where there was a surprising peak in fish density well below the thermocline at $\sim 23.5 \mathrm{~m}$. The average fish density estimates for the fall survey period was highest within the 8.0 to 18.0 m depth zones in the SC, W, and NE, but slightly higher in the water column in the N sector (Figure 13a-d). In contrast to the summer and fall, fish were more evenly distributed throughout the available water column during the spring surveys, with the exception of deeper waters in NE.

The GAMs were highly significant for each season (Spring F=6.2, p<0.0001; Summer F=11.9, p<0.0001; Fall F=7.3, p<0.0001) and explained 19\% (Spring and Fall) and 34\% (Summer) of the deviance. Standardizing the z-axis emphasizes the peak in fish density that is present in the western part of the harbour during the summer (Figure 14). This region is also an area of high fish density during the spring and fall; however, the magnitude is lower and a comparable second peak is present in the fall in the south-eastern part of the harbour (Windermere Arm, a portion of the SC sector; Figure 14).

### 4.0 DISCUSSION

Surveys conducted in 2016 demonstrate the stark seasonal and spatial differences in the density and biomass of pelagic fishes in Hamilton Harbour. By assessing density and biomass as a function of volume of water surveyed, we were able to partially standardize survey effort in areas with different water depths and therefore compare among seasons and sectors. The western portion of the harbour generally had the highest density and biomass estimates; this trend was most apparent in the summer and fall. This peak in the western sector suggests that biomass of pelagic fishes is not equally distributed throughout the harbour. In a regional context, similar data were collected in the Toronto and Region AOC in the fall of 2016. While these data cannot be directly compared because they were collected during the day (fish were predominantly in schools), they suggest that the observed mean biomass and densities of pelagic fish in Hamilton Harbour are comparable to some of the open coast areas in Toronto, but well below values observed in Inner and Outer Toronto Harbour (Midwood et al. 2018). It is important to note, that fish were found at a lower proportion of EDSU in the daytime Toronto surveys ( 0.42 overall) than in the nighttime Hamilton Harbour surveys ( 0.89 overall). This is an indication of schooling behaviour since fish aggregated in schools are less likely to occur in an one EDSU. Aggregations of fish in schools may also artificially increase the mean values for biomass and density since a single large school will have a disproportionate influence on the ultimate mean estimates for each analysis sector. Regardless, future nighttime surveys in other parts of Lake Ontario would help place the current surveys in a regional context and control for potential differences in fish distribution and aggregation between day and night surveys.

### 4.1 MID-WATER TRAWLING

Trawl data were primarily collected to support the interpretation of the hydroacoustic data (i.e., linking observed fish traces to species or size groups); however, they also provide a means to compare capture rates among sectors and the associated species composition. In general, species captured during trawling have been characterized as either tolerant or mesotolerant to anoxia ( R . Tang, pers. comm.), which is consistent with the observed conditions in the harbour, particularly in the summer and fall. From a species-richness perspective, the SC consistently had the highest richness across all seasons, followed closely by the NE sector. This difference was most evident in the summer and may be partially explained by the amount of area surveyed in each sector. While efforts were made to standardize capture by effort, richness was not
adjusted for sampling effort and the apparent differences in richness are likely a function of increased effort (effectively a standard species-area relationship; Arrhenius 1921).

When effort was standardized, there was generally low CPUE of fishes in spring as well as in the W and N sectors across all seasons with peaks in overall summer CPUE primarily driven by catch in the NE and SC sectors. This spike in summer CPUE was driven by high rates of capture of YOY Alewife in the NE and SC sectors. YOY of this species typically remain close to their nursery grounds and in more protected areas until they have reached a sufficient size to move into deeper pelagic waters (Scott and Crossman 1998). High rates of capture of Alewife during the late summer are consistent with results from Toronto Harbour, and suggests that Hamilton Harbour similarly provides important nursery habitat for this species prior to their movement into Lake Ontario. Catch of YOY Gizzard Shad also peaked during the summer (albeit at lower levels than Alewife), which is an encouraging sign since early life stages of both of these species are important forage fishes for commercial and recreationally valuable piscivores (Scott and Crossman 1998).

There was some evidence for a shift in the fish community in analysis sectors across seasons. This was most apparent in the W sector with a decline in the proportional capture of Alewife from the summer to fall and an increase in Gizzard Shad during this period. Novel, more littoral species (i.e., Goldfish and Brown Bullhead) also appeared in the fall trawl surveys in the W sector, suggesting that either fall conditions in this sector are less favourable for YOY pelagic fishes as they grow (i.e., warmer temperatures) and/or the deeper position of the oxycline in the fall allows pelagic fishes to use deeper waters of the harbour (generally found in the NE and SC sectors). Low catch in the W sector makes it challenging to make strong conclusions related to the drivers behind seasonal changes in the fish community. This sector is adjacent to productive littoral habitats (i.e., Cootes Paradise, Bayfront Park) and the presence of littoral fishes may be related to a spill-over effect from these areas. Alternately, the periodic presence of harmful algal blooms in the shallow waters of the W sector may push typically littoral fishes into deeper waters where they may be encountered by the mid-water trawling gear.

Some other key pelagic forage fishes were captured during trawling including Rainbow Smelt, which were primarily captured in the spring and, based on the mean sizes, were likely adults that had or were preparing to spawn (timing window is March-May) and Emerald Shiner, which were found (albeit in low numbers) across all seasons, but were more dominant in the catch during the spring. Two non-native fishes were also frequently encountered: White Perch, which were mostly adults captured in the spring and fall, and Round Goby, a benthic species. The presence of benthic Round Goby, which do not possess a swim bladder, in mid-water trawl nets is somewhat surprising; however, the majority of captured individuals were juveniles and previous works have suggested that these smaller individuals can be encountered in pelagic waters (Hayden and Miner 2009). Occasionally larger individuals that should be restricted to benthic habitats were captured, and this suggests that in some instances the mid-water trawl may have come close to (allowing capture of benthic fish swimming just above the bottom) or in contact with benthic substrates.

### 4.2 HYDROACOUSTICS

Lower than expected encounter probabilities of fish in the spring in N and NE and higher than expected levels in the fall (SC) and summer (W) support a non-random distribution of pelagic fish within the harbour across seasons (and during our surveys in particular). This non-random distribution is further confirmed based on clear differences in density and biomass among sectors and seasons and through a visual interpretation of the GAMs. Particularly for the
summer and fall it is clear that there is higher pelagic fish density and biomass per volume in the western portion of the harbour. There was also a general increase in density and biomass from the spring to the summer, but the summer to fall pattern was less consistent and often not deemed significantly different. This is consistent with the spawning ecology of many of the pelagic fish that were encountered, with their core spawning window in the spring and early summer, and the appearance of their YOY in the pelagic waters of the harbour in the late summer into the early fall (as documented in the trawl data).

The observed peaks in density and biomass of fishes in the western part of the harbour align with acoustic telemetry results that show this part of the harbour frequently falls within the core ranges for top predators (i.e., Walleye, Northern Pike, Largemouth Bass, Midwood, unpublished data). It is therefore likely that pelagic fishes are keying in on available abundant plankton productivity in the western portion of the harbour (Bowen and Currie 2017) and the top predators are targeting these aggregations of prey fish.

There were clear changes in the vertical distribution of fishes across seasons and we attribute this largely to changes in the depth of the thermocline and associated oxycline. Anoxia is a wellestablished issue in Hamilton Harbour (Bowlby et al. 2016), and its influence on the vertical distribution of fishes was evident during both the summer and fall surveys. Since waters below the thermocline were typically anoxic ( $<3 \mathrm{mg} / \mathrm{L}$ ), we expect that this was likely the main factor in structuring the depth distribution of pelagic fishes. Indeed the most vertically restricted season was the summer, with the vast majority of fish density occurring above the thermocline (generally between $7.0-8.5 \mathrm{~m}$ depth). While there were certainly instances where fish were present below the thermocline, this may partially be due to differences in thermocline and oxycline depths as well as differences among survey transects in the depth at which DO fell below $3 \mathrm{mg} / \mathrm{L}$ (oxycline does not necessarily fall at the thermocline and during the summer was typically 1.0-2.0 m below the thermocline). Wind induced epilimnetic mixing within the fall survey period pushed the thermocline to at or below 12.0 m , thus providing more pelagic habitat for fish and the resulting shift in the vertical distribution of fish supports this change in thermocline position as a driving factor.

Large fish ( $>500 \mathrm{~mm}$ ) were absent from the summer surveys (also absent from N/SC in spring and W in fall), which may be driven by restricted water depths caused by anoxia (i.e., only a small volume of water is available and this is focused near the surface). With oxygen rich waters only available near the surface during the summer, and to a lesser extent the fall, this may increase the potential for avoidance by larger fishes of the survey vessel and therefore reduce the probability of measuring large fish in the hydroacoustic surveys. The apparent absence of large fishes should therefore not be deemed conclusive from these sectors and ongoing tracking of large fishes using acoustic telemetry suggests they are present in all analysis sectors during the summer (Midwood, unpublished data). Collectively, changes in the vertical distribution of fish and absence of large fishes provides an indication of how anoxia can influence the spatial ecology of fish and how the dynamic nature of the thermocline/oxycline can result in changes in available fish habitat across seasons.

### 4.3 DIFFERENCES TO PAST SURVEYS

Future efforts should aim to integrate the current results with other hydroacoustic surveys that have been undertaken in Hamilton Harbour (2006) and other regions in western Lake Ontario (i.e., Bronte Harbour 2010, Toronto Harbour 2009, 2010, 2016, open coast areas). It is important to identify some of the adjustments made in the present survey that may affect comparisons. As previously noted, differences in the timing of the surveys (day/night) may
preclude comparisons with past efforts in Toronto Harbour, Bronte Harbour, and the open coast of Lake Ontario. The majority of these surveys were undertaken during the day and pelagic fishes were therefore mostly found in schools. While daytime surveys are safer and easier to undertake, their estimates of density and biomass can be biased as a result of school shadowing (Appenzeller and Leggett 1992) and may be lower than nighttime estimates. Past surveys in Hamilton Harbour have been undertaken during both the day and night; therefore there is the potential for a direct comparison of estimates from the present study with some of the data collected in 2006. An additional variant for day and night surveys is that while fish are more dispersed at night, they may also be closer to the surface and therefore outside of the detection zone of the hydroacoustics as they were setup for the present study. This may partially explain apparent differences in estimated density and biomass between Toronto and Hamilton. Determining the number of fish in surface waters during night surveys is an important future step to ensure night surveys are accurately depicting local conditions.

The biggest change from past surveys was the use of a mid-water trawl instead of a benthic trawl. This change was made due to safety issues with the use of a benthic trawl in a harbour (likely to catch or rip on submerged objects) and the desire to capture a sample of the fish community that was completely ensonified by the acoustic beam (instead of benthic trawls that capture fish that fall within the acoustic "dead-zone" that is just above the bottom substrates). Trawl effort was also different in 2016 (time-based) relative to the 2006 surveys (distance based), but this change is of less importance to the shift in gear, which effectively precludes any comparison of species composition between the two time periods.

### 4.4 FUTURE WORK

Given the breadth of ongoing water chemistry, primary production, and fisheries assessments in Hamilton Harbour, there are numerous opportunities to integrate the present results with other datasets. As noted previously, a comparison should be made between nighttime hydroacoustics data collected in 2006 and those presented in this report. In the intervening 10 years there have been considerable efforts to improve conditions in the harbour and also a successful stocking program for Walleye. Assessing whether there have been changes in the pelagic fish community during this time period will therefore be of great interest to both the RAP and as a potential measure of the influence of the reintroduction of a previously extirpated top-predator on the pelagic prey fish community.

Surveys of water chemistry and primary (phytoplankton) and secondary (zooplankton) production were undertaken by the Freshwater Ecosystem Research Lab at GLLFAS at similar times as the present fish hydroacoustic work (Bowen and Currie 2017; Currie et al. 2018; Munawar et al. 2018). Merging these two datasets would allow for an exploration of some potential drivers of the observed differences in fish density and biomass (i.e., limnological and biological habitat) among seasons and analysis sectors. Similarly, the present dataset could be merged with nearshore ( $<1.5 \mathrm{~m}$ ) electrofishing surveys undertaken by GLLFAS across all three seasons to determine whether pelagic production estimates are correlated to nearshore production.

The results from the present study can also be linked to data from the Hamilton Harbour acoustic telemetry project to determine whether there are associations with the core range of tagged fishes (i.e., Walleye, Northern Pike, and Largemouth Bass) and seasonal changes in the spatial distribution of pelagic fishes.

Finally, there are two main changes to the overall approach used in the present report that are recommended. First, the use of a quieter vessel may reduce vessel avoidance, particularly in larger fishes. The Great Lakes Laboratory for Fisheries and Aquatic Sciences has recently acquired a new smaller vessel (R.V. Cisco) that use jet propulsion. This alternate propulsion method is quieter and an evaluation of the extent of avoidance of this vessel should be undertaken. Second, the analysis unit used for this study was the EDSU and this resulted in a skewed dataset (a factor that is even more exaggerated when daytime surveys are undertaken, see Midwood et al. 2018). A re-evaluation of the size (length) of the analysis unit is therefore warranted as it would likely reduce the skewness of the dataset and make the application of parametric statistics more appropriate.

### 4.5 CONCLUSIONS

The major objective of this study was to document the spatial distribution of pelagic fish density and biomass in the harbour and results indicate there is an unequal distribution of pelagic fish with higher density and biomass in the western portion of the harbour. These results may partially explain similar spatial patterns for littoral fishes (which are primarily the target for the RAP) as top predators are reliant on forage fish and therefore likely to track their distribution within the harbour. Assessments of primary productivity in the harbour also suggest spatial differences that are consistent with the observed patterns in pelagic fish density and biomass. If desirable, unequal patterns in fish distributions may therefore be hard to remedy without first equalizing the location and source of primary production (which is in turn linked to nutrient inputs) and resolving issues with hypolimnetic anoxia. This clear spatial pattern in trophic structure also likely warrants further exploration as it pertains to assessments of fish communities in the harbour. Specifically, it may be beneficial to break whole-system assessments into regions to highlight areas of the harbour that are driving the documented lack of change in a fish-based index of biotic integrity (Boston et al. 2016) and dominance of primarily eutrophic fishes. We also documented a strong influence of anoxia on fish vertical distributions in the summer and fall, which likely contributes to their structuring throughout the harbour. Linking the present data to a more detailed empirical study of oxygen dynamics that is currently underway will help to quantify the changes in pelagic habitat, and consequently fish productivity, in the harbour across seasons. Finally, in the present study we did not link density and biomass estimates from Hamilton Harbour to other regions in Lake Ontario, other than to descriptively compare conditions to those documented during day surveys in Toronto Harbour (with many caveats). This form of comparison will be critical for assessing the condition of pelagic fish stocks in Hamilton Harbour as well as for determining their potential for supporting higher trophic fishes in the numbers required to meet delisting targets.

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Table 1. A summary and description of the six fish size categories used to partition the observed integrated acoustic backscatter. The size partition limits are the total length (mm) and equivalent target strength (TS) estimated from Love's (1971a, 1971b) generalized fish length equation.

| Size <br> Class | Min <br> TLEN <br> $(\mathrm{mm})$ | Max <br> TLEN <br> $(\mathrm{mm})$ | Min TS <br> $(\mathrm{dB})$ | Max <br> TS <br> $(\mathrm{dB})$ |
| :--- | :--- | :--- | :--- | :--- |
| 1 | 29 | 58 | -55.00 | -49.43 |
| 2 | 58 | 82 | -49.43 | -46.56 |
| 3 | 82 | 130 | -46.56 | -42.73 |
| 4 | 130 | 250 | -42.73 | -37.31 |
| 5 | 250 | 500 | -37.31 | -31.56 |
| 6 | 500 | 1200 | -31.56 | -24.12 |

Table 2. Summary of the effort and results for nighttime trawling in Hamilton Harbour in 2016 by season and analysis sector. The depth of the mid-water trawls varied throughout the survey. An indication of the distribution of fish catches is included with the trawl depths where ' indicate catches > 30\% and * > $50 \%$ of the total fishes within each analysis sector. Catch per unit effort was calculated by dividing the total number of fish caught within the sector by the total trawl area swept ( $\mathrm{m}^{2}$ ), including those trawls where no fish were caught.

|  | Analysis Sector | \# of Trawls | \# Trawls Without Fish | Approximate Trawl Depths (m) | \# of Fish Caught | CPUE ( $\mathrm{m}^{2}$ ) | Species Richness |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | N | 2 | 1 | 7, 9* | 1 | 0.0003 | 1 |
|  | NE | 7 | 2 | 1, 4, 6, 7, 8, 8', 8' | 13 | 0.0011 | 4 |
|  | SC | 8 | 1 | 4, 6, 6, 7, 7', 8, 8, 10 | 20 | 0.0015 | 5 |
|  | W | 3 |  | $3^{*}, 3,5$ | 34 | 0.0071 | 4 |
|  | All | 20 | 4 |  | 68 | 0.0020 | 5 |
| 品品 | N | 3 |  | 3', 5, 7' | 75 | 0.0139 | 5 |
|  | NE | 11 |  | 1', 1, 1, 1, 3, 3, 5, 5, 9, 9, 9 | 1357 | 0.0715 | 8 |
|  | SC | 8 | 1 | 1, 1, 2*, $3,5,9,9,9$ | 1532 | 0.0989 | 9 |
|  | W | 4 | 1 | 3, 5, 5, 5 | 51 | 0.0093 | 5 |
|  | All | 26 | 2 |  | 3015 | 0.0665 | 12 |
| لـ | N | 4 | 1 | 3, 9', 9*, 11 | 25 | 0.0031 | 5 |
|  | NE | 11 | 1 | 1, 1, 1, 3, 3, 3, 5, 7, 9, 9, 11 | 142 | 0.0072 | 7 |
|  | SC | 12 |  | 2, 5, 7, 7, 9', 9, 9, 11, 11, 11, 11, 14 | 334 | 0.0156 | 7 |
|  | W | 3 | 1 | $3^{*}, 5,7$ | 25 | 0.0060 | 7 |
|  | All | 30 | 3 |  | 526 | 0.0098 | 12 |
| Grand Total |  | 76 | 9 |  | 3609 | 0.0273 | 16 |

Table 3. Summary of the nighttime trawl catches in Hamilton Harbour in 2016 by species, season and analysis sector. Included is the mean total length ( mm ) and standard deviation for up to 20 fishes of each species caught in the trawl. Range of fish size includes all fishes caught; either from the individual fishes that were measured or fishes from the bulk counts as applicable.

\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline \& SPECIES \& \multicolumn{3}{|l|}{NORTH} \& \multicolumn{3}{|l|}{NORTHEAST} \& \multicolumn{3}{|l|}{SOUTH CENTRAL} \& \multicolumn{3}{|l|}{WEST} \\
\hline \[
\begin{aligned}
\& \grave{V} \\
\& \frac{\underset{\alpha}{\alpha}}{\substack{N}}
\end{aligned}
\] \& \begin{tabular}{l}
Alewife \\
Emerald Shiner \\
Rainbow Smelt \\
Round Goby \\
White Perch
\end{tabular} \& 1 \& 85 \& \& \[
\begin{aligned}
\& 6 \\
\& 4 \\
\& 1 \\
\& 2
\end{aligned}
\] \& \[
\begin{aligned}
\& 88 \pm 15 \\
\& 93 \pm 20 \\
\& 30 \\
\& 105 \pm 13
\end{aligned}
\] \& \[
\begin{aligned}
\& 58-100 \\
\& 74-120 \\
\& 96-114
\end{aligned}
\] \& \[
\begin{aligned}
\& 1 \\
\& 4 \\
\& 8 \\
\& 4 \\
\& 3
\end{aligned}
\] \& \[
\begin{aligned}
\& 132 \\
\& 94 \pm 4 \\
\& 95 \pm 24 \\
\& 29 \pm 2 \\
\& 85 \pm 9
\end{aligned}
\] \& \[
\begin{aligned}
\& 89-99 \\
\& 72-132 \\
\& 27-31 \\
\& 75-91
\end{aligned}
\] \& \[
\begin{aligned}
\& 6 \\
\& 2 \\
\& 25 \\
\& 1
\end{aligned}
\] \& \[
\begin{aligned}
\& 139 \pm 30 \\
\& 98 \pm 8 \\
\& 81 \pm 12 \\
\& 36
\end{aligned}
\] \& \[
\begin{aligned}
\& 108-193 \\
\& 93-104 \\
\& 57-113
\end{aligned}
\] \\
\hline  \& \begin{tabular}{l}
Alewife \\
Bluegill \\
Brook Silversides \\
Brown Bullhead \\
Chinook Salmon \\
Emerald Shiner \\
Gizzard Shad \\
Notropis sp \\
Rainbow Smelt \\
Round Goby \\
Three Spine Stickleback \\
Walleye \\
White Perch
\end{tabular} \& \begin{tabular}{l}
46 \\
1 \\
21 \\
1 \\
6
\end{tabular} \& \begin{tabular}{l}
\(58 \pm 13\) \\
40 \\
\(24 \pm 7\) \\
547 \\
\(146 \pm 8\)
\end{tabular} \& \[
24-75
\]
\[
11-49
\]
\[
136-159
\] \& \begin{tabular}{l}
4 \\
10 \\
64 \\
2 \\
6 \\
1 \\
10
\end{tabular} \& \[
\begin{aligned}
\& 57 \pm 16 \\
\& 37 \pm 3 \\
\& \\
\& 84 \pm 14 \\
\& 47 \pm 10 \\
\& 92 \pm 60 \\
\& 25 \pm 6 \\
\& 30 \\
\& 140 \pm 27
\end{aligned}
\] \& \[
\begin{aligned}
\& 19-172 \\
\& 34-42 \\
\& 47-97 \\
\& 36-88 \\
\& 50-135 \\
\& 19-32 \\
\& 75-164
\end{aligned}
\] \& \begin{tabular}{l}
1270 \\
1 \\
1 \\
1 \\
249 \\
1 \\
4 \\
1 \\
4
\end{tabular} \& \begin{tabular}{l}
\(49 \pm 17\) \\
89 \\
165 \\
85 \\
\(45 \pm 8\) \\
40 \\
\(50 \pm 18\) \\
30 \\
\(120 \pm 32\)
\end{tabular} \& \[
\begin{aligned}
\& 23-87 \\
\& \\
\& 32-71 \\
\& 24-63 \\
\& 76-154
\end{aligned}
\] \& \begin{tabular}{l}
28 \\
4 \\
12 \\
4 \\
3
\end{tabular} \& \[
\begin{aligned}
\& 48 \pm 22 \\
\& 30 \pm 10 \\
\& 139 \pm 26 \\
\& \\
\& 24 \pm 1 \\
\& \\
\& 132 \pm 15
\end{aligned}
\] \& \[
21-92
\]
22-42
114-197
\[
23-26
\]
\[
119-149
\] \\
\hline \[
\frac{\underset{1}{4}}{\stackrel{1}{4}}
\] \& \begin{tabular}{l}
Alewife \\
Bluegill \\
Brown Bullhead \\
Emerald Shiner \\
Gizzard Shad \\
Goldfish \\
Rainbow Smelt \\
Round Goby \\
Rudd \\
Spottail Shiner \\
Three Spine Stickleback \\
White Perch
\end{tabular} \& \begin{tabular}{l}
7 \\
7 \\
2 \\
8 \\
1
\end{tabular} \& \[
\begin{aligned}
\& 53 \pm 12 \\
\& 87 \pm 25 \\
\& 73 \pm 2 \\
\& 25 \pm 5 \\
\& 58
\end{aligned}
\] \& \[
\begin{aligned}
\& 28-63 \\
\& 32-100 \\
\& 71-74 \\
\& 21-35
\end{aligned}
\] \& \begin{tabular}{l}
117 \\
1 \\
9 \\
1 \\
4 \\
9 \\
1
\end{tabular} \& \[
\begin{aligned}
\& 80 \pm 23 \\
\& 60 \\
\& 91 \pm 15 \\
\& 95 \\
\& 59 \pm 47 \\
\& 25 \pm 7 \\
\& 89
\end{aligned}
\] \& \(33-120\)
\(63-107\)

$35-130$

$18-37$ \& | 306 |
| :--- |
| 4 |
| 6 |
| 3 |
| 4 |
| 7 |
| 4 | \& \[

$$
\begin{aligned}
& 58 \pm 17 \\
& 59 \pm 27 \\
& 68 \pm 25 \\
& 108 \pm 60 \\
& \\
& 114 \pm 49 \\
& 27 \pm 6
\end{aligned}
$$
\]

$$
154 \pm 36
$$ \& \[

$$
\begin{aligned}
& 28-160 \\
& 39-99 \\
& 39-101 \\
& 60-176 \\
& 41-140 \\
& 19-39
\end{aligned}
$$
\]

116-199 \& | $2$ |
| :--- |
| 6 |
| 1 |
| 9 |
| 1 |
| 5 |
| 1 | \& \[

$$
\begin{aligned}
& 46 \pm 2 \\
& 143 \pm 47 \\
& 59 \\
& 91 \pm 15 \\
& 60 \\
& \\
& 25 \pm 6 \\
& 62
\end{aligned}
$$

\] \& \[

$$
\begin{aligned}
& 45-48 \\
& 75-200 \\
& 76-120 \\
& 19-33
\end{aligned}
$$
\] <br>

\hline
\end{tabular}

Table 4. Summary of the effort within each analysis sector for the hydroacoustic surveys completed in the Hamilton Harbour AOC in 2016. The number of Elementary Distance Sampling Units (EDSUs) where fish were present or absent are presented.

| Analysis <br> Sector | Season | Total <br> EDSU | Fish <br> Present | Absent | Proportion with <br> Fish |
| :--- | :--- | :--- | :--- | :--- | :--- |
| N | spring | 72 | 52 | 20 | 0.72 |
|  | summer | 80 | 72 | 8 | 0.90 |
| NE | fall | 165 | 157 | 8 | 0.95 |
|  | spring | 125 | 97 | 28 | 0.78 |
|  | summer | 216 | 201 | 15 | 0.93 |
| SC | fall | 372 | 308 | 64 | 0.83 |
|  | spring | 208 | 188 | 20 | 0.90 |
|  | Summer | 213 | 187 | 26 | 0.88 |
| W | fall | 286 | 277 | 9 | 0.97 |
|  |  | spring | 62 | 55 | 7 |
|  |  |  |  |  |  |
|  | summer | 70 | 69 | 1 | 0.89 |
|  | fall | 51 | 49 | 2 | 0.99 |
|  | Total |  | 1920 | 1712 | 208 |



Figure 1. Location of the Hamilton Harbour AOC within Lake Ontario is shown in the top panel. The target sampling location for each transect (both trawling and hydroacoustics) is shown in the bottom panel. As noted in Figure 2, there were slight seasonal differences between the the target transect path and the path completed during each season. The littoral zone ( $<2 \mathrm{~m}$ ) is shown in dark brown and the survey area ( $>5 \mathrm{~m}$ ) in shades of blue.


Figure 2. Locations of the analysis sectors and dissolved oxygen and temperature (DOT) profiles in the Hamilton Harbour AOC are shown in the top left panel. Completed transects for the fish hydroacoustics in each season are shown in the remaining panels with sampling regions highlighted in yellow denoting the sections used for analysis (EDSU) and the red lines denoting where mid-water trawling was undertaken (either concurrent with the hydroacoustics or during a separate survey). The littoral zone ( $<2 \mathrm{~m}$ ) is shown in dark brown and the survey area ( $>5 \mathrm{~m}$ ) in shades of blue.


Figure 3. Temperature (red) and dissolved oxygen (blue) profiles for Hamilton Harbour fish hydroacoustic transects averaged by depth for each season. The solid lines denote the mean value at each depth and the shade areas cover $\pm$ two standard deviations. Horizontal dotted lines represent the estimated mean depth of the thermocline based on the thermo.depth function in the rLakeAnalyzer package. Vertical lines represent $6 \mathrm{mg} / \mathrm{L}$ (solid line) and $3 \mathrm{mg} / \mathrm{L}$ (dashed line) of dissolved oxygen to aid interpretation.


Figure 4. Variation in nighttime trawl area swept by season and analysis sector for the 2016 Hamilton Harbour hydroacoustic and trawling survey.


Walleye
$\square$ Spotail Shiner
$\square$ Rudd
Notropis sp
Goldfish
Chinook Salmon
Brook Silversides
Three Spine Stickleback
Gizzard Shad
Brown Bullhead
Bluegill
White Perch
Round Goby
Rainbow Smelt
Emerald Shiner
Alewife

Figure 5. Relative percentage of CPUE by species, season and analysis sector from nighttime trawling in Hamilton Harbour in 2016. The numbers above each bar represent the total catch by sector.


Figure 6. Difference between the regional and sector/season-based proportions of EDSU where fish were detected using 2016 Hamilton Harbour hydroacoustic data. Bar colour represents season where yellow $=$ spring, green $=$ summer, and orange $=$ fall. Asterixes denote deviations from the regional proportion (0.89; Table 4) that were significantly different based on a Fisher's Exact test where ${ }^{*} p<0.05,{ }^{* *} p<0.01,{ }^{* * *} p<0.001,{ }^{* * * *} p<0.0001$


Figure 7. Mean density $\left(\# / m^{3}\right)$ for each analysis sector and season. Colours denote the seasons where yellow = spring, green = summer, and orange = fall. Error bars show the standard deviation.

Hamilton Harbour Fish Biomass


Figure 8. Mean biomass $\left(\mathrm{g} / \mathrm{m}^{3}\right)$ for each analysis sector and season. Colours denote the seasons where yellow $=$ spring, green $=$ summer, and orange $=$ fall. Error bars show the standard deviation.


Figure 9. Proportion of density in each analysis sector by size class for each season. Colours denote the mean values for each size class where: light blue = size class 1 ( $29-58 \mathrm{~mm}$, Total Length, TL), dark blue = size class $2(58-82 \mathrm{~mm}, \mathrm{TL})$, light green $=$ size class $3(82-130 \mathrm{~mm}$, $\mathrm{TL})$, dark green $=$ size class $4(130-250 \mathrm{~mm}, \mathrm{TL})$, light red $=$ size class $5(250-500 \mathrm{~mm}, \mathrm{TL})$, and dark red = size class $6(500-1200 \mathrm{~mm}, \mathrm{TL})$. Analysis sectors are $\mathrm{N}=$ North, $\mathrm{NE}=$ Northeastern, $\mathrm{SC}=$ South-central, and $\mathrm{W}=$ West and seasonal abbreviations are: $\mathrm{Sp}=$ spring, $\mathrm{Su}=$ summer, and $\mathrm{Fa}=$ fall.


Analysis Sector
Figure 10. Proportion of biomass in each analysis sector by size class for each season. Colours denote the mean values for each size class where: light blue = size class 1 ( $29-58 \mathrm{~mm}, \mathrm{TL}$ ), dark blue $=$ size class $2(58-82 \mathrm{~mm}, \mathrm{TL})$, light green $=$ size class $3(82-130 \mathrm{~mm}, \mathrm{TL})$, dark green $=$ size class 4 (130-250 mm, TL), light red = size class 5 ( $250-500 \mathrm{~mm}, \mathrm{TL}$ ), and dark red = size class 6 (500-1200 mm, TL). Analysis sectors are N = North, NE= Northeastern, SC = Southcentral, and $\mathrm{W}=$ West and seasonal abbreviations are: $\mathrm{Sp}=$ spring, $\mathrm{Su}=$ summer, and Fa = fall.


Figure 11. 2016 echo integration estimates of nighttime fish density within Hamilton Harbour across seasons. Shown is the spatial distribution of the estimated fish density (numbers $/ \mathrm{m}^{3}$, with total length $>2.9 \mathrm{~cm}$ ) through the water column (sum of 1 m bins) for each 50 m EDSU.


Figure 12. 2016 echo integration estimates of nighttime fish biomass within Hamilton Harbour across seasons. Shown is the spatial distribution of the estimated fish biomass ( $\mathrm{g} / \mathrm{ha}$, with total length $>2.9 \mathrm{~cm}$ ) through the water column (sum of 1 m bins) for each 50 m EDSU.


Figure 13a. Vertical distribution of fish density for the North sector from the 2016 Hamilton Harbour acoustic surveys generated from echo integration analysis of the acoustic backscatter for all fish $>2.9 \mathrm{~cm}$ (excluding schools). Data shown are the average estimated fish density by 1-m depth bins by analysis sector and season (spring = yellow, summer = green, fall = orange). The average estimated thermocline depth for each sector in the summer (green dashed line) and fall (orange dashed line) are shown as is the maximum depth recorded during surveys in each region (black line)


Figure 13b. Vertical distribution of fish density for the North-Eastern sector from the 2016 Hamilton Harbour acoustic surveys generated from echo integration analysis of the acoustic backscatter for all fish $>2.9 \mathrm{~cm}$ (excluding schools). Data shown are the average estimated fish density by $1-\mathrm{m}$ depth bins by analysis sector and season (spring = yellow, summer = green, fall $=$ orange). The average estimated thermocline depth for each sector in the summer (green dashed line) and fall (orange dashed line) are shown as is the maximum depth recorded during surveys in each region (black line).


Figure 13c. Vertical distribution of fish density for the South-Central sector from the 2016 Hamilton Harbour acoustic surveys generated from echo integration analysis of the acoustic backscatter for all fish $>2.9 \mathrm{~cm}$ (excluding schools). Data shown are the average estimated fish density by $1-\mathrm{m}$ depth bins by analysis sector and season (spring = yellow, summer = green, fall = orange). The average estimated thermocline depth for each sector in the summer (green dashed line) and fall (orange dashed line) are shown as is the maximum depth recorded during surveys in each region (black line).


Figure 13d. Vertical distribution of fish density for the West sector from the 2016 Hamilton Harbour acoustic surveys generated from echo integration analysis of the acoustic backscatter for all fish $>2.9 \mathrm{~cm}$ (excluding schools). Data shown are the average estimated fish density by $1-\mathrm{m}$ depth bins by analysis sector and season (spring = yellow, summer = green, fall = orange). The average estimated thermocline depth for each sector in the summer (green dashed line) and fall (orange dashed line) are shown as is the maximum depth recorded during surveys in each region (black line).


Figure 14. Visualization of general additive model (GAM) output for spatial smoothing of fish density by season. A clear peak in the western sector of the harbour is evident in all seasons (summer in particular), but an additional peak is also observable in the south-east in fall.

## APPENDIX 1: HYDROACOUSTIC DATA PROCESSING

Inspection The information contained in this appendix represent an abridged version of the processing approach from the Milne 2017 contractor report that was provided by Milne Technologies to Fisheries and Oceans Canada in March 2017 (Milne 2017). Some elements of this section are not relevant to the present work (i.e., reference to school detection or Toronto Harbour), but are kept in place to provide some guidance on different analytical approaches from different systems.

All hydroacoustic data were processed using Echoview (Echoview Software Pty. Ltd., version "7.1.34.30284") processing software. Echoview project files (*.EVI) were created from the available echograms for all transects. For each echogram type, the appropriate parameter and calibration settings were updated from the acoustic systems parameter settings. Other required settings such as water temperature and speed of sound in water were measured directly or estimated using parameter calculators within Echoview (Table A1.1).

## A1.1 Elementary Distance Sampling Unit (EDSU)

The Elementary Distance Sampling Unit (EDSU) is the length of cruise track along which measures of backscattered energy (or echogram "pixels") are integrated to provide one sample (Simmonds and MacLennan, 2005). The survey provides a series of "samples" from contiguous sections of tracks or EDSUs. If the chosen EDSU is too large, potentially useful information about the spatial patterning and distribution of fish patches might be lost. Conversely, if the chosen EDSU is too small, meaningful ecological patterns might be dominated by local variability thus inflating the error around the estimate (Simmonds and MacLennan, 2005).

We have chosen 50 m as an appropriate EDSU or survey bin for the fisheries analysis component of this project. The 50 m EDSU size is consistent with previous 2006 Hamilton Harbour surveys, 2009 and 2010 Toronto Harbour surveys as well as the 2011 Bay of Quinte surveys.

## A1.2 Echo Integration

Estimates of fish density (numbers/ha) and biomass (kg/ha) were calculated from the mean echo integrated acoustic backscatter ( 199 kHz only) using the equation;

$$
\begin{aligned}
\rho_{a_{i}} & =s_{a_{i}} / \sigma_{b s_{i}} \\
F_{\text {Bioma }_{i}} & =\rho_{a_{i}} \times R W T_{i}
\end{aligned}
$$

Where $\rho_{a}$ is the estimated fish density (numbers $/ \mathrm{m} 2$ ), sa is the average area backscattering coefficient ( $\mathrm{m} 2 / \mathrm{m} 2$ ), $\sigma \mathrm{bs}$ is the expected backscattering cross-section (m2), $F_{\text {Bioma }}$ is fish biomass ( $\mathrm{kg} / \mathrm{m} 2$ ), and $R W T$ is the mean round weight $(\mathrm{kg})$ of fish size class i .

Echoview acoustic processing software was used to calculate the echo integral (Ei) and the average integrated volumetric backscattering strength (Sv) across each sample or 50 m EDSU. A 20log R time varied gain compensation factor was applied to all integrated values during logging to account for sound attenuation.

The integrated average volumetric backscattering strength (Sv) was expressed as area and volume backscattering coefficients (sa in units $\mathrm{m} 2 / \mathrm{m} 2$ and sv in units $\mathrm{m} 2 / \mathrm{m} 3$ ) using the equations:

$$
\begin{gathered}
s_{a}=\left(10^{\left(\frac{S v}{10}\right)} \times T\right) \\
s_{v}=\left(10^{\left(\frac{S_{v}}{10}\right)}\right)
\end{gathered}
$$

where sa is the area backscattering coefficient (m2/m2), Sv is the mean volumetric backscattering strength ( dB re: $1 \mathrm{~m}-1$ ), T is the mean thickness of the integrated domain and sv is the volume backscattering coefficient ( $\mathrm{m} 2 / \mathrm{m} 3$ ).
The area backscattering can also be expressed as the nautical area backscattering coefficient (sA or NASC) and is related to sa using the equation:

$$
N A S C=s_{a} \bullet(1852)^{2} \bullet 4 \pi
$$

The NASC area backscattering coefficient is the sa scaled to the surface area of a sphere with a radius of 1 nautical mile ( 1852 m ). This terminology is common within the hydroacoustics literature and follows MacLennan et al. (2005).

## A1.3 Partitioning the Echo Integral

The conversion of acoustic backscatter into meaningful estimates of fish density and biomass requires specific information about the species and size composition of the ensonified targets. This information is specific to a particular spatial region or depth stratum of the survey area and time period. Usually these areas are defined by attributes of the available habitat (i.e., depth, temperature, and oxygen preferences, substrate features), presence of migration barriers (i.e., thermal limitations, basin entrapment) or from other fish sampling evidence (i.e., trawling, index netting etc.).
Estimates of fish density and biomass were generated for each of the "analysis sectors" described above. In addition to this, we also separated the water column of each sector into various depth layers and strata.

## A1.4 Single Target Detection, Fish Tracks, and Target Strength

The target strength is a measure of the echo amplitude from a single target and provides information about the size of the ensonified fish; generally, larger fish have stronger echoes.

Single target (ST) detection data and the measured target strength (TS in dB) information were processed using the "Single Target Detect (Method 2) Operator" variable in Echoview. This virtual variable uses the uncompensated 40LogR target strength and angular position (electrical phase) telegrams as operands to best distinguish those echoes coming from isolated fish targets. Based on user settings, Echoview identifies only those echoes that are within a suitable range of amplitude and pulse duration (termed the "echo envelope") as single targets. Analysis boundaries and target strength thresholds were applied in Echoview before final processing. Target strength estimates from single target detections within fish school regions were considered biased due to fish target coincidence issues and therefore excluded from the analysis.

The range limit for unbiased detection of a target of interest with a compensated target strength of -55.0 dB with an expected SNR (signal-to-noise ratio) of 10 dB was estimated to be $89 \mathrm{~m}, 97$ m and 95 m for May, August and October, respectively (Table A1.2). Given that the maximum depth of the 2016 surveys is $\sim 78 \mathrm{~m}$, we are confident that range dependent biases will have limited effects on the overall fish density estimate. We used the "Fish Track" detection function
within Echoview to identify those individual targets that might have been acoustically sampled multiple times and therefore potentially detected as multiple single targets (see Table A1.3 for settings). For those targets identified within a "fish track" we used the observed mean target strength within the region as a measure of the target strength. Fish tracks that include one or more single targets were included in the analysis.

Plots of the target strength frequency distribution from the observed fish tracks across all transects within an analysis sector were used to identify size class modes. We attempted to discriminate class modes by comparing the observed in situ target strength distributions from the acoustic surveys to the size frequency distributions of all fish sampled within the trawl survey. We used Love's (1971a, 1971b) general multi-species model to predict the equivalent target strength of all fish in the trawl catches for comparison with the observed average target strength of the acoustic fish track detections. The equivalent target strength (TS) of the catch was estimated from the observed total length (TLEN) of the fish track where:

$$
T S=19.1 \times \log \left(L_{m}\right)+0.9 \times \log ((c / f) / 1000)-23.9
$$

where Lm is the total length $(\mathrm{m}), \mathrm{c}$ is the speed of sound in water $(\mathrm{m} / \mathrm{s})$, and $f$ is the transmitted frequency ( kHz ).

The GLFC's "Standard Operating Procedures for Fisheries Acoustic Surveys in the Great Lakes" (or "Great Lakes SOP", 2009) provides a table summarizing empirical target strength/length relationships for several Great Lakes species including alewife, rainbow smelt and mixed species assemblages. The SOP recommends that ex situ estimates of average target strength be species specific to account for the potential variation in target strength across fish of different species but maybe of the same size (Parker-Stetter et al. 2009).

Although there are several Great Lakes TS models to choose from, all of them are species specific whereas we feel a more generalized model is required to reflect the diversity of nonschooling species encountered within the Hamilton Harbour survey area. To our knowledge, no TS models have been developed for many of the species encountered in the trawl surveys. It is also important to note that none of the current Great Lake's models are applicable to 199 kHz and therefore frequency response biases may also exist. Therefore, we used Love's (1971a, 1971b) general TS-Length relationship as a more suitable model for the Toronto and Hamilton Harbour surveys. This approach will also standardize the 2016 analyses for comparison with previous DFO acoustic surveys (i.e. 2009/2010 Toronto Harbour, 2010 Bronte Harbour, 2006 Hamilton Harbour and 2011 Bay of Quinte surveys) that also used Love's (1971a, 1971b) general multi-species TS model.

Simmonds and McLennan (2005) suggest that the target strength for a particular species or size class of fish should be considered a stochastic variable. In situ experimental work has shown that the variation around the observed mean target strength recorded from similar sized targets might be as great as 20 dB depending on a number of factors including transducer movement, the behavioural and physiological condition of the target (e.g., stomach fullness, parasites), and fish density (Simmonds and McLennan 2005). The application of in situ target strength information for partitioning the echo integral should be treated as a probability distribution where the mean TS (or average $\sigma b s$ ) would have a systematic dependence on the size class or species of the ensonified targets.

Size partitioning of the echo integral was completed using 6 fish size classes. These general fish size class categories were chosen to standardize the size-stratified fish density estimates
with previous DFO acoustic surveys (i.e. 2009/2010 Toronto Harbour and 2006 Hamilton Harbour surveys; Table A1.4).

## A1.5 Fish Density Effects

When fish densities are high, multiple scattering and acoustic shadowing can have non-linear effects on the summation of echoes within the beam volume (Parker-Settler 2009). The most common problem is single target coincidence where two or more fish targets occupy the same pulse volume and are thus detected as a single target with an inflated target strength value. Therefore in situ target strength values are not reliable under these conditions.

Sawada et al. (1993) provide a diagnostic tool for identifying those segments of the survey where single target coincidence may be an issue. They provide a method to calculate Nv index for each EDSU and is calculated from the number of fish per acoustic sampling volume where:

$$
N_{v}=\frac{c t \psi R^{2} \rho_{v}}{2}, \text { where } \rho_{v}=\frac{s_{v}}{\sigma_{b s}} .
$$

c is the speed of sound ( $\mathrm{m} / \mathrm{s}$ ), $\tau$ is the pulse duration (msec), $\psi$ is the equivalent beam angle (steradians), $R$ is the range ( m ), and $\rho v$ is the theoretical density of targets. We used the minimum expected target strength of size class 2 fish ( -49.43 dB ) to generate the Nv index values for all EDSU cells. An Nv index $>0.1$ suggests that the target coincidence effect may be a problem within the given EDSU and therefore in situ estimates of the mean target strength should not be used to partition the echo integral.

## A1.6 Steps for Estimating Fish Density and Biomass from Echo Integration

The following steps describe the general methodology used to estimate biomass from the hydroacoustic information using the echo integration method.
Echo integration estimates of fish density using hydroacoustics can be generally separated into "schooling" and "non-schooling" fish components, as well as all fish combined. However, for the 2016 Hamilton Harbour survey schools were not present therefore all analysis followed the "ExcldSchools" function outlined below.
"..._ExcldSchools": We used Echoview's SHAPES School Detection module to detect aggregations of fish schools. Before echo integration, all school regions were set to "no data" and excluded from the analysis (Figure 9-2). Echoview acknowledges that cells with many "bad data" regions may bias the echo integration estimate because Echoview uses the number of "valid" samples in the cell to calculate the mean height of the cell. To compensate for this, the latest version of Echoview allows the user to "include the volume of No Data samples". From the Echoview Help file: "These samples are assigned a value of no data and are deemed to have a volume and hence a sample thickness. [The user is] assuming, in effect, that these samples have a backscatter value equal to the mean of the good samples in the domain."

## A1.7 Echogram (Sv and TS) Processing Results

All of the hydroacoustic data were processed (echo integration and single target detection) using four different depth strata (and agency strata). Within each depth stratum, echo integration and single target detect information was exported from Echoview for each 50 m survey bin (EDSU). All of the processed data were exported from Echoview into Microsoft Access databases for analysis. Outliers and anomalous data values (i.e., from cavitation, bottom interference, and line analysis line breaks, etc.) were identified and verified visually within the echogram and, if required, removed from the database.

The following Sv thresholds were applied to the data to reduce reverberation from electromechanical noise, cavitation, and invertebrate backscatter.

Minimum TS Threshold -We applied a time-varied $\mathrm{TS}_{u}$ threshold of -66 dB . This Echoview filter allows thresholding of the 20LogR Sv data using uncompensated target strength ( $\mathrm{TS}_{\mathrm{u}}$ ) minimum thresholds. This provides a method to remove noise and reverberation from small invertebrates and colonizing algae. For example, if we include a minimum -60 dB compensated target strength threshold to eliminate all fish smaller than $\sim 2 \mathrm{~mm}$, than a $\mathrm{TS}_{\mathrm{u}}$ threshold of -66 dB is required to ensure that all backscatter from fish at least 6 dB off axis ( $-60 \mathrm{~dB}+-6 \mathrm{~dB} 2$-way beam angle) are included in the volume scattering estimate. We can then apply a -66 dB TSu threshold to the $\mathrm{S}_{\mathrm{v}}$ data using the 20LogR time-varied function in Echoview.

Automated Noise Removal - Upon initial inspection of the echograms, it was apparent that a constant but significant electrical and/or acoustical interference was present throughout the surveys. As a result of the time-varied gain function, the noise appeared to become more intense with range from the transducer. We used Echoview's Virtual Variable module to estimate the intensity of the noise and to apply time-varied filters to the data to reduce the influence of the noise on the echo integration estimates. Passive data was collected on all survey days and were processed within Echoview. Regions were defined and we calculated the estimated ambient acoustic noise within the $\mathrm{S}_{\mathrm{v}}$ domain at 1 m from the transducer as:

$$
S_{v N 1}=S_{v N R}-20 \log _{10} R-2 \alpha R
$$

$S_{V_{N R}}$ is the echo integrated volumetric backscatter (dB) through a given layer of the passive data, $R$ is the mean range of the echo integrated layer, and $\square$ is the estimated absorption coefficient (dB/m). We then created a virtual echogram to simulate the noise ramp by calculating a time varied gain function from the noise estimate at 1 m . We then arithmetically subtracted the noise function from the raw $\mathrm{S}_{\mathrm{v}}$ echogram to enhance the signal to noise ratio.

## A1.8 TS versus TLEN Model

We used Love's (1971a, 1971b) target strength model to estimate the equivalent target strength of the class limits for each of the 6 fish size categories (Table A1.5).

Using the target strength limits defined for each size class we summed the total number of fish track detections within the local area of each EDSU. We defined the "local area" of each EDSU as the region within 90 seconds of the EDSU start and end ping (horizontal plane) as well as the area within a defined depth range (vertical plane) that varied depending on the depth strata (Table A1.6). For each EDSU we assumed that the observed target strength distribution of the fish tracks within the local area of the EDSU is indicative of the size composition of fish included within the integrated backscatter estimate. The total number of fish track detections in each size class were then expressed as a proportion of the total number of fish track detections between 55.0 dB and -24.12 dB.

## A1.9 Fish Density Conversion Coefficient - Backscattering Cross-section ( $\sigma$ )

The expected backscattering cross-section (бi) is required to scale the observed integrated backscatter into an estimate of fish density within each size class. We estimated the expected backscattering cross-section from the observed mean backscattering cross-section of all fish
track detections (mean TS) within each local Region (+/-90 seconds) of the EDSU. The mean backscattering cross-section for each of the size categories was calculated as:

$$
\bar{\sigma}_{i}=\frac{\sum \sigma_{1}+\sigma_{2}+\ldots . \sigma_{n}}{N_{i}}
$$

where,

$$
\sigma_{n}=10^{\left(\frac{T S_{n}}{10}\right)}
$$

and where TSn, is the observed mean target strength from a fish track detect region within the size class i and Ni is the number of fish track detects within size class i . The size class of an individual target (or fish track region) was determined by the target strength class limits summarized in Table A1.5.

For those EDSUs where single target information was not available we applied the mean backscattering cross-section of all fish tracks within a given size class across the depth stratum.

## A1.10 Fish Biomass Conversion Coefficient - Mean Round Weight (RWT)

Instantaneous fish biomass ( ${ }^{\text {FBiom }}{ }_{a_{i}}$ ) within each EDSU was estimated as the product of the numerical fish density estimate ( ${ }_{a_{i}}$ ) and the round weight (RWTi) of a target within size class i. The round weight (RWT) for targets within a given size class was estimated using the following methods:

Direct Observation - Where available, we used the observed round weight from the trawl catch data (Gear Type ="TW03"). For those netting strata where no or only a few fish were sampled (<3), we estimated the mean round weight from pooling across all gear types and depth strata. Aggregated estimates of the mean round weight were assigned using a hierarchy with each record being flagged to indicate the source. Flagged records are summarized in table
"ConversionCoefficient_Estimates_Step03_Table" in database "2016_THHH_Surveys_Netting_Data.mdb".

In Situ Target Strength and Length-Weight Relationships - Given that fish sampling data for large (> 20 cm ) fish size classes were not available (except one 54.7 cm Walleye), we estimated the mean size of fish within these large size classes from the observed mean in situ target strength of fish tracks using Love's (1971a, 1971b) generalized target strength model. For each target we estimated the mean round weight from the equivalent total length using length-weight regression functions generated from the trawl catches. The round weight $(\mathrm{g})$ of the catch was estimated as,

$$
R W T=10^{\left((\mathrm{b}) * \log \left(\mathrm{~L}_{\mathrm{mm}}\right)+(\mathrm{a})\right)}
$$

where $L_{m m}$ is total length in mm , $a$ is the regression intercept, and b is the regression slope. A summary of the regression parameters for the 2016 Hamilton Harbour surveys is shown in Table A 1.7.

## A1.11 Partitioning NASC

From the observed single target proportions and the mean backscattering cross-section (obs) for each size class within the local area of each EDSU, we partitioned the observed integrated backscattered energy into the 6 fish size categories using a modified "mixed species" method
described in Simmonds and MacLennan (2002). This method partitions the observed integrated backscattered energy by the proportion of observed single targets within each size category weighted on the expected area backscatter contribution of a given fish within the size class. We estimated the integrated backscattered energy (Ei) within size category as,

$$
E_{i}=w_{i}\left\langle\sigma_{i}\right\rangle E_{m} /\left(\sum_{j} w_{j}\left\langle\sigma_{j}\right\rangle\right)
$$

where Ei is the integrated backscattered amplitude (energy integral), w is the proportional number of single targets within the size class, $\sigma$ is the expected backscattering cross-section, and the sub-script i refers to one of the 6 size classes. We estimated the expected backscatter cross-section ( $\sigma$ ) from the mean target strength of all targets observed within each of the 6 size classes. The term indicated with the subscript $j$ is the weighted mean backscatter cross-section across all size class categories and is estimated from the mean observed target strength of all targets.

In some instances, there was significant backscatter energy observed within a cell but few or no single targets detected within the local area. Several criteria must be satisfied for a particular echo to be included as a single target detect. Acoustic shadowing, position within the acoustic beam, fish density (i.e., presence of schooling), and overlapping targets might limit the ability to resolve individual fish targets. If no fish tracks were detected within a cell where integrated backscattered energy was greater than the minimum threshold, or the estimated Nv Index was $>0.1$, we applied the proportional number of fish track detections observed within the 6 size classes across the lake-wide layer. A summary of the proportion of analysis cell for each analysis sector where valid fish tracks were detected within the 90 second search window is shown in Table A1.8. The expected backscatter cross-section ( $\sigma$ ) for the remaining EDSU's were estimated from transect-wide, sector-wide or lake-wide average target strength values. Note that as the analysis cells become smaller (i.e., 1 m depth strata), the proportion of cells where no single targets were detected increases.

## A1.12 Estimates of Fish Density and Biomass

"..._ExcldSchools": Substituting estimates of the mean backscattering cross-section $\left(\bar{\sigma}_{b s}\right)$ the partitioned integrated backscattered energy (Ei) and the mean round weight (RWTi) for each of the 6 size classes i into the echo integration equation, we estimated the fish density and standing fish biomass for each analysis cell in numbers or weight per m2. This estimate can then be expressed in numbers or kilograms per hectare by multiplying the m 2 term by 10,000. The sum of the estimated fish density or biomass across all 6 fish size classes provides an estimate of the total biomass or fish density per unit area for every 50 m EDSU.

> The total fish density estimate (schooling and non-schooling species) for a given EDSU = "..._ExcldSchools" + ".._SchoolsOnly"

## References

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Simmonds, E.J. and D. MacLennan. 2005. Fisheries Acoustics: Theory and Practice 2nd Edition. Blackwell Publishing, Oxford, UK

Table A 1.1. Summary of the data logging and processing parameter settings used within Echoview to process the 2016 Hamilton Harbour 199 kHz hydroacoustic data.

| Sv | $\begin{aligned} & \text { Logging } \\ & 199 \mathrm{kHz} \end{aligned}$ | Processing $199 \text { kHz }$ | Units |
| :---: | :---: | :---: | :---: |
| Array Frequency | 199.00 | 199.00 | kHz |
| Bandwidth | 6.82 | 6.82 | kHz |
| $S_{v}$ Offset | 0.00 | 1.11 | db |
| Transducer Pulse Length | 0.300 | 0.300 | ms |
| Ping Rate | Variable | Variable | pps |
| Sample Depth (Range) | Variable | Variable | m |
| Min $1 / R^{2}$ Sv Threshold Applied | -130 | None | db |
| Minimum TS Threshold |  | -66 | db |
| Minimum TS Threshold Calibration Offset |  | 0.77 | db |
| Single Target Detections | Logging 199 kHz | Processing 199 kHz | Units |
| Uncompensated TS Threshold ( $\mathrm{Ts}_{u}$ ) |  | -61 | dBre $1 \mathrm{~m}^{2}$ |
| Single Target Detection TS Threshold |  | -55 | dB re $1 \mathrm{~m}^{2}$ |
| Minimum Normalized Pulse Length |  | 0.6 | - |
| Maximum Normalized Pulse Length |  | 1.5 | - |
| Pulse length determination level (PLDL) |  | 6 | dB re $1 \mathrm{~m}^{2}$ |
| Echoview Max. st. dev. of $+/$ - axis angles |  | 0.6 | 。 |
| School Detection Parameters | Logging 199 kHz | Processing 199 kHz | Units |
| Min. total school length |  | 2 | m |
| Min. total school height |  | 1.1 | m |
| Min. candidate length |  | 0.15 | m |
| Min. candidate height |  | 0.15 | m |
| Max. vertical linking distance |  | 0.25 | m |
| Max. horizontal linking distance |  | 1.25 | m |
| Distance mode |  | GPS | m |

Table A 1.2a. Summary of the estimated TSu noise and the expected range limit for unbiased detection of a -55.0 dB single targets. Noise test results are shown for the 2016 Hamilton Harbour spring and summer surveys.


Table A 1.2b. Summary of the estimated $T S_{u}$ noise and the expected range limit for unbiased detection of a -55.0 dB single targets. Noise test results are shown for the 2016 Hamilton Harbour fall surveys.

## 2016 HH and TH Surveys <br> 199 kHz



Table A 1. 3. Summary of the Fish Track detection settings used within Echoview to process the 2016 Hamilton Harbour single target detection data.

## Fish Track Detection Parameters

Data (range, angles and time) 4D

## Track Detection

| Alpha Major axis | 0.50 |
| ---: | ---: |
| Alpha Minor axis | 0.50 |
| Beta Range | 0.25 |
| Beta Major axis | 0.20 |
| Beta Minor axis | 0.20 |
| Beta Range | 0.30 |

## Target Gates

| Excl. Dist. (m) Major Axis | 12.00 | m |
| ---: | :---: | :---: |
| Excl. Dist. (m) Minor Axis | 12.00 | m |
| Excl. Dist. (m) Range | 0.35 | m |
| Missed Ping Exp. (\%) Major Axis | 10.00 | $\%$ |
| Missed Ping Exp. (\%) Minor Axis | 10.00 | $\%$ |
| Missed Ping Exp. (\%) Range | 0.45 | $\%$ |

## Weights

| Major Axis | 30 |
| ---: | :---: |
| Minor Axis | 30 |
| Range | 40 |
| TS | 0 |
| Ping gap | 0 |

Track Acceptance

| Min \# of STs in Track | 1 | ST's |
| ---: | :--- | :--- |
| Min \# of Pings in Track | 1 | pings |
| Max Gap Between STs | 1 | pings |

Table A 1.4. A summary and description of the 6 fish size categories used to partition the observed integrated acoustic backscatter. The size partition limits are the total length (mm) and equivalent target strength (TS) estimated from Love's (1971a, 1971b) generalized fish length equation.

| Project Code | Lake | Year | Size Class | Description | Min TLEN (mm) | $\begin{gathered} \text { Max TLEN } \\ (\mathrm{mm}) \end{gathered}$ | Min TS <br> (dB) | Max TS (dB) | Depth | Ping | Std_Dev_ off_Axis | Time | $\mathrm{N}_{\mathrm{v}}$ Test Class |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| HHA_IA16_001 | HH | 2016 | 1 | YOY UNKNOWN | 29 | 58 | -55.00 | -49.43 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_001 | HH | 2016 | 2 | ALWF, SMLT | 58 | 82 | -49.43 | -46.56 | 1.5 | 0 | 0.637 | 01:30 | 1 |
| HHA_IA16_001 | HH | 2016 | 3 | ALWF, SMLT, EMSH | 82 | 130 | -46.56 | -42.73 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_001 | HH | 2016 | 4 | ALWF | 130 | 250 | -42.73 | -37.31 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_001 | HH | 2016 | 5 | LKWH | 250 | 500 | -37.31 | -31.56 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_001 | HH | 2016 | 6 | Large Fish | 500 | 1200 | -31.56 | -24.12 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_002 | HH | 2016 | 1 | YOY UNKNOWN | 29 | 58 | -55.00 | -49.43 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_002 | HH | 2016 | 2 | ALWF, SMLT | 58 | 82 | -49.43 | -46.56 | 1.5 | 0 | 0.637 | 01:30 | 1 |
| HHA_IA16_002 | HH | 2016 | 3 | ALWF, SMLT, EMSH | 82 | 130 | -46.56 | -42.73 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_002 | HH | 2016 | 4 | ALWF | 130 | 250 | -42.73 | -37.31 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_002 | HH | 2016 | 5 | LKWH | 250 | 500 | -37.31 | -31.56 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_002 | HH | 2016 | 6 | Large Fish | 500 | 1200 | -31.56 | -24.12 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| THA_IA16_003 | TH | 2016 | 1 | YOY UNKNOWN | 29 | 58 | -55.00 | -49.43 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| THA_IA16_003 | TH | 2016 | 2 | ALWF, SMLT | 58 | 82 | -49.43 | -46.56 | 1.5 | 0 | 0.637 | 01:30 | 1 |
| THA_IA16_003 | TH | 2016 | 3 | ALWF, SMLT, EMSH | 82 | 130 | -46.56 | -42.73 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| THA_IA16_003 | TH | 2016 | 4 | ALWF | 130 | 250 | -42.73 | -37.31 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| THA_IA16_003 | TH | 2016 | 5 | LKWH | 250 | 500 | -37.31 | -31.56 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| THA_IA16_003 | TH | 2016 | 6 | Large Fish | 500 | 1200 | -31.56 | -24.12 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_003 | HH | 2016 | 1 | YOY UNKNOWN | 29 | 58 | -55.00 | -49.43 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_003 | HH | 2016 | 2 | ALWF, SMLT | 58 | 82 | -49.43 | -46.56 | 1.5 | 0 | 0.637 | 01:30 | 1 |
| HHA_IA16_003 | HH | 2016 | 3 | ALWF, SMLT, EMSH | 82 | 130 | -46.56 | -42.73 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_003 | HH | 2016 | 4 | ALWF | 130 | 250 | -42.73 | -37.31 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_003 | HH | 2016 | 5 | LKWH | 250 | 500 | -37.31 | -31.56 | 1.5 | 0 | 0.637 | 01:30 | 0 |
| HHA_IA16_003 | HH | 2016 | 6 | Large Fish | 500 | 1200 | -31.56 | -24.12 | 1.5 | 0 | 0.637 | 01:30 | 0 |

Table A 1.5. Summary and description of the 6 fish size categories used to partition the observed integrated acoustic backscatter. The size partition limits are the total length (mm) and equivalent target strength (TS) estimated from Love's (1971a, 1971b) generalized fish length equation.

| Size <br> Class | Min <br> TLEN <br> $(\mathrm{mm})$ | Max <br> TLEN <br> $(\mathrm{mm})$ | Min TS <br> $(\mathrm{dB})$ | Max <br> TS <br> $(\mathrm{dB})$ |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 29 | 58 | -55.00 | -49.43 |
| 2 | 58 | 82 | -49.43 | -46.56 |
| 3 | 82 | 130 | -46.56 | -42.73 |
| 4 | 130 | 250 | -42.73 | -37.31 |
| 5 | 250 | 500 | -37.31 | -31.56 |
| 6 | 500 | 1200 | -31.56 | -24.12 |

Table A 1.6. Summary of the horizontal and vertical boundary parameters used to define the limits of the fish track search region around each EDSU by depth strata. Only those single targets observed within the local area of the EDSU were included in the calculations for partitioning the observed integrated backscatter.

|  | Single Target Detection Region |  |
| :---: | :---: | :---: |
| Analysis Strata | Horizontal <br>  <br> Aft of EDSU) | Vertical <br> (Depth (m)) |
| Water Column | 90 | - |
| Benthic | 90 | - |
| Pelagic | 90 | - |
| 1mBins | 90 | 1.0 m Above \& Below EDSU |

Table A 1.7. Summary of the intercept and slope coefficients used to estimate the mean round weight (RWT, $g$ ) of a fish within each size class. The round weight was estimated from the equivalent total length (TLEN) of all in situ fish tracks, within a size category, calculated from Love's (1971a, 1971b) generalized target strength model.

## Database Table "TL_LengthvsRWT" - Used to estimate RWT from in situ estimates of Fish Track total length. LogTLEN vs. LogRWT

| SPC | SPC_NM | Ont. SPC Code | N | Intercept | Slope | Lake | Comments | $\mathrm{R}^{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ALWF-5 | Alewife | $\checkmark 061$ | 221 | -4.64174 | 2.722571 | HHA_IA16_002 | Pelagic Trawl - Hamilton Harbour Summer | 0.71 |
| SHAD-1 | Gizzard Shad | 063 | 104 | -5.60303 | 3.283196 | LkOnt_HH | 2006 HH Trawls |  |
| CHNK-1 | Chinook Salmon | 075 |  | -5.31348 | 3.113913 | Lake Michigan | Wesley 1996 |  |
| SMLT-8 | Rainbow Smelt | 121 | 36 | -5.85955 | 3.260869 | HHA IA16_001 | Pelagic Trawl - Hamilton Harbour Spring | 0.87 |
| SHNR-2 | Emerald Shiner | 196 | 513 | -4.64857 | 2.726291 | LkOnt_HH | 2006 HH Trawls |  |
| BULL-1 | Brown Bullhead | 233 | 10 | -5.43216 | 3.232554 | LkOnt_HH | 2006 HH Trawls |  |
| WHPR-3 | White Perch | 301 | 25 | -5.51307 | 3.284042 | HHA_IA16_002 | Pelagic Trawl - Hamilton Harbour Summer | 0.99 |
| WALL-4 | Walleye | - 334 | 5923 | -5.70646 | 3.268439 | Lake Huron | UGLMU Lake Huron Various Projects |  |

Table A 1.8. The percent of analysis cells (EDSUs) for each analysis sector within the 2016 Hamilton and Toronto Harbour acoustic surveys where significant backscattered energy was observed and fish tracks were detected within the +/-90 second search window. Values are expressed as the percentage of all cells where "valid" fish tracks were detected and the observed integrated NASC was greater than " 0 " ( $\mathrm{m} 2 / \mathrm{n} . \mathrm{mi}$ ). EDSU's may be considered "invalid" if insufficient fish tracks were detected within the search window (<= 3 fish tracks) or the estimated Nv index was $>0.1$.

| Project Code | Year | Lake | Period | SAM | 0 <br> 0 | Number of EDSU's <br> where in situ Fish <br> Tracks available and <br> valid | Total <br> Number of <br> EDSU's | Proportion of EDSU's <br> where Fish Tracks <br> available (\%) <br> (where NASC >0) |
| :--- | :--- | :--- | :--- | :---: | :---: | :---: | :---: | :---: |
| HHA_IA16_001 | 2016 | HH | Night | 1 | N | 125 | 152 | 82.2 |
| HHA_IA16_001 | 2016 | HH | Night | 1 | NE | 477 | 570 | 83.7 |
| HHA_IA16_001 | 2016 | HH | Night | 1 | SC | 1085 | 1301 | 83.4 |
| HHA_IA16_001 | 2016 | HH | Night | 1 | W | 121 | 145 | 83.4 |
| HHA_IA16_002 | 2016 | HH | Night | 1 | N | 413 | 584 | 70.7 |
| HHA_IA16_002 | 2016 | HH | Day | 1 | NE | 29 | 77 | 37.7 |
| HHA_IA16_002 | 2016 | HH | Night | 1 | NE | 921 | 1324 | 69.6 |
| HHA_IA16_002 | 2016 | HH | Day | 1 | SC | 30 | 102 | 29.4 |
| HHA_IA16_002 | 2016 | HH | Night | 1 | SC | 1463 | 2083 | 70.2 |
| HHA_IA16_002 | 2016 | HH | Day | 1 | W | 4 | 15 | 26.7 |
| HHA_IA16_002 | 2016 | HH | Night | 1 | W | 406 | 471 | 86.2 |
| HHA_IA16_003 | 2016 | HH | Night | 1 | N | 996 | 1399 | 71.2 |
| HHA_IA16_003 | 2016 | HH | Day | 1 | N | 157 | 261 | 60.2 |
| HHA_IA16_003 | 2016 | HH | Day | 1 | NE | 147 | 236 | 62.3 |
| HHA_IA16_003 | 2016 | HH | Night | 1 | NE | 2390 | 2878 | 83.0 |
| HHA_IA16_003 | 2016 | HH | Night | 1 | SC | 3533 | 4320 | 81.8 |
| HHA_IA16_003 | 2016 | HH | Day | 1 | SC | 176 | 323 | 54.5 |
| HHA_IA16_003 | 2016 | HH | Night | 1 | W | 169 | 223 | 75.8 |
| THA_IA16_003 | 2016 | TH | Day | 1 | BLUF | 6 | 20 | 30.0 |
| THA_IA16_003 | 2016 | TH | Day | 1 | EHDL | 147 | 378 | 38.9 |

## APPENDIX 2: GAS BUBBLES

Inspection of the 2016 Hamilton Harbour AOC acoustic surveys echograms revealed the presence of gas bubbles throughout the water column of several transects. The bubbles appear within the echograms as stacked columns of individual targets extending up from the acoustically detected bottom (Figure A1a). Gas bubbles are problematic for acoustics as they often share the same acoustic properties as small fish targets and therefore fish density estimates can be biased (Ostrovsky 2009).

We used two methods for detecting and removing acoustic backscatter from gas bubbles:

1. For those echogram segments where the gas bubbles appear as vertical columns, we used the Echoview School Detection module to manually identify and remove regions of bubble stacks. These bubble regions were assigned as "Bad Data - Air Bubbles" in Echoview and set to Sv data below threshold. This method is described in Milne (2011) in section "3.1 GAS-BUBBLE EMISSIONS FROM THE SEDIMENT."
2. For those segments where gas bubbles appear more random and/or isolated (i.e. not in vertical columns), we used the single target detection algorithm within Echoview to auto-detect "bubble track" regions using region properties such as target strength ( dB ) and target change in range rate $(\mathrm{m} / \mathrm{s})$. For most paired trawling transects the vessel speed was sufficiently slow and the ping rate was fast enough to provide multiple ensonifications, or "hits" on a single rising bubble. As the ascent rate of the bubbles was constant, they appeared on the echogram as individual single targets sloping up towards the surface (Figure A1a). Contiguous single targets were clustered to create track regions using the Echoview Fish Track Detection algorithm. Frequency histogram plots of the change in depth ( $\mathrm{m} / \mathrm{s}$ ) of the exported bubble regions showed a bimodal distribution suggesting that detection regions with a change in depth $<=-0.075$ $\mathrm{m} / \mathrm{s}$ are likely gas bubbles. All track regions that met these criteria were classified as "Bad Data - FT Bubbles" and set to "Bad Data". Bubble track regions with a change in depth $>-0.075 \mathrm{~m} / \mathrm{s}$ were assumed to be fish and deleted. Although there is the potential to erroneously remove upward swimming fish targets using this method, we feel this is unlikely given the evidence of fish schools diving in response to vessel noise. Positive identification of bubbles from those transects ([TRAN_TYPE] = "EV_Only") where trawling was not completed was more uncertain because the increased vessel speeds did not produce long bubble tracks within the echogram. Our criteria required 3 or more single targets within a bubble track to calculate change in range.

An example of the spatial distribution of all bubble regions detected within the 2016 Hamilton Harbour AOC surveys is shown in Figure A1b.


Figure A 2.1. Echogram (Sv) segment from the 2016 Hamilton Harbour hydroacoustic surveys (October 5, 2016 a. 22:04 and b. 00:13) where significant densities of gas-bubbles were identified. Gas bubble regions appeared on the echogram as either vertical columns and/or individual targets moving upwards towards the surface at a constant rate.


2016 Hamilton Harbour (Summer, HHA_IA16_002) - Gas bubble reverberation.
Acoustically detected methane gas-bubble emissions from the bottom sediment observed during the hydroacoustic survey. Bubble regions were manually and automatically identified within the echogram Not For Navigation
Version 2017.03 .24 and excluded from echo integrations calculations.

Figure A 2.2. Shown is the spatial distribution of regions identified as gas bubbles rising from the bottom sediments in the summer.

## APPENDIX 3: DISSOLVED OXYGEN PROFILES



Figure A 3.1. Temperature (red) and dissolved oxygen (blue) profiles for Hamilton Harbour fish hydroacoustic transects in 2016. Horizontal dotted lines represent the estimated depth of the thermocline based on the thermo.depth function in the rLakeAnalyzer package. Vertical lines represent $6 \mathrm{mg} / \mathrm{L}$ (solid line) and $3 \mathrm{mg} / \mathrm{L}$ (dashed line) of dissolved oxygen to aid interpretation. Profiles were collected at the start of each transect. No data were available for T 2 in the spring.


Figure A 3.2. Temperature (red) and dissolved oxygen (blue) profiles for Hamilton Harbour fish hydroacoustic transects. Horizontal dotted lines represent the estimated depth of the thermocline based on the thermo.depth function in the rLakeAnalyzer package. Vertical lines represent $6 \mathrm{mg} / \mathrm{L}$ (solid line) and $3 \mathrm{mg} / \mathrm{L}$ (dashed line) of dissolved oxygen to aid interpretation. Profiles were collected at the start of each transect.


Figure A 3.3. Temperature (red) and dissolved oxygen (blue) profiles for Hamilton Harbour fish hydroacoustic transects. Horizontal dotted lines represent the estimated depth of the thermocline based on the thermo.depth function in the rLakeAnalyzer package. Vertical lines represent $6 \mathrm{mg} / \mathrm{L}$ (solid line) and $3 \mathrm{mg} / \mathrm{L}$ (dashed line) of dissolved oxygen to aid interpretation. Profiles were collected at the start of each transect. No data were available for T11 in the spring.


Figure A 3.4. Temperature (red) and dissolved oxygen (blue) profiles for Hamilton Harbour fish hydroacoustic transects. Horizontal dotted lines represent the estimated depth of the thermocline based on the thermo.depth function in the rLakeAnalyzer package. Vertical lines represent $6 \mathrm{mg} / \mathrm{L}$ (solid line) and $3 \mathrm{mg} / \mathrm{L}$ (dashed line) of dissolved oxygen to aid interpretation. Profiles were collected at the start of each transect.


Figure A 3.5. Temperature (red) and dissolved oxygen (blue) profiles for Hamilton Harbour fish hydroacoustic transects. Horizontal dotted lines represent the estimated depth of the thermocline based on the thermo.depth function in the rLakeAnalyzer package. Vertical lines represent $6 \mathrm{mg} / \mathrm{L}$ (solid line) and $3 \mathrm{mg} / \mathrm{L}$ (dashed line) of dissolved oxygen to aid interpretation. Profiles were collected at the start of each transect.

T18A - Spring


T18B - Spring


T18C - Spring


T18A - Summer


T18B - Summer


T18C - Summer


T18A - Fall


T18B - Fall


T18C - Fall


Figure A 3.6. Temperature (red) and dissolved oxygen (blue) profiles for Hamilton Harbour fish hydroacoustic transects. Horizontal dotted lines represent the estimated depth of the thermocline based on the thermo.depth function in the rLakeAnalyzer package. Vertical lines represent $6 \mathrm{mg} / \mathrm{L}$ (solid line) and $3 \mathrm{mg} / \mathrm{L}$ (dashed line) of dissolved oxygen to aid interpretation. Profiles were collected at the start of each transect. No data were available for T18A and T18C in the spring.


Figure A 3.7. Temperature (red) and dissolved oxygen (blue) profiles for Hamilton Harbour fish hydroacoustic transects. Horizontal dotted lines represent the estimated depth of the thermocline based on the thermo.depth function in the rLakeAnalyzer package. Vertical lines represent $6 \mathrm{mg} / \mathrm{L}$ (solid line) and $3 \mathrm{mg} / \mathrm{L}$ (dashed line) of dissolved oxygen to aid interpretation. Profiles were collected at the start of each transect.

## APPENDIX 4: SUMMARY OF DENSITY AND BIOMASS ESTIMATES

Table A 4.1. Estimated mean fish density (numbers per $\mathrm{m}^{3}$ ) from echo integration analysis by size class and analysis sector within the water column stratum (sum of 1 m Bins) from the 2016 Hamilton Harbour hydroacoustic surveys. Analysis sectors are $\mathrm{N}=$ North, $\mathrm{NE}=$ Northeastern, $\mathrm{SC}=$ South-central, and $\mathrm{W}=$ West and seasonal abbreviations are: $\mathrm{Sp}=\mathrm{spring}, \mathrm{Su}=$ summer, and $\mathrm{Fa}=$ fall.

| Analysis Sector | Size Class 1 |  | Size Class 2 |  | Size Class 3 |  | Size Class 4 |  | Size Class 5 |  | Size Class 6 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\overline{\mathrm{X}}$ | SE | $\overline{\mathrm{X}}$ | SE | $\overline{\mathrm{X}}$ | SE | $\overline{\mathrm{X}}$ | SE | $\overline{\mathrm{X}}$ | SE | $\overline{\mathrm{X}}$ | SE |
| N_Sp | 2.8E-04 | 0.8E-04 | 4.3E-04 | $1.6 \mathrm{E}-04$ | 2.2E-04 | 0.7E-04 | 2.1E-04 | 0.6E-04 | 0 | 0 | 0 | 0 |
| N_Su | 12.5E-04 | 4.2E-04 | 3.1E-04 | $1.5 \mathrm{E}-04$ | 7.1E-04 | 2.0E-04 | 8.5E-04 | 4.0E-04 | 0 | 0 | 0 | 0 |
| N_Fa | 12.3E-04 | 2.2E-04 | 3.3E-04 | 0.7E-04 | 2.5E-04 | 0.7E-04 | 1.7E-04 | 0.6E-04 | 0.6E-04 | 0.3E-04 | 0.1E-04 | 1.3E-04 |
| NE_Sp | 4.1E-04 | $1.0 \mathrm{E}-04$ | 3.2E-04 | 0.6E-04 | 4.3E-04 | $1.0 \mathrm{E}-04$ | 1.7E-04 | 0.6E-04 | 0.1E-04 | 0.09E-04 | 0.1E-04 | 0.9E-04 |
| NE_Su | 17.4E-04 | 2.0E-04 | 6.6E-04 | 1.0E-04 | 8.7E-04 | 1.3E-04 | 2.9E-04 | 0.7E-04 | 0.1E-04 | 0.07E-04 | 0 | 0 |
| NE_Fa | 20.6E-04 | $3.4 \mathrm{E}-04$ | 7.5E-04 | $1.1 \mathrm{E}-04$ | 5.8E-04 | 0.9E-04 | 4.7E-04 | 2.7E-04 | 0.2E-04 | 0.06E-04 | 0.05E-04 | 0.5E-04 |
| SC_Sp | $6.1 \mathrm{E}-04$ | 1.0E-04 | $4.2 \mathrm{E}-04$ | 0.7E-04 | 4.3E-04 | 0.6E-04 | $1.7 \mathrm{E}-04$ | 0.3E-04 | 0.1E-04 | 0.009E-04 | 0 | 0 |
| SC_Su | 13.5E-04 | 2.1E-04 | 4.0E-04 | 0.9E-04 | 1.9E-04 | 0.4E-04 | 1.1E-04 | 0.4E-04 | 0 | 0 | 0 | 0 |
| SC_Fa | 24.0E-04 | 3.4E-04 | 17.0E-04 | 4.9E-04 | 9.7E-04 | 2.1E-04 | 3.2E-04 | 0.6E-04 | 0.3E-04 | 0.08E-04 | 0.1E-04 | 1.1E-04 |
| W_Sp | 52.5E-04 | 26.9E-04 | 7.0E-04 | 2.2E-04 | 16.5E-04 | 11.4E-04 | 13.1E-04 | 8.3E-04 | 0 | 0 | 1.0E-01 | 6.8E-04 |
| W_Su | 115.0E-04 | 23.0E-04 | 52.7E-04 | 12.4E-04 | 96.6E-04 | 27.5E-04 | 62.9E-04 | 21.2E-04 | 4.9E-04 | 1.8E-04 | 0 | 0 |
| W_Fa | 63.4E-04 | 15.3E-04 | 18.0E-04 | 4.5E-04 | 48.9E-04 | 13.4E-04 | 20.2E-04 | 5.0E-04 | 0.8E-04 | 0.4E-04 | 0 | 0 |

Table A 4.2. Estimated mean fish biomass $\left(\mathrm{g}\right.$ per $\mathrm{m}^{3}$ ) from echo integration analysis by size class and analysis sector within the water column stratum (sum of 1 m Bins) from the 2016 Hamilton Harbour hydroacoustic surveys. Analysis sectors are $\mathrm{N}=\mathrm{North}, \mathrm{NE}=$ Northeastern, SC = South-central, and $\mathrm{W}=$ West and seasonal abbreviations are: $\mathrm{Sp}=$ spring, $\mathrm{Su}=$ summer, and $\mathrm{Fa}=$ fall.

| Analysis Sector | Size Class 1 |  | Size Class 2 |  | Size Class 3 |  | Size Class 4 |  | Size Class 5 |  | Size Class 6 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\overline{\mathrm{x}}$ | SE | $\overline{\mathrm{x}}$ | SE | $\overline{\mathrm{x}}$ | SE | $\overline{\mathrm{x}}$ | SE | $\overline{\mathrm{x}}$ | SE | $\overline{\mathrm{x}}$ | SE |
| N_Sp | 3.3E-04 | 1.0E-04 | $9.4 \mathrm{E}-04$ | 3.3E-04 | 10.5E-04 | 2.8E-04 | 72.6E-04 | 0 | 0 | 0 | 0 | 0 |
| N_Su | 12.4E-04 | 3.3E-04 | $8.9 \mathrm{E}-04$ | 5.2E-04 | 36.3E-04 | 10.3E-04 | 371.0E-04 | 0 | 0 | 0 | 0 | 0 |
| N_Fa | 17.9E-04 | 3.4E-04 | 6.2E-04 | $1.1 \mathrm{E}-04$ | 17.4E-04 | 5.7E-04 | 66.5E-04 | 116.0E-04 | 191.0E-04 | 116.0E-04 | 219.0E-04 | 155.0E-04 |
| NE_Sp | 3.5E-04 | 0.9E-04 | 8.4E-04 | $1.5 \mathrm{E}-04$ | 23.9E-04 | 5.2E-04 | 59.4E-04 | 32.6E-04 | 44.0E-04 | 32.6E-04 | 158.0E-04 | 121.0E-04 |
| NE_Su | 14.6E-04 | 1.6E-04 | 16.0E-04 | 2.6E-04 | 54.2E-04 | 8.7E-04 | 119.0E-04 | 31.3E-04 | 62.6E-04 | 31.3E-04 | 0 | 0 |
| NE_Fa | 21.9E-04 | $3.6 \mathrm{E}-04$ | $22.5 \mathrm{E}-04$ | 3.7E-04 | 43.7E-04 | 7.1E-04 | 179.0E-04 | 21.0E-04 | 60.7E-04 | 21.0E-04 | 74.2E-04 | 39.8E-04 |
| SC_Sp | 4.8E-04 | 0.8E-04 | $9.1 \mathrm{E}-04$ | $1.4 \mathrm{E}-04$ | 21.2E-04 | 2.6E-04 | 35.9E-04 | 3.5E-04 | 5.8E-04 | 3.5E-04 | 0 | 0 |
| SC_Su | 7.2E-04 | $1.0 \mathrm{E}-04$ | $8.0 \mathrm{E}-04$ | $1.8 \mathrm{E}-04$ | $20.1 \mathrm{E}-04$ | 4.7E-04 | 24.9E-04 | 0 | 0 | 0 | 0 | 0 |
| SC_Fa | 25.7E-04 | $4.0 \mathrm{E}-04$ | 49.6E-04 | 15.4E-04 | 105.0E-04 | 25.9E-04 | 63.2E-04 | 27.7E-04 | 90.0E-04 | 27.7E-04 | 195.0E-04 | 101.0E-04 |
| W_Sp | 28.0E-04 | 13.7E-04 | 12.4E-04 | 4.0E-04 | 117.0E-04 | 87.5E-04 | 744.0E-04 | 0 | 0 | 0 | 1580.0E-04 | 1370.0E-04 |
| W_Su | 44.2E-04 | $8.9 \mathrm{E}-04$ | $110.0 \mathrm{E}-04$ | 28.8E-04 | 1880.0E-04 | 508.0E-04 | 3080.0E-04 | 783.0E-04 | 2121.0E-04 | 783.0E-04 | 0 | 0 |
| W_Fa | 50.6E-04 | 9.8E-04 | 65.4E-04 | 24.0E-04 | 589.0E-04 | 174.0E-04 | 1440.0E-04 | 140.0E-04 | 256.0E-04 | 140.0E-04 | 0 | 0 |

