Analysing the impact of freshwater aquaculture on wild fish populations using Dual Frequency Identification Sonar (DIDSON) technology

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ABSTRACT

Dual-frequency identification sonar (DIDSON) technology has been used for a wide range of fisheries applications. The DIDSON offers important advantages over other sampling techniques since surveys are non-invasive and do not require capturing, handling or disturbing fish or their environments. Consequently, DIDSON technology is well-suited for use in an aquaculture setting. DIDSON images are constructed from sound compared to light, allowing for DIDSON sampling 24 h a day and in all turbidity conditions. Using the DIDSON, we collected data on wild fish distribution and abundance before and after the development of a new aquaculture site at impact and control sites in Lake Diefenbaker, Saskatchewan. A standardized field protocol was established to improve the environmental monitoring design for DIDSON field studies on wild fish in pelagic environments. DIDSON recordings were standardised to detection-per-unit-effort (DPUE in number of fish $\cdot 10\ m^{-3} \cdot 2\ h^{-1}$) in four depth strata for the three different study sites. DPUE at the Kadla cages were greatest during the early morning feeding period when large schools of fish (50 fish) were detected. In addition, gillnets were set to allow ground-truthing of the DIDSON footage. Six fish species (Cisco (*Coregonus artedi*), Walleye (*Sander vitreus*), Lake Whitefish (*Coregonus clupeaformis*), Yellow Perch (*Perca flavescens*), Goldeye (*Hiodon alosoides*), and Rainbow Trout (*Oncorhynchus mykiss*)) were caught during gillnetting with higher catch rates in the vicinity of the cages compared to the control site. DIDSON technology is valuable to assess the behaviour of wild fish surrounding aquaculture infrastructures.

RÉSUMÉ

La technologie d'identification sonar à double-fréquence (DIDSON) a de nombreuses applications en science halieutique. Le DIDSON offre des avantages importants par rapport à d’autres techniques d’échantillonnage puisque cette technologie est non-invasive et ne nécessite pas de capture, de manipulation ou de perturbation des poissons ou de leur environnement. Par conséquent, la technologie DIDSON est bien adaptée pour une utilisation en aquaculture. Les images DIDSON sont construites à partir de fréquences acoustiques permettant l’échantillonnage des données 24 h par jour et dans toutes les conditions de turbidité. À l’aide du DIDSON, nous avons recueilli des données sur la distribution et l’abondance des poissons sauvages avant et après l’aménagement d’un nouveau site aquicole et sur deux sites de contrôle au Lac Diefenbaker en Saskatchewan. Un protocole d’utilisation de la technologie DIDSON a été établi afin d’améliorer la surveillance environnementale des poissons sauvages dans les environnements pélagiques. Les enregistrements de DIDSON ont été standardisés au nombre de poisson détecté par unité d’effort (DPUE en nombre de poissons $\cdot$ 10 m^{-3} $\cdot$ 2 h^{-1}) dans quatre strates de profondeur d’eau pour les trois sites d’étude. L’indice de détection DPUE observé près

des cages aquicoles de Kadla était le plus élevé lors des périodes d'alimentation matinale des poissons d'enlevage présent dans les cages. Durant ces périodes d'alimentation de grands bancs de poissons (50 poissons) ont été détectés près des cages. D'autant plus, des filets maillants ont été déployés afin d'identifier les espèces de poisson détectés par le DIDSON. Six espèces de poissons ont été capturées : cisco (*Coregonus artedi*), doré (*Sander vitreus*), grand corégone (*Coregonus clupeaformis*), perchaude (*Perca flavescens*), laquaiche aux yeux d'or (*Hiodon alosoides*) et truite arc-en-ciel (*Oncorhynchus mykiss*). Tel que l'indique le DPUE, le taux de capture au filet maillant était lui aussi plus élevé à proximité des cages qu'aux sites de contrôle. Nous pouvons conclure que la technologie DIDSON est adéquate afin d'évaluer le comportement de poissons sauvages autour des infrastructures aquicoles.

1.0 INTRODUCTION

In a time when the abundance of wild fish populations is decreasing and commercial fisheries of wild populations are declining, aquaculture helps alleviate stress on wild fish populations (FAO 2013). Estimates predict that by 2030, over half of the fish consumed by the world's population will be produced by aquaculture (FAO 2013). Canada is well positioned to become a world leader in sustainable aquaculture production due to the abundance of "pristine" water resources (Standing Senate Committee on Fisheries and Oceans 2015). However, as the demand for farmed fish increases, there is a risk that aquaculture may affect wild fish populations and consequently the productivity of commercial, recreational, and Aboriginal (CRA) fisheries. Consequently, as the Canadian freshwater aquaculture industry continues to expand there is a need for the development of regulations and policies to ensure sustainable growth within this sector (Report of the Commissioner for Aquaculture Development 2003). The Government of Canada is committed to ensuring the responsible and sustainable development of the aquaculture industry in Canada while protecting fishes that are important for CRA fisheries. Currently, the growth of freshwater cage aquaculture in Canada is limited and future growth is uncertain due to regulatory and environmental challenges (DFO 2015). Therefore, the Canadian government is actively working towards developing policies, regulations, and positive public perceptions that accept and promote the future growth and sustainability of the aquaculture industry. Fisheries and Oceans Canada's Program for Aquaculture Regulatory Research (PARR) supports targeted research on understanding the environmental and biological interactions between freshwater cage aquaculture and the aquatic environment to gain new knowledge and advice to support policy and decision making.

Cage culture of fishes is an intensive form of aquaculture in which fish are raised in mesh nets suspended from floating structures within an existing water resource such as a lake. Cage aquaculture has a high potential for environmental impacts as egested and excreted waste and uneaten food can freely flow through the mesh of the cages into the surrounding environment without treatment. Cage farms also alter the physical structure of the natural environment providing both shelter and a source of food that may attract wild fish species (Dempster 2005). Wild fish communities may be affected by cage farms via a number of different factors such as the physical alteration of habitat, increased noise, release of farm waste, and escaped domestic fish (Dempster et al. 2002, Dempster et al. 2009). These factors may influence fish distributions, trophic relationships, and abundances of wild fish species.

Cage farms have been shown to attract wild fish in various ecosystems (Dempster et al. 2002, Boyra et al. 2004, Dempster et al. 2009, Johnston et al. 2010). Both the physical structure of the cage farms (e.g., cages, anchors, buoys, walkways) and the farming activity itself (released waste and enhanced productivity) could attract wild fish (Gabrielsen 1999, Tuya et al. 2006). Fish can be attracted to the cages for 1) habitat and shelter; 2) waste food; and 3) predation on smaller fish. In northern Lake Huron, Rainbow Trout (*Oncorhynchus mykiss* Walbaum) cage culture operations were found to attract and alter the normal distribution of wild fish (Johnston et al. 2010). Rainbow Trout cage farming also occurs in Lake Diefenbaker and is a potential attractant for wild fish species. In the fall of 2014, fish farm activities expanded to a new site (Kadla Coulee) in Lake Diefenbaker. This occasion was used to monitor the potential impacts of the farm on the surrounding wild fish community.

The objectives of this study were to determine the distribution of wild fish surrounding aquaculture cages with innovative Dual-frequency identification sonar (DIDSON) (Sound Metrics Corporation, Lake Forest Park, Washington, USA) in Lake Diefenbaker, Saskatchewan. The specific research objectives were to determine (i) if there were differences in fish abundance pre- and post- aquaculture development, (ii) if the presence of a fish farm alters the habitat use of wild fish, and (iii) if wild fish were attracted to the fish farm, particularly during the morning feeding period. DIDSON footage was collected before (2011-13) and after (2014-15) the installation of net cages at a new aquaculture site in Kadla Coulee and at a reference site in Lake Diefenbaker. In addition, gillnetting was conducted in the fall (September and October) of 2015 to ground-truth the DIDSON footage. We then compared the detections per unit effort (DPUE) of wild fishes between cage and reference sites in Lake Diefenbaker, Saskatchewan.

2.0 MATERIALS AND METHODS

2.1 STUDY AREA

The study was carried out at an aquaculture cage site in Kadla Coulee (366465 m E; 5652175 m N, UTM Zone 13N) in Lake Diefenbaker in south central Saskatchewan. Lake Diefenbaker is a dimictic and mesotrophic prairie reservoir used for irrigation, hydroelectricity, drinking water, flood control, industry and livestock, and recreation. It is also the site of one of Canada's largest freshwater Rainbow Trout farms.

Formed in 1967 by the Qu'Appelle River Dam and the Gardiner Dam, Lake Diefenbaker is the largest water body within the Saskatchewan River Basin (Figure 1). The commercial aquaculture operation for Rainbow Trout in Lake Diefenbaker has existed since 1993. Historically, Kadla Coulee was the original aquaculture site operated by AgPro Grain Inc. from 1992-1994. Relocation of the cage site from Kadla Coulee to Cactus Bay occurred in 2004 under new management by Wild West Steelhead (WWS). In 2010, WWS applied for a new aquaculture site in Kadla Coulee, Lake Diefenbaker, Saskatchewan to increase production by 300 metric tons (MT) (Environmental Impact Statement[1]). In fall 2014, cages were re-installed in Kadla Coulee

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[1] Application for a new aquaculture site at Kadla Coulee for Wild West Steelhead by Wild West Steelhead and SIMCorp Marine Environmental Inc. March 16, 2010. http://www.environment.gov.sk.ca/2005-190EnvironmentalImpactStatement

with the intent to use the site for juvenile fish rearing before transfer into the adjacent embayment Cactus Bay once the fish grew to a weight of 0.5 kg. The footprint of the cages in Kadla Coulee is approximately 600 m x 200 m (12 ha) with a cage depth of 15 m (Sweeney International Management Corp. 2010).

We examined the response of the wild fish community to cage farms at the site of expansion in Kadla Coulee (hereafter referred to as Kadla cages) in comparison to two reference sites in Kadla Coulee and Friday Bay (Table 1). Kadla Coulee was chosen as a “near reference” site approximately 500 m away from the Kadla cages. The second reference is situated in a nearby bay, hereafter referred to as Friday Bay, approximately 4.5 km away from the cage site.

Table 1. Locations and corresponding water depths of impact and reference sites in Lake Diefenbaker (UTM Zone 13N).

Site		**UTM E**	**UTM N**	**Depth (m)**
Kadla cages	impact	366465 m E	5652175 m N	36
Kadla Coulee	reference	365949 m E	5652128 m N	30
Friday Bay	reference	367136 m E	5647933 m N	23

Three years of baseline data was collected from 2011-2013 prior to the installation of the cages in Kadla Coulee in fall 2014. In 2014 and 2015, DIDSON footage was recorded at the impact site and reference sites while the farm was under full-scale operation.

In total, 50 2-h DIDSON footages were recorded amongst the impact site (Kadla cages) and the two reference sites (Kadla Coulee and Friday Bay) between 2011 and 2015 (Table 2). There were differences in sonar range and resolution between 2011-2014 (low frequency detection mode) and 2015 (high frequency identification mode). Since there is a trade-off between range and resolution, the 2015 data displayed fish at a higher quality for fish total length measurements than in previous years but over a shorter detection range.

2.2 FIELD PROCEDURE

DIDSON sampling design

DIDSON recordings were captured in 2011-2014 primarily in the morning during the regular feeding. In 2015, afternoon and evening (during dusk and full darkness) were also recorded (Table 2).

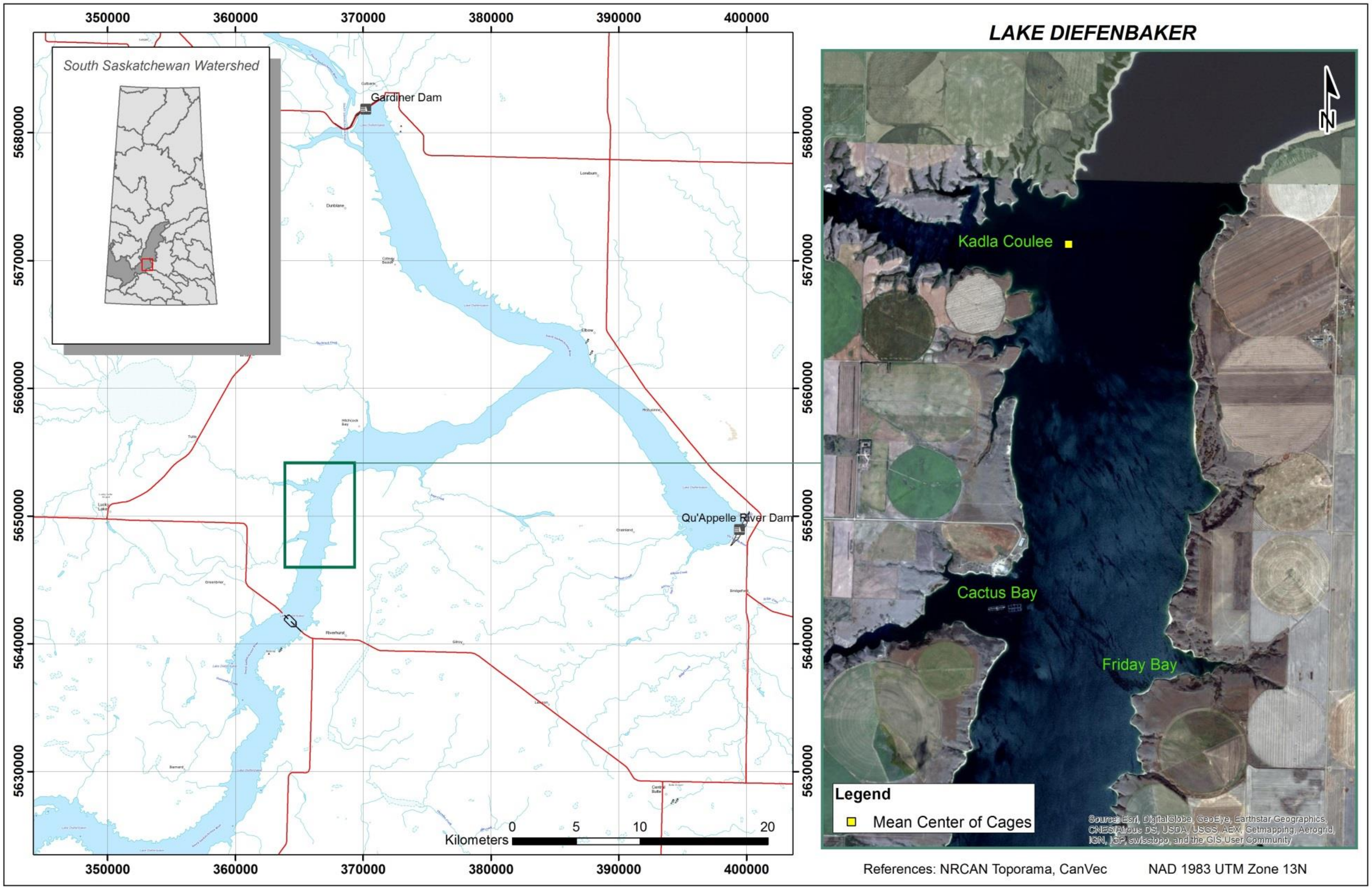


Figure 1. Map of the Wild West Steelhead Aquaculture location in Lake Diefenbaker, a 225 km long reservoir located on the South Saskatchewan River.

Table 2. DIDSON sampling effort summary per year, site, and month (number of recordings in each month).

	Month (number of ~2-h DIDSON recordings) per site		
Year	**Kadla cages**	**Kadla Coulee**	**Friday Bay**
2011	Nov (1)	Jul (1)	Jul (2)
2012	Jun (3)	Jun (3), Jul (1)	Jun (2), May (2)
2013	Jul (1), Aug (2)	Jul (2), Aug (2)	Jun (1)
2014	Oct (3), Nov (1)	Oct (2), Nov (2)	Oct (4)
2015	Sep (2), Oct (4)	Sep (3), Oct (2)	Sep (2), Oct (2)
TOTAL	**17**	**18**	**15**

In 2015, approximately 28 h of DIDSON footage was recorded (Table 3). Each site was monitored twice during September and October for a period of 2-h per site. At the Kadla cages location, two 2-h recordings were captured in the evening of October 21, 2015, and a 3-h recording was captured before, during, and after the fish were fed in the morning of on October 22nd, 2015.

Table 3. DIDSON sampling effort in 2015 summarized by site, date, and time.

Site	Sep 2015 Recordings (2 h)	Oct 2015 Recordings (2 h)
Kadla cages	no morning recording	Oct 22, 8 h (3 h morning)
	(paired evenings) Sep 23, 16 h Sep 24, 22 h	(paired evenings) Oct 21, 14 h Oct 21, 23 h
Kadla Coulee	(paired evenings) Sep 23, 16 h Sep 24, 22 h	(paired evenings) Oct 21, 14 h Oct 21, 23 h
Friday Bay	(paired evenings) Sep 20, 16 h Sep 20, 20 h	(paired evenings) Oct 21, 17 h Oct 22, 19 h

Gillnet surveys

Confirmatory sampling with gillnetting occurred in September and October of 2015. At each study site, three 23 m long single paneled clear monofilament gillnets of graduating mesh sizes of 25 mm, 76 mm, and 127 mm were deployed in parallel within the pelagic column and left to soak (~24 h) overnight.

The nets were deployed approximately 20 m apart at a depth of 5-7 m below surface and anchored with cinder blocks. At the cage site, net sets were placed just outside of the anchor zone marked by the buoys (~20-30 m from cages) to avoid entanglement with the cage anchor lines. Captured fish were identified to species and enumerated while mortalities were disposed of at the fish processing facility. Length measurements were recorded to later ground-truth the results of the fish length obtained from the DIDSON recordings.

2.3 DIDSON EQUIPMENT SET-UP

The DIDSON was mounted to a ROS Helios tilt-pan unit (ROS Remote Ocean Systems, San Diego, California, USA), which was then attached to a custom-designed aluminum frame and secured to a small Jon boat at a depth of approximately 1 m below the water surface (36 cm frame + 32 cm tilt-pan unit + 21 cm DIDSON camera; Figure 2). The DIDSON was powered by a small portable gasoline generator (Figure 3).

The transducer beams were directed downward and slightly forward at an angle of 45° relative to the water surface. During the deployment, the boat was held in a stationary position with anchors or by mooring to the aquaculture cages.

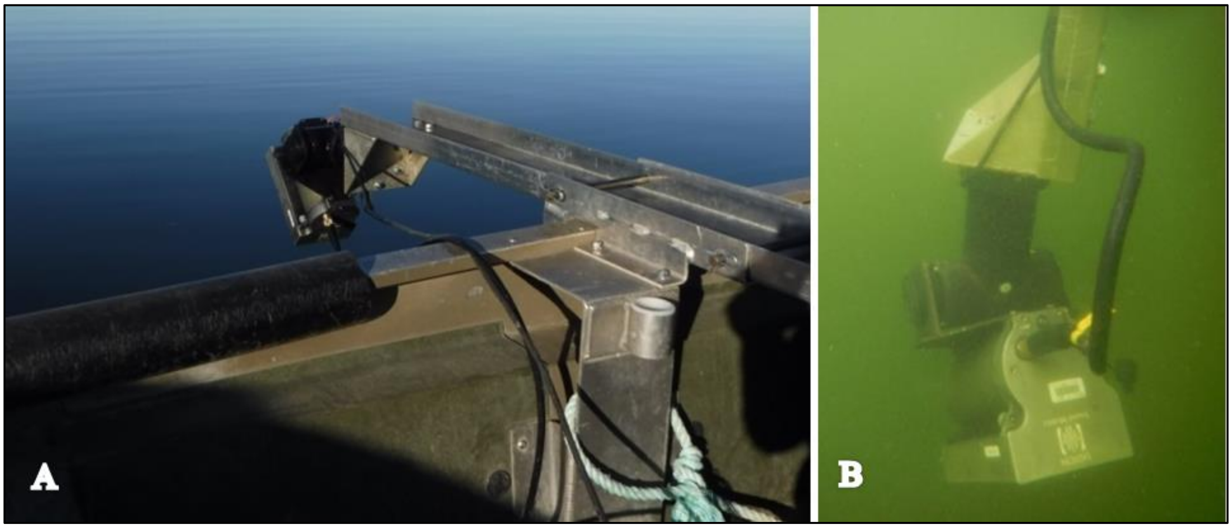


Figure 2. (A) Custom-designed aluminum DIDSON boat mount secured to the starboard side of the boat. (B) The DIDSON was securely mounted with four bolts onto the ROS Helios tilt-pan unit, which was secured to the aluminum mount with six bolts.

A sonar cable connected the DIDSON to a Topside Box which was connected to a field laptop via an Ethernet crossover cable and powered by a generator (Figure 3). A video patch cable was also connected between the Topside Box and field laptop to allow real-time surveys of the DIDSON footage.

2.4 DIDSON SOFTWARE SETTINGS

DIDSON and ROS Helios software packages were installed on the field laptop. Sonar controls including the frame rate, receiver gain, window start, window length and focus were chosen. Auto frequency and auto rate settings as well as low or high frequency mode were selected. After selection of the DIDSON software settings, the recording of a 2-h DIDSON file was started.

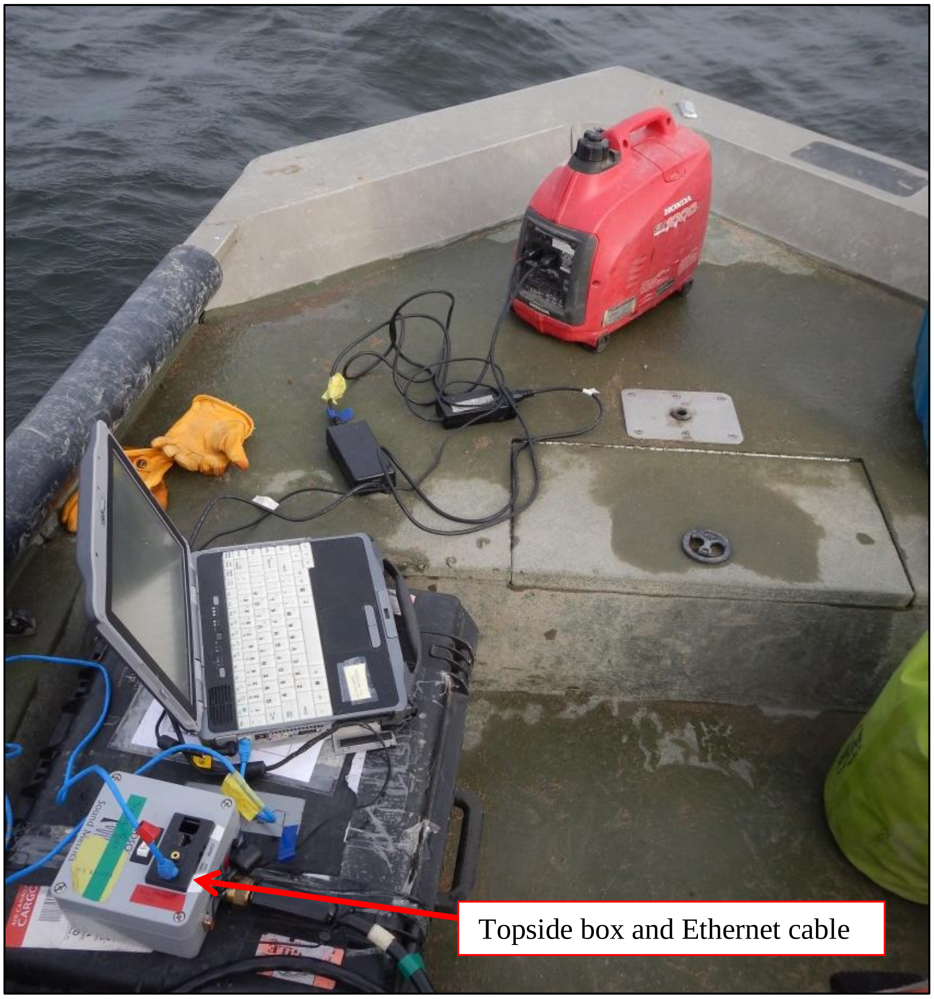


Figure 3. The DIDSON was connected to a field laptop via the topside control box and powered by a generator.

Frame rate (auto frame rate versus manual)

The frame rate (frames·s^{-1}, fps) is the number of still images that are created from the audio signals per second. At a higher frame rate, movement and swimming behaviour can be detected. The frame rate will be slower with increases in maximum range due to a longer time for sound to travel to the maximum range and return. At a low frame rate, there is little ability to detect the difference from floating debris, bubbles or small fish. Data that was captured at 1 fps was not of high enough resolution to isolate individual fish (estimates of school size could be highly inaccurate). It is always recommended to operate at a frame rate of 7 fps or greater. Frame rate can be as high as 25 fps. Higher frame rates will create larger DIDSON data files (*.ddf).

Window start length, end length, range and window length

These settings will result in changes in the “esonified window”, which is a 3D volumetric area, known as an irregular rectangular frustum. The sonar recording will be standardized to this volume and it is therefore important to consider using the same settings for these window length and range parameters amongst the different survey sites.

Additional DIDSON display controls

a. Check off “Reverse” (this allows you to see the image in the proper orientation within the display)
b. Check off “Smooth”
c. Check off “Measure” (allows measurements between displayed objects)

The esonified image is produced from a fan-shaped field-of-view (FOV) pattern across a 29° horizontal and 14° vertical sector. The sonar can be operated in both low frequency (LF) and high frequency (HF) modes. At a low frequency mode (1.1 MHz), the 29° horizontal axis is divided horizontally into 48 separate 0.5° x 14° beams. Larger window lengths (ranges of up to 40 m) can be obtained at a low frequency mode. At a high frequency mode (1.8 MHz), the 29° horizontal axis is divided horizontally into 96 separate 0.3° x 14° beams with a window length (range) of either 5 or 10 m. Each beam is longitudinally divided into 512 equal bins providing high resolution images composed of 96 x 512 data values (Figure 4).

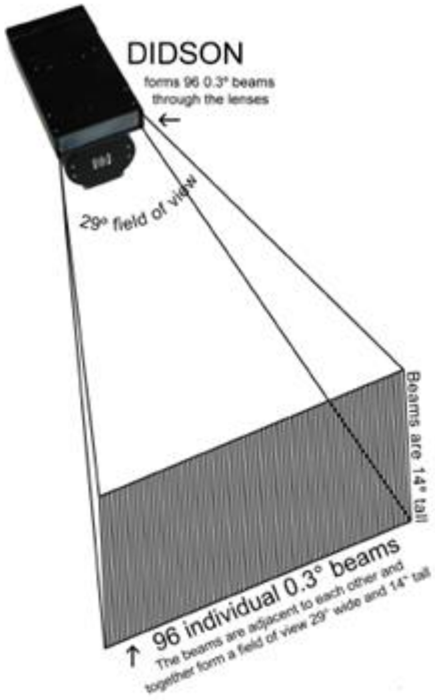


Figure 4. The field-of-view of the DIDSON showing the high frequency setting with 96 beams (Sound Metrics Corporation 2007) .

Data from 2011-2014 was recorded in low frequency (LF) mode. In the LF mode, fish were detected over a 40 m distance 5-45 m away from the transducer lens. Data from 2015 was recorded in high frequency (HF) mode. At the HF mode, fish were detected over a 5 or 10 m distance that was situated 2.5-7.5 m or 2.5-12.5 m away from the transducer lens, respectively.

2.5 DIDSON DATA PROCESSING

Software download

The most current version of the DIDSON software and manual were downloaded from the Sound Metrics website.

1 - Go to http://www.soundmetrics.com/user/login?destination=home and create account
2 – Once logged in select the "Download" icon
3 – Once in the Download webpage select Customers > DIDSON folder
4 – Download folders named Manuals and Software

DIDSON data analysis

Although the DIDSON Software (V5.26.06) provides an auxiliary tool for automated fish counting and sizing, neither the automated counting nor the sizing function were adequate for measuring the pelagic fish in our study. The software was, however, used to visually identify fish on the PC monitor from other objects such as bubbles, anchor lines, cages, etc. The echogram provides a view of the averaged beams in the centre of the sonar image versus time allowing the review of sonar images at 600-frame intervals.

Measurements of fish length were performed using the manual fish measuring feature included in the DIDSON Software (Figure 5). The observer attempted to choose the best frame in which the fish swam perpendicular to the sonar beams and the full length of the fish was visible. When fish were difficult to measure, several frames were checked before and after the analytical frame to confirm the length measurement. Fish processed using the mark-and-measure method received a time stamp. Manual measurements conducted frame by frame were more laborious; however, there was better accuracy and repeatability with manual measurements of each fish-presence event (either school or individual fish). Also abundances were determined manually or, for large schools, by making an estimate of the number of fish and the approximate average total length (based on averages of several measurements). Fish abundance index for fish occurring in the sonar image during each of the 2 h of DIDSON recordings was estimated.

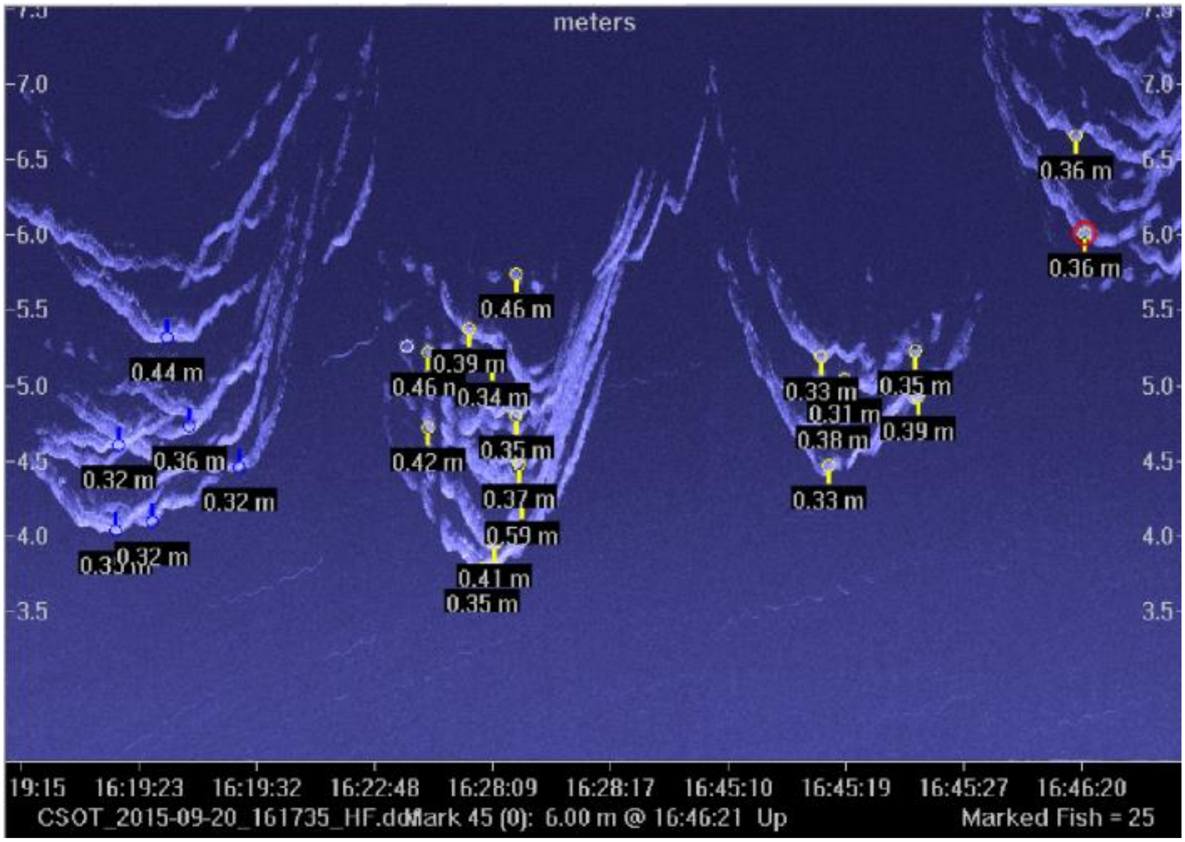


Figure 5. Echogram image showing schools of fish. Fish were marked and their total lengths were determined. The direction of fish movement (blue verus yellow) changed between the different schools of fish, which could have been caused by 1) the same school of fish swimming in and out of the field-of-view or 2) different schools of fish.

The depth of the fish position (m) in the water column was calculated using the following formula based on the sonar tilt and hypotenuse (target distance, *R*, m):

$$Depth_{Fish}(m) = 1.0\ m + \cos(90° - sonar\ tilt) * R$$

where the aluminum mount for the DIDSON was approximately 1 m below the water surface and *R* is the target distance from the sonar lens (i.e., range of the detected fish obtained from the manual measuring tool of the DIDSON Software) (Figure 6).

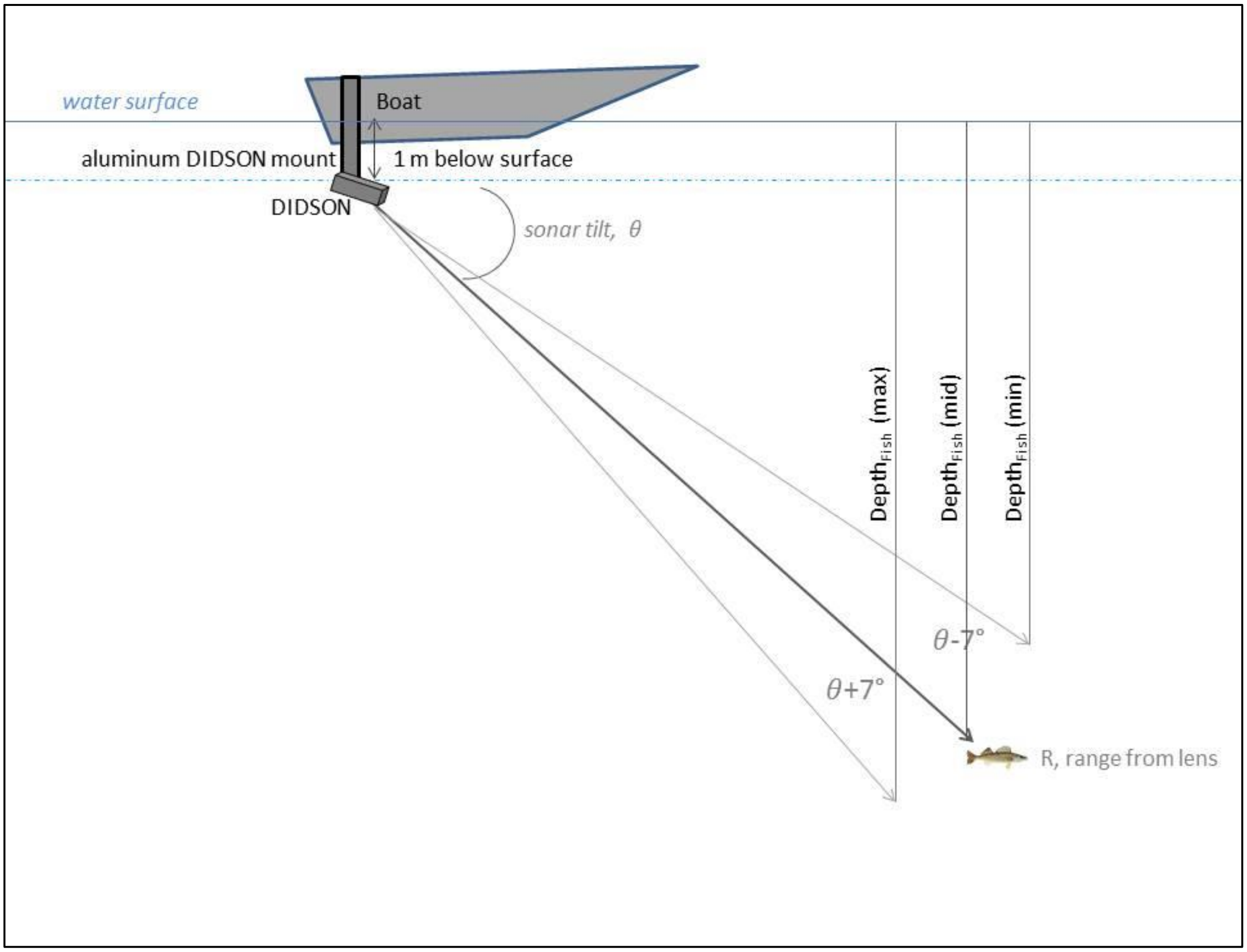


Figure 6. Depth of fish position as calculated from the target distance (R) and the tilt angle (θ) of the DIDSON.

Detection per unit effort (DPUE) calculation

DIDSON data was standardised by calculating the detections per unit effort (DPUE) with one unit of effort in space and time equivalent to the number of fish detected in 10 m^3 of water during a 2 h time period. Water volumes were calculated according to the settings of the DIDSON unit (i.e., angle of the transducer and window length) that were used at a given recording (**Error! Reference source not found.**). Abundance estimates were further categorised n four depth strata (0-4.9 m, 5-9.9 m, 10-14.9 m, 15-19.9 m) surveyed by the DIDSON using a method described in Han and Uye (2009).

Measured fish were classified into three different size bins according to total fish length: (1) 0-29.9 cm; (2) 30.0 - 59.9 cm; and (3) > 60.0 cm. DIDSON images were captured with sufficient resolution to permit the identification of different classes of objects (bubbles, small fish, and debris).

2.6 ENVIRONMENTAL CONDITIONS

Air temperature

We obtained relevant data for the weather condition during DIDSON recordings from the Environment and Climate Change Canada's Historical Climate Database (http://climate.weather.gc.ca/) using data from the Lucky Lake Weather Station (Table 4). We extracted the mean maximum and minimum air temperatures (°C) observed at the location for the relevant month. Additionally, heating degree-days, which are the number of degrees Celsius that the mean temperature is below 18 °C for a given day was calculated. If the temperature is equal to or greater than 18 °C, then the number will be zero. For example, a day with a mean temperature of 15.5 °C has 2.5 heating degree-days; a day with a mean temperature of 20.5 °C has zero heating degree-days.

Table 4. Temperature data from the Lucky Lake Weather Station (Government of Canada 2016).

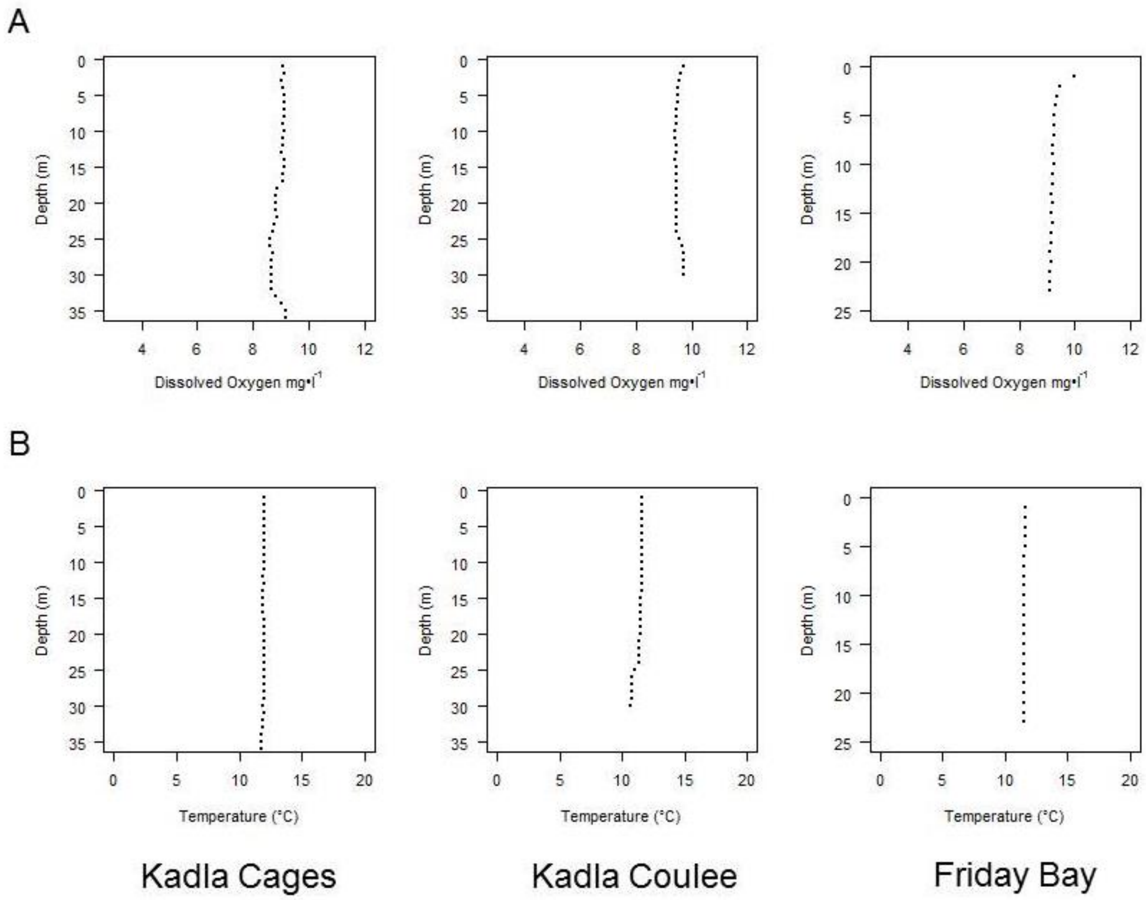
Year	**Month**	**Max temp (°C)**	**Min temp (°C)**	**Mean average daily temp (°C)**	**Sum of total precipitation (mm)**	**Heating degree days**
2011	July	24.8	11.5	18.1	26.0	35.3
	November	1.0	-9.0	-4.0	*na*	660.1
	May	15.9	4.0	10.0	117.2	248.8
2012	June	21.7	9.8	15.8	105.8	75.0
	July	25.9	13.3	19.6	53.4	7.7
	June	21.2	9.4	15.3	89.0	84.0
2013	July	23.6	10.0	16.8	32.4	62.7
	August	26.8	10.1	18.5	21.6	44.6
2014	October	7.8	14.1	1.6	13.2	307.2
	November	-3.7	-12.8	-8.3	18.9	788.3
2015	September	19.3	6.0	12.7	43.3	166.6
	October	13.8	1.3	7.6	30.0	323.9

Water quality

To ensure that study and reference sites were comparable in terms of water quality parameters, temperature and dissolved oxygen were measured during the months of DIDSON deployment. Data was collected at every meter throughout the water column with a multi-parameter sonde (model YSI 600MS, YSI Environmental, Yellow Springs, Ohio, USA) with at least six measures taken at each depth.

Water samples and chemical profiles were collected at the impact and reference sites. At each station, water samples were collected 1 m below the surface and at 10 m intervals until near the lake bottom. Samples were collected with a stainless steel 1.2 l Kemmerer sampler that had been rinsed thoroughly with lake water prior to sampling. Acid-washed 500 ml Nalgene bottles were rinsed three times with sample water and were then filled to overflowing. Lids were closed tightly while slowly squeezing the bottle to dispel as much air as possible and bottles were immediately placed into a cooler with ice and then refrigerated upon returning to shore. Samples were transported to Winnipeg the day after sampling and were processed by the Freshwater Institute Analytical Chemistry Laboratory the day after arriving to Winnipeg. Samples were analysed for suspended, total dissolved, soluble reactive, and total phosphorus; suspended, total dissolved, and total particulate nitrogen; total suspended solids; and conductivity using methods outlined in Stainton (1977).

An ordination analysis was conducted to assess the similarities and differences in water chemistry between cage and reference sites. A matrix of Bray-Curtis dissimilarities between 612 water samples was calculated and subjected to a nonmetric multidimensional scaling (NMDS). From 20 random starts in two dimensions, the minimum stress value of 0.05 was achieved. The dimensionality was determined using the scree plot of stress versus dimensionality. The goodness of fit was determined by the nonmetric r^2-value based on stress S from the Shepard plot. Distinct groupings between the three sites based on water chemistry were not apparent (Figure 7. Depiction of the water chemistry (suspended phosphorus [SUSPP, µg·l-1], total dissolved phosphorus [TDP, µg·l-1], soluble reactive phosphorus [SRP, µg·l-1], total phosphorus [TP, µg·l-1], suspended nitrogen [SUSPN, µg·l-1], total dissolved nitrogen [TDN, µg·l-1], and total nitrogen [TN, µg·l-1], total suspended solids [TSS, mg·l-1], and conductivity [µS·cm-1 at 25 °C] in Kadla cages (n=196), Kadla Coulee (n=210), and Friday Bay (n=215) sampled at various depths from 2011 to 2015.



All statistical analyses were conducted using R version 3.1.3 (R Core Team 2015).

Inspection of depth profiles between the three sites (Kadla cages, Kadla Coulee, and Friday Bay) showed little variability in the temperature and dissolved oxygen profiles between sites (Figure 8). Lake Diefenbaker is known to be a well-mixed reservoir (Saskatchewan Water Security Agency 2012)

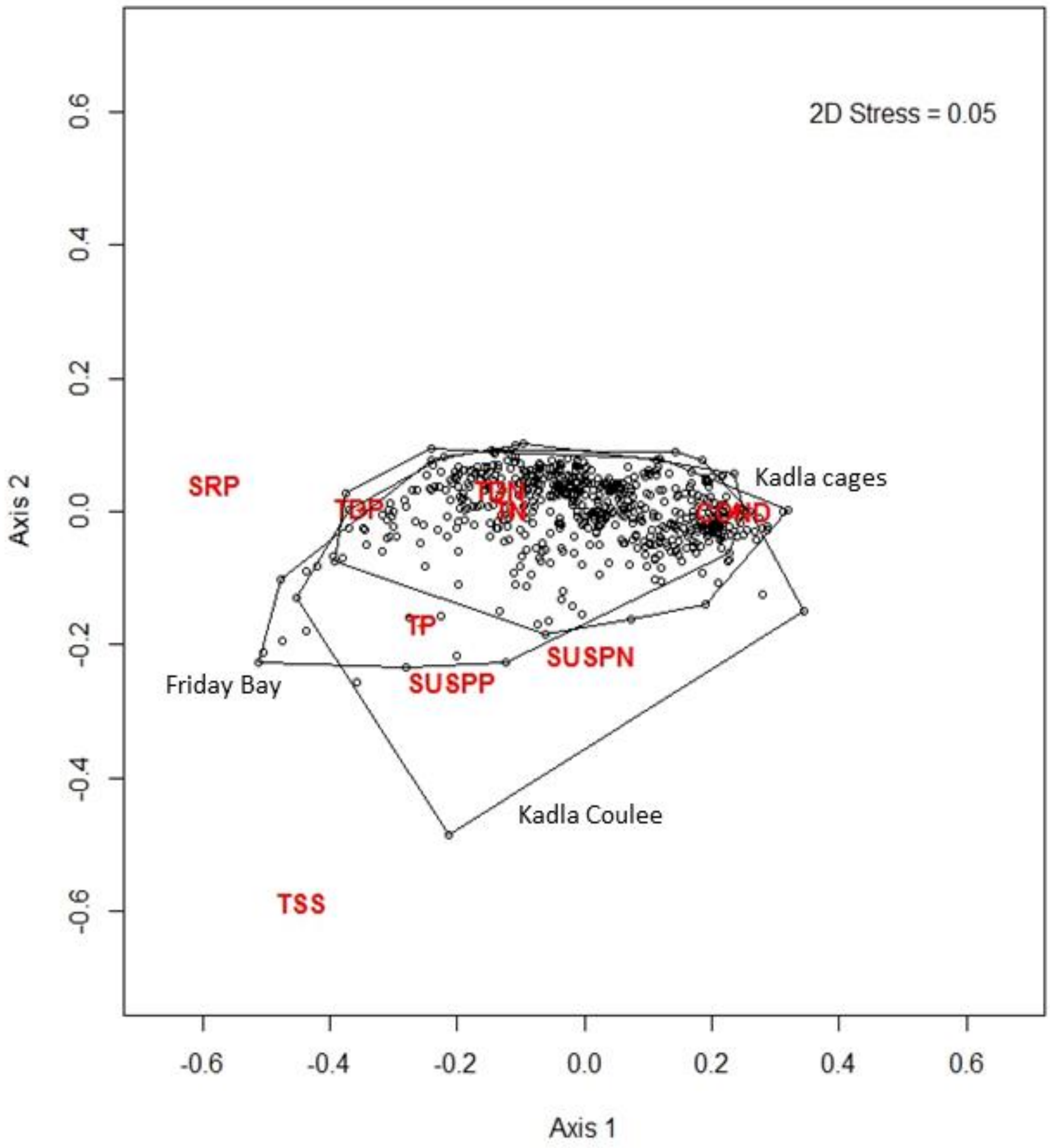


Figure 7. Depiction of the water chemistry (suspended phosphorus [SUSPP, µg·l^{-1}], total dissolved phosphorus [TDP, µg·l^{-1}], soluble reactive phosphorus [SRP, µg·l^{-1}], total phosphorus [TP, µg·l^{-1}], suspended nitrogen [SUSPN, µg·l^{-1}], total dissolved nitrogen [TDN, µg·l^{-1}], and total nitrogen [TN, µg·l^{-1}], total suspended solids [TSS, mg·l^{-1}], and conductivity [µS·cm^{-1} at 25 °C] in Kadla cages (n=196), Kadla Coulee (n=210), and Friday Bay (n=215) sampled at various depths from 2011 to 2015.

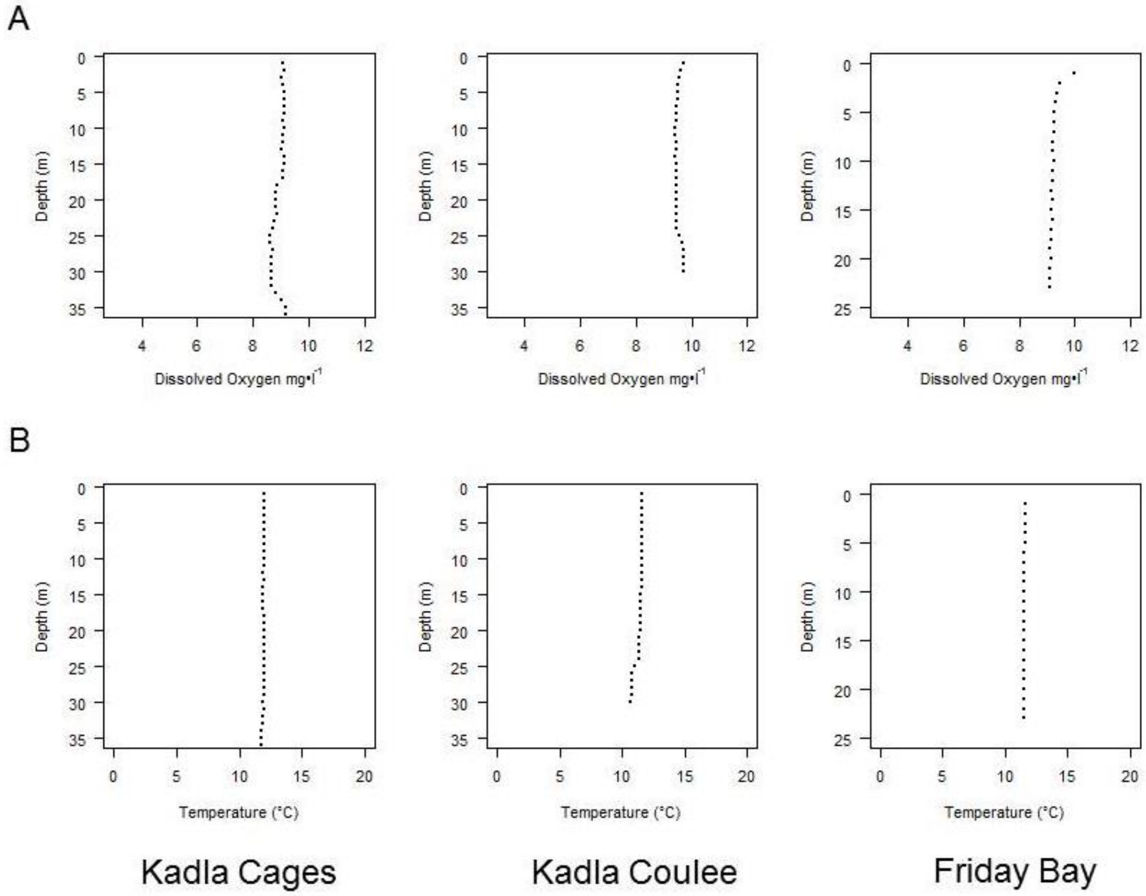


Figure 8. Examples of (A) dissolved oxygen and (B) temperature profiles at the Kadla cages, Kadla Coulee, and Friday Bay locations taken in October 2014 after the installation of the aquaculture cages.

Calculation of the resolution of the sonar images

The clarity of DIDSON images is determined by both the window length and the frequency.

Down-range resolution = Y Pixel height = *window length* / 512

where *window length* is the R (range from the lens)

Cross-range resolution = X Pixel height = $R \cdot \sin(\textit{beam spacing})$

where *beam spacing* is 0.6° for LF and 0.3° for HF

The cross-range resolution is non-linear across the field of view, because of the behaviour of the acoustic lens. The beams in the centre are slightly wider than 0.3° at HF and slightly narrower at the edges of the image.

The measurement uncertainty is about ± one beam cross range width (assuming the fish is primarily at a side aspect to the sonar). Fish with a head/tail aspect are very hard to measure accurately.

In LF, at a range of 5-45 m away from the lens, sample resolution varied between 0.39-7.81 cm in the horizontal plane and 2.09-41.89 cm per pixel in the vertical plane (Appendix 1). Consequently, images with smaller window lengths are better resolved as the DIDSON display is limited to 512 samples (pixels).

In HF, at a range of 2.5-12.5 m away from the lens, resolution varies between 0.20-2.54 cm per pixel in the horizontal plane and 0.52-6.81 cm per pixel in the vertical plane (Appendix 1). At this resolution, objects as small as 8 cm are readily identified as a fish in the very near field of view. However, at the furthest detectable distance from the lens a fish of 8 cm is represented by only a couple of pixels and may be undetectable.

2.7 FEEDING OF THE AQUACULTURE FISH

Fish feeding at Kadla Coulee occurred mostly during weekdays while the farm was fully-staffed. However, up to 5-day intervals with no feeding took place (no feeding from September 17-21, 2015). WWS farm workers fed the fish 3 mm and 4 mm pelleted feed by using an automated dispenser on a barge. Different lots of fish were placed in each cage and fed different pellet sizes and amounts according to the size requirement. WWS used automated food dispensers and staff monitored the fish consumption rates to avoid overfeeding. The amount of feed applied to the cages was determined by feeding tables (based on water temperature and fish size) to produce conservative feed rates at approximately 80% capacity as well as visually whereby fish were allowed to feed fully once per week until staff observe a deceleration in feeding activity (Table 5). The average feed conversion ratio of feed:gain is 1.22-1.25:1 for the Rainbow Trout raised in Lake Diefenbaker (Podemski et al. in preperation).

In both 2014 and 2015, the fish were transferred from the hatchery into the net cages while cages were located in Cactus Bay. These juvenile fish were then towed in their net cages to Kadla Coulee and fixed in place to the anchoring system and associated gear. The duration of installation and cage configuration varied from 2014 to 2015 (Figure 9). In 2014, fish occupied Kadla Coulee for approximately two full months (September and October). In 2015, the cages were installed for approximately four full months (July, August, September, and October). The cage structure was removed from Kadla Coulee in the fall before freeze-up and fish were transferred into cages at Cactus Bay for the final stages of growth.

Figure 9. (A) The 2014 and (B) 2015 configuration of Kadla cages with an arrangement of four or five cages in a cross pattern. The 5th cage was only temporarily installed.

Table 5. Summary of pellet feed applied to the Kadla cages in 2014 and 2015.

Year	Month (number of days during the month fish were fed)	Metric tons of feed applied
2014	September (19)	11.52
	October (12)	11.60
	Total Feed	**23.12**
2015	July (15)	3.72*
	August (16)	5.96*
	September (19)	13.66
	October (16)	17.58
	Total Feed	**40.92**

Note: No data during 2011-2013 as fish were first moved to Kadla Coulee on September 5, 2014. *Less feed was presented in the summer months when water temperature increased.

3.0 RESULTS

3.1 FISH DETECTION-PER-UNIT-EFFORT USING THE DIDSON

The number of fish observed in a given recording varied between 2-160 at Kadla cages, 0-124 at Kadla Coulee, and 0-174 at Friday Bay (Table 6, 7, and 8). Low number (DPUE = 0-3) of fish were observed in lower depth strata (10-19.9 m) at all three study sites. In the upper depth strata, DPUE varied widely. At the Kadla cages, DPUE was 0-19 in the uppermost strata (0-4.9 m) and ranged from 0-20 DPUE in the 5-9.9 m depth strata. In comparison, fewer fish were observed at Kadla Coulee in the upper water column ranging from 0-4 DPUE at 0-4.9 m and 0-10 DPUE at 5-9.9 m. At Friday Bay, a very wide range was observed due to repeatedly counting the same school of fish. On September 20 (evening: 4:17 pm), numerous schools were counted and measured within a short period of time. This is an example where fish counts may be overestimated due to fish milling within the esonified area of the DIDSON. The observed schools of fish consisted of fish of the same size range.

Table 6. Total number of fish observed in recording, length of recording, fish detection-per-unit-effort (DPUE in number of fish $\cdot 10\ m^{-3} \cdot 2\ h^{-1}$) in four depth strata (0-4.9, 5-9.9, 10-14.9, and 15-19.9 m), and maximum observation depth (m) at the Kadla cages.

Date	Fish (n)	Time (min)	DPUE 0 to 4.9	DPUE 5 to 9.9	DPUE 10 to 14.9	DPUE 15 to 19.9	Max depth
November 3, 2011 (am)	82	115	0.47	0.38	0.00	na	13.5
June 28, 2012 (am)	6	18	0.00	3.68	0.00	0.00	31.5
June 29, 2012 (am)	13	119	1.06	1.17	0.00	0.00	32.2
June 8, 2012 (am)	24	119	0.00	1.81	0.33	0.00	33.7
August 1, 2013 (am)	98	120	0.00	2.86	2.23	0.96	37.7
August 2, 2013 (am)	98	121	0.00	5.49	2.26	0.59	37.7
July 3, 2013 (am)	20	120	0.00	1.96	0.52	0.03	39.1
November 1, 2014 (am)	130	118	3.15	4.09	1.39	0.39	30.1
October 15, 2014 (am)	58	119	0.89	4.34	0.13	0.03	31.0
October 16, 2014 (am)	33	120	0.00	0.00	0.75	0.13	30.8
October 30, 2014 (am)	19	120	0.78	0.32	0.17	0.10	30.1
October 21, 2015 (pm)	3	125	0.86	0.27	na	na	9.6
October 21, 2015 (pm)	5	120	1.04	0.46	na	na	8.1
October 22, 2015 (am)	160	189	19.06	19.53	1.42	na	11.7
October 22, 2015 (am)	5	17	17.77	0.00	na	na	8.0
September 23, 2015 (pm)	2	123	1.10	na	na	na	4.8
September 24, 2015 (pm)	3	121	1.67	na	na	na	4.6

Table 7. Total number of fish observed in recording, length of recording, fish detection-per-unit-effort (DPUE in number of fish $\cdot 10\ m^{-3} \cdot 2\ h^{-1}$) in four depth strata (0-4.9, 5-9.9, 10-14.9, and 15-19.9 m), and maximum observation depth (m) at the reference site in Kadla Coulee.

Date	Fish (n)	Time (min)	DPUE 0 to 4.9	DPUE 5 to 9.9	DPUE 10 to 14.9	DPUE 15 to 19.9	Max depth
July 26, 2011 (am)	124	117	1.34	10.24	1.09	0.09	33.6
July 5, 2011 (am)	3	120	1.77	0.09	0.00	0.00	31.0
June 4, 2012 (am)	2	105	0.00	0.00	0.08	0.00	32.2
June 1, 2012 (am)	2	122	0.00	0.21	0.00	0.00	32.9
June 4, 2012 (am)	0	15	0.00	0.00	0.00	0.00	32.4
August 7, 2013 (am)	124	115	0.00	7.29	2.75	1.04	37.7
August 9, 2013 (am)	78	120	0.00	5.33	1.56	0.50	37.6
July 4, 2013 (am)	28	118	0.00	2.13	0.67	0.06	37.0
July 8, 2013 (am)	57	120	0.00	8.23	0.05	0.00	36.7
November 2, 2014 (am)	27	120	0.77	1.25	0.23	0.03	30.0
November 5, 2014 (am)	22	119	0.79	0.56	0.31	0.09	31.0
October 17, 2014 (am)	37	127	0.00	0.88	0.48	0.20	31.7
October 18, 2014 (am)	34	119	0.93	0.90	0.49	0.12	31.3
October 21, 2015 (pm)	10	122	1.03	1.21	*na*	*na*	8.1
October 21, 2015 (pm)	4	120	0.82	0.42	*na*	*na*	9.3
September 23, 2015 (pm)	6	117	3.68	*na*	*na*	*na*	5.1
September 23, 2015 (pm)	5	88	4.13	*na*	*na*	*na*	5.1
September 24, 2015 (pm)	0	65	0.00	*na*	*na*	*na*	4.7

Table 8. Total number of fish observed in recording, length of recording, fish detection-per-unit-effort (DPUE in number of fish·10 m^{-3}·2 h^{-1}) in four depth strata (0-4.9, 5-9.9, 10-14.9, and 15-19.9 m), and maximum observation depth (m) at the reference site in Friday Bay.

Date	**Fish (n)**	**Time (min)**	**DPUE 0 to 4.9**	**DPUE 5 to 9.9**	**DPUE 10 to 14.9**	**DPUE 15 to 19.9**	**Max depth**
July 22, 2011 (am)	61	119	0.78	1.43	0.41	0.36	30.1
July 22, 2011 (am)	43	120	0.82	0.74	0.76	0.11	30.5
June 25, 2012 (am)	1	112	0.00	0.00	0.00	0.02	31.8
June 26, 2012 (am)	3	124	0.00	0.26	0.00	0.00	31.4
May 29, 2012 (am)	2	121	0.00	0.10	0.04	0.00	32.9
May 30, 2012 (am)	0	122	0.00	0.00	0.00	0.00	32.2
June 28, 2013 (am)	167	121	0.00	14.15	1.74	0.95	36.9
October 14, 2014 (am)	174	119	0.88	14.50	0.10	0.03	30.9
October 28, 2014 (am)	13	120	0.78	0.32	0.06	0.07	30.1
October 29, 2014 (am)	42	120	0.78	0.71	0.20	0.37	30.1
October 3, 2014 (am)	27	112	0.00	2.24	0.07	0.02	31.1
October 21, 2015 (pm)	35	122	14.24	1.19	*na*	*na*	8.2
October 22, 2015 (pm)	5	97	2.14	0.37	*na*	*na*	8.4
September 20, 2015 (pm)	155	120	61.52	304.80	*na*	*na*	5.2
September 20, 2015 (pm)	15	124	5.48	*na*	*na*	*na*	5.0

3.2 DIFFERENCES IN FISH ABUNDANCE PRE- AND POST-DEVELOPMENT

There was an increase in wild fish abundance around the net cages when comparing the average DPUE of 0.22 ± 0.41 fish·10 m^{-3}·2 h^{-1} at the Kadla cages from 2011-2013 in the upper most depth strata before installation of the cages with the DPUE of 4.63 ± 7.32 fish·10 m^{-3}·2 h^{-1} after the installation of the cages.

The 0-4.9 m depth strata of is the most comparable between all recording conducted at different high and low frequency settings (Table 9). DPUE at the Kadla cages was highest during the early morning feeding period when large schools of fish (50 fish) were detected. The increase in DPUE in Friday Bay in 2014-15 is due to the repeated counting of milling fish.

Table 9. Summary of the average, standard deviation (S.D.), minimum (Min), and maximum (Max) Detection-per-Unit-Effort (DPUE in number·10 m^{-3}·2 h^{-1}) according to the depth strata at the impact site (Kadla cages) and at two reference sites (Kadla Coulee and Friday Bay).

Depth Strata	Site	Years	n	Average DPUE	S.D. DPUE	Min DPUE	Max DPUE
0 – 4.9 m	Kadla cages	2011-2013	7	0.22	0.41	0.00	1.06
		2014-2015	10	4.63	7.32	0.00	19.06
	Kadla Coulee	2011-2013	9	0.34	0.69	0.00	1.77
		2014-2015	9	1.35	1.50	0.00	4.13
	Friday Bay	2011-2013	7	0.23	0.39	0.00	0.82
		2014-2015	8	10.73	21.06	0.00	61.52

3.3 ATTRACTION OF WILD FISH TO THE FISH FARM DURING FEEDING PERIODS

Large differences in the abundance of wild fish (DPUE) close to the aquaculture cages were observed during the morning relative to evening feeding periods. For example, September and October 2015, average DPUEs of 19.06 and 17.77 fish·10 m^{-3}·2 h^{-1}, respectively, were observed in the morning whereas the DPUEs were only 0.86 and 1.04 fish·10 m^{-3}·2 h^{-1}, respectively, during evenings in the upper water strata (0-4.9 m). These results indicate that wild fish preferentially move to the net cages during the morning feeding.

3.4 SPECIES ABUNDANCE IN GILLNET SURVEYS

Overall, 114 fish comprising six different species were caught during the gillnet surveys. In the September survey, 41 fish were caught, whereas 73 fish were caught in the October. Most fish (n = 63) were caught near the aquaculture site at Kadla cages (25 in Sep., 38 in Oct.). Only 28 fish were caught at Kadla Coulee and 23 fish in Friday Bay.

Cisco (*Coregonus artedi*) were the most abundant with 79 individuals caught, followed by 27 Walleye (*Sander vitreus*) and four Lake Whitefish (*Coregonus clupeaformis).* Only two Yellow

Perch (*Perca flavescens)*, one Goldeye (*Hiodon alosoides)*, and one non-native Rainbow Trout (*Oncorhynchus mykiss*) were captured in gillnets.

According to the mean size of each species caught, it is possible to gain insight into which species could have been present in the echogram; small fish of 0-29.9 cm total length (L_t) are likely Yellow Perch, Cisco, Whitefish or Rainbow Trout; medium fish of 30.0-59.9 cm L_t Cisco, Walleye or Whitefish; and fish > 60.0 cm are likely larger Walleye (Table 10). The largest fish caught was a Walleye (L_t: 55.8 cm) at Kadla cages.

Catch-per-unit-effort (CPUE) at Kadla cages was higher than the reference sites in September and October 2016. The combined mean CPUE at Kadla cages was greater than (0.45 (±0.63 S.D.) fish·m^{-2}·min^{-1}) the reference site at Kadla Coulee (0.13 (±0.26 S.D.) fish·m^{-2}·min^{-1}) and Friday Bay (0.12 (±0.14 S.D.) fish·m^{-2}·min^{-1}) (Figure 10). These CPUE results corresponded with the DPUE of the DIDSON.

Table 10. Gillnet catch data from 2015 summarizing the mean (S.D.) total length (mm) and the number of fish among species captured at the three different locations on Lake Diefenbaker, SK.

Site	**Date**	**Cisco**	**Goldeye**	**Rainbow Trout**	**Walleye**	**Whitefish**	**Yellow Perch**
Kadla cages	Sep	293 (28) n=18	355 (*na*) n=1	0	443 (72) n=5	425 (*na*) n=1	0
Kadla cages	Oct	291 (28) n=28	0	0	363 (43) n=10	0	0
Kadla Coulee	Sep	278 (*na*) n=1	0	0	364 (*na*) n=1	0	0
Kadla Coulee	Oct	298 (11) n=21	0	230 (*na*) n=1	371 (56) n=3	285 (*na*) n=1	0
Friday Bay	Sep	303 (29) n=10	0	0	402 (84) n=4	0	0
Friday Bay	Oct	291 (*na*) n=1	0	0	370 (94) n=4	433 (31) n=2	217 (19) n=2

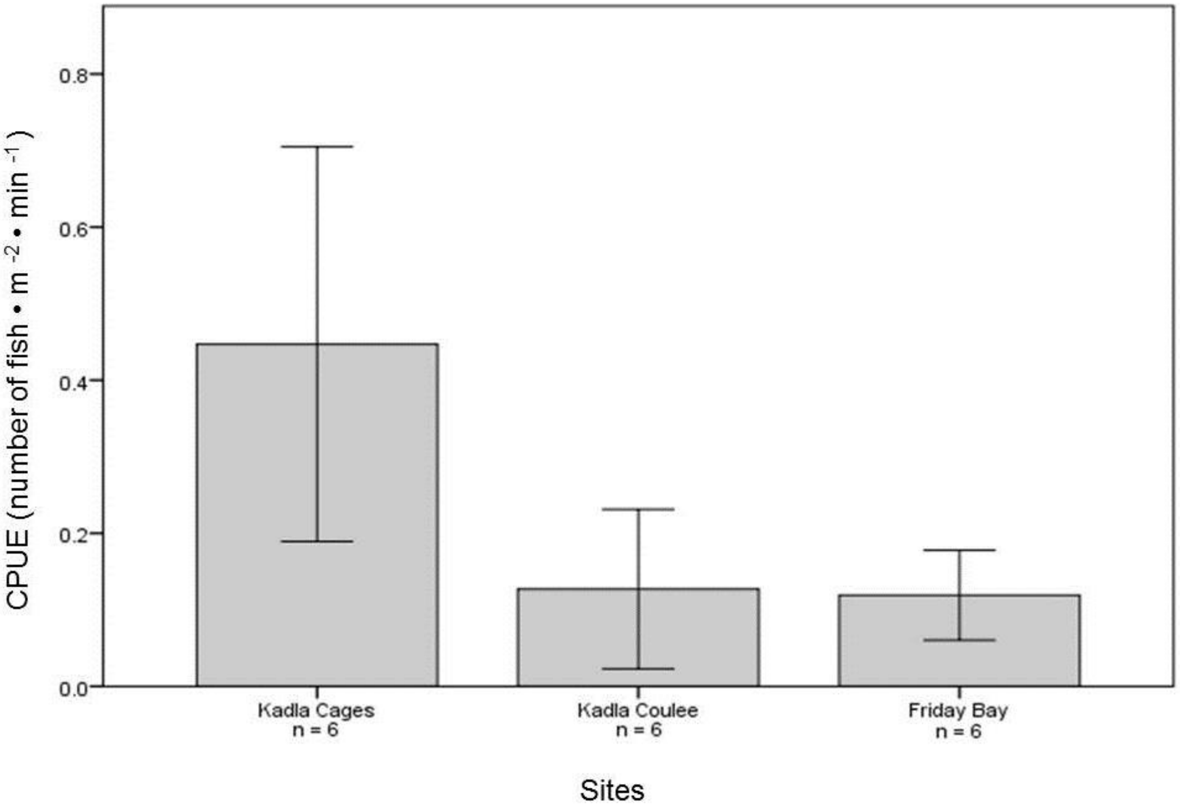


Figure 10. Average catch-per-unit-effort (CPUE) for fish abundance at the impact site Kadla cages and two references sites Kadla Coulee and Friday Bay in Lake Diefenbaker, SK. Error bars represent ± 1 standard error (S.E.) and n= the number of gill net sets per location.

4.0 DISCUSSION

4.1 DIDSON APPLICATION FOR AQUACULTURE IMPACT MONITORING

The aim of this study was to test the efficacy of the DIDSON technology for imaging and enumeration of the wild fish community surrounding a Rainbow Trout aquaculture farm in the freshwater environment of Lake Diefenbaker, Saskatchewan, Canada. The fish counting capability of the DIDSON technology has been shown to generate accurate accounts in river settings when counting upstream migrating adult salmon (Holmes et al. 2006, Maxwell and Gove 2007), American Shad (*Alosa sapidissima*), Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*), Striped Bass (*Morone saxatilis*), White Perch (*Morone americana*), and Channel Catfish (*Ictalurus punctatus*) (Hightower et al. 2013, Grote et al. 2014). The DIDSON has also been used for monitoring smolt behaviour (Moursund et al. 2003), salmon redds (Tiffan et al.

2004), and studying fish behaviour surrounding traps and fishway entrances (Baumgartner et al. 2006).

This study demonstrated that the DIDSON technology can be used to explore the distribution of the pelagic community of wild fishes surrounding aquaculture cages. Estimates of fish lengths can be obtained and predictions of species compositions can be made by ground-truthing with gillnet surveys. However, due to the patchiness in the occurrence of the wild fish, a high level of effort has to be invested in the length and frequency of the DIDSON survey to obtain reliable data. Results from this study present a snap-shot of the composition (in terms of size), distribution, and abundance of wild fish within the pelagic environment (0-20 m) in the cage-impacted and reference locations on Lake Diefenbaker.

Our results provide evidence that the aquaculture cages function as a floating fish aggregating devices (FADs) (Dempster 2005) and attract fish towards the net cages particularly during feeding times. As observed by Goodbrand et al. (2013), we saw wild fish distribution being impacted by the aquaculture cages, which function as a novel and highly predictable resource patch. Feeding and physical structure of the cages provides shelter and habitat, impacting the distribution of the wild fish community (Dempster et al. 2005).

Influences of aquaculture cages on fish distribution are likely to depend on the scale and stage of the aquaculture operation. Kadla Coulee is operated as a satellite site of Cactus Bay in Lake Diefenbaker for rearing juvenile fish. Therefore, impacts on the wild fish community are likely smaller than a full operating aquaculture site raising adult fish to market size. In comparison to the North Channel of Lake Huron, where cage farms have been in operation for 12 years, there are likely lower impacts at the Kadla Coulee location as the operation was only in place for the past two years and the feeding of the juvenile stages in aquaculture production was less intensive with lower faecal production. In addition, the Kadla cages are not permanently installed all year round at this location but are removed during the winter months. This period of fallowing may help reduce impacts to the lake by (1) providing time for bacterial breakdown and assimilation of organic material on the lake bottom, (2) dispersing of the organic material due to a strong flow-through in the spring freshet, and (3) inaccessibility of supplementary food and habitat sources for wild fish due to removal of the cages (Podemski in preparation).

4.2 ASSUMPTIONS AND LIMITATIONS OF DIDSON DATA

This study demonstrated that a fixed DIDSON station is capable of surveying a large volume of water within the pelagic environment surrounding an aquaculture site. The images enabled the identification of fish, enumeration, and determination of their spatial distributions. Movement, size, and outline are key characteristics to identify fish species. Species identification is highly unlikely unless there are clear and consistent differences in fish size or behaviour (Holmes et al. 2006). However, at the low frequency setting the DIDSON (300 m Standard and Long Range) was not effective in determining species composition since it was not possible to identify species based upon outline and size.

There are a few drawbacks to the DIDSON technology in this study (Table 11):

1. size limit on sonar detection,
2. depth limitation (depends on window length and transducer tilt),
3. surface blind zone (closest to the lens (0.0-0.84 m), and
4. compromise between range and resolution.

Since we focused only on pelagic fish when surveying fish response to aquaculture, one major concern with using DIDSON for abundance estimates is the potential for counting-bias (sedentary species = transect designs versus active swimmers = fixed radius or point-count surveys). Many of the records could be from the same individuals observed multiple times as it is not possible to distinguish if fish have been marked and measured repeatedly. A school of fish exhibiting back-and-forth behaviour could inflate the total fish counts as the school could be measured numerous times.

Fish sizing errors are considered to be mainly caused by the following reasons:

1. the angle of the inclination of the fish in the vertical direction,
2. the resolution in the ranging direction, and
3. the circumferential resolution (may result in smaller measurement values).

It was particularly challenging to detect and measure individual fish that school in tight groups within the acoustic beam. Another shortcoming has been DIDSON's inability to detect small (< 40 mm) fishes (Boswell et al. 2008) or to effectively separate these from bubbles, acoustic noise, and non-fish particulates. However, reasonable measurements from free swimming fish in close distances to the DIDSON (<12 m) were obtained with the high frequency 1.8 MHz) mode in our study similar to other studies (Burwen et al. 2010). Acoustic instruments, such as high-definition imaging sonars, can assess the population of wild fish both vertically and horizontally during all hours. In addition, Grote et al. (2014) demonstrated that the DIDSON may be used as an effective tool for estimating species proportions based on length frequencies distributions, provided that limited number of species are present and size overlap among the species is limited.

In some cases, recordings were captured at slow frame rates (1-4 frames$\cdot$s^{-1}; fps). Fish were more challenging to detect and measure with a frame rate that is slower than 8 fps. Due to various constraints, the number of data collected between replicates, sites, and years was sparse and interpretation based on this information is limited to interpreting anecdotal observations. It is possible that normal seasonal and daily variations in fish movement and behaviour confounded the result of the study, i.e., fish are more active in the morning during feeding and will, therefore, have higher abundance or detections in the morning DIDSON recording.

Table 11. Advantages and disadvantages of DIDSON.

Advantages	Disadvantages/Challenges
- Transect designs versus fixed radius or point-count surveys - Salmon counting in rivers (unidirectional movement of large fish) - DIDSON images can be generated during day/night and regardless of the turbidity - DIDSON does not disturb or attract fauna, non-destructive for fish habitat and non-intrusive detection of fish - Selected behavior (schooling, predator-prey, swimming behaviour, and other social interactions) under natural conditions - Ability to view large fish - Sample rare/endangered fish (no chance of mortality and no sampling permits required) - Advantages over the split-beam sonar include deployment over a wider range of site conditions, a more straightforward visual image is produced, less training for technicians is required, easier setup and deployment, potential to have increased capacity for species determination under some conditions	- Inability to detect small (<40 mm) fish - Bubbles, acoustic noise, non-fish particulates can be confused with small fish - Measurement bias (subjective) - Typical range of DIDSON (1.5 - 7 m) - Difficult to operate from a boat because of changing tilt pan angle (particular when boat is rocking, angle can change by ~5°) - Bias from double counting fish that are milling or swimming in vicinity of cages - Expensive

4.3 ALTERATION IN HABITAT USE OF WILD FISH DUE TO FISH FARM PRESENCE

In Canada, the production of aquaculture has increased four-fold since the early 1990's and continues to expand with the increasing demand for seafood. Currently, freshwater aquaculture comprises a small percentage of the overall aquaculture industry. It has been shown that cage culture facilities can function as floating pelagic structures that appear to attract wild fish (Phillips et al. 1985, Dempster et al. 2002, Boyra et al. 2004, Dempster et al. 2009, Johnston et al. 2010). Increases in presence, abundance, and biomass of wild demersal and pelagic fishes in the immediate vicinity of net cages have been observed particularly in marine environments (Dempster et al. 2002, Boyra et al. 2004, Dempster et al. 2009). In a freshwater aquaculture operation, Johnson et al. (2010) reported approximately 1.5-2.3 times higher fish abundance at aquacultures sites compared to reference sites (Johnston et al. 2010). In contrast, at marine aquaculture sites, wild fish abundances have been observed to be >50 times higher than at reference sites (Dempster et al. 2002, Tuya et al. 2006, Dempster et al. 2009).

Similarly, our study demonstrated an increase in wild fish abundance around aquaculture cages in a freshwater environment of Lake Diefenbaker. These results were corroborated in the gillnet catches as catch-per-unit-effort (CPUE) at Kadla cages was higher than at the reference sites both in September and October 2016. Consequently, observations indicate the cages function as fish aggregating devices (FADs). Fish are likely using the habitat surrounding the fish farm for several reasons: larger predatory fish (presumably Walleye based on ground-truthing) appear to perform forage movements to feed on pellets that fall through the cages. Schools of smaller fish (likely Cisco) seem to use the net cages as food sources. These results support findings by Tuya et al. (2006), who found that daily feeding and presence of caged fishes affect wild fish more than the added structure due to cages and moorings or the artificial reef effect in aggregating wild demersal fishes at the farm. This result implies that aggregations of wild fishes around fish farms may substantially decline if levels of feed loss from operating farms to the environment are significantly reduced. However, feed loss at Kadla cages is considered very low (personal communication Dean Foss, WWS).

4.4 FISH COMMUNITY IN LAKE DIEFENBAKER

The recreational fishery on Lake Diefenbaker is primarily targets Walleye, Rainbow Trout, Sauger, and Northern Pike. The Kadla cages site is not thought to be in a prime fishing area as it is located in the mouth of Kadla Coulee where the water is deep and the bottom is relatively flat. However, recreational fishermen are regularly observed at the Kadla Cages site, which is typical around fish farms.

During the gillnet survey of this study, the gillnets were set a 20 m away from net cages to avoid entanglement with the anchoring buoys and lines, which may led to a slight underestimation of the fish abundance around the net cages. Gillnets are also selective and the minimum mesh size

(25 mm) used may not have caught small bodied and juvenile fish that are likely to occur around the cages. Anecdotal evidence from farm workers and local recreational fisherman suggests that anglers have increased fishing success in Cactus Bay and Kadla Coulee in proximity to the aquaculture cages, in particular for large Walleye. However, fishing is not permitted to occur within 100 m of the cage sites.

4.5 SUGGESTIONS FOR FUTURE DIDSON INVESTIGATIONS

Future investigations on the behaviour of wild fish in areas impacted by freshwater aquaculture would benefit from more consistent field procedures. Ideally, more replications of the DIDSON recording at each study site would be beneficial. Consistent data collection of additional years of data over a number of months, twice daily at each site (once during the morning feeding period and another time either during the afternoon or evening representing dusk or during darkness) would benefit the study design and allow for more powerful statistical analysis of the DIDSON results.

Instead of standardizing fish abundance to a detection-per-unit-effort (based on time and volume of strata sampled), less mathematically complicated point counts would be possible if consistent DIDSON setup parameters would have been used. The same transducer angle, frame rate, and esonified range (window start length, focus length, and total window length) should be used for all surveys. The lens direction should be aimed consistently in the same direction from the cage. Recordings would ideally be taken during low wind conditions to ensure minimal boat movement (drifting from anchor location or rocking in the waves). Fish were observed to appear/disappear/reappear in the echograms during recordings where winds rocked the boat resulting in a ± error in the transducer angle. The boat should be securely anchored at two points or moored to the fish cages.

5.0 CONCLUSION

The viability of aquaculture is directly dependent upon a healthy and productive aquatic environment. The aim of this project was to test the DIDSON technology as a monitoring tool for the impact of freshwater aquaculture on wild fish populations. We assessed the efficacy of the DIDSON to detect changes in wild fish habitat use around fish farms. We established an operational protocol and data analysis procedure and provided advice for future DIDSON surveys.

The DIDSON serves as a passive monitoring tool, which does not interfere with fish behaviour. It is effective at low light conditions and high turbidity, which is essential for detecting wild fish surrounding fish farms. One limiting factor of the DIDSON data for the estimate of fish abundance is potential milling behaviour of wild fish surrounding the cages and potentially double counting of fish. Consequently, the use of DIDSON as a monitoring tool may provide detection of fish occurrences but not provide reliable fish abundance estimates.

In the future, we will investigate the use of the DIDSON to promote sustainable aquaculture in freshwater and marine ecosystems by (1) analysing the size frequency, abundance, and timing of wild fish moving towards the net cages in relation to tide, time of the day, and water temperature, and (2) determining if it is possible to detect benthic macro-invertebrates and fishes with the DIDSON technology.

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APPENDICES

Appendix 1. DIDSON pixel resolution at different target distances from the sonar lens.

	Low Frequency (Detection Mode)		High Frequency (Identification Mode)	
Range (m)	X Pixel Resolution (cm)	Y Pixel Resolution (cm)	X Pixel Resolution (cm)	Y Pixel Resolution (cm)
Blind zone	0-0.84	0-0.84	0-0.42	0-0.42
1	*na*	*na*	0.20	0.52
2	0.39	2.09	0.39	1.05
3	0.59	3.14	0.59	1.57
4	0.78	4.19	0.78	2.09
5	0.98	5.24	0.98	2.62
6	1.17	6.28	1.17	3.14
7	1.37	7.33	1.37	3.67
8	1.56	8.38	1.56	4.19
9	1.76	9.42	1.76	4.71
10	1.95	10.47	1.95	5.24
11	2.15	11.52	2.15	5.76
12	2.34	12.57	2.34	6.28
13	2.54	13.61	2.54	6.81
14	2.73	14.66		
15	2.93	15.71		
16	3.13	16.76		
17	3.32	17.80		
18	3.52	18.85		
19	3.71	19.90		
20	3.91	20.94		
21	4.10	21.99		
22	4.30	23.04		
23	4.49	24.09		
24	4.69	25.13		
25	4.88	26.18		
26	5.08	27.23		
27	5.27	28.27		
28	5.47	29.32		
29	5.66	30.37		
30	5.86	31.42		
31	6.05	32.46		
32	6.25	33.51		
33	6.45	34.56		
34	6.64	35.61		
35	6.84	36.65		
36	7.03	37.70		
37	7.23	38.75		
38	7.42	39.79		
39	7.62	40.84		
40	7.81	41.89		

Appendix 2. Steps to calculate the volume estimate of the esonified frustum (truncated rectangular pyramid) projected into open water.

The DIDSON standard lens has a horizontal field of view of ~30° and a vertical field of view of ~15°. Consequently, the horizontal coverage at range R is:

$$a = R \cdot \sin(\text{FOV}°) = R \cdot \sin(\sim 30°) \sim= R/2$$

The vertical coverage at range R is:

$$b = R \cdot \sin(\text{FOV}°) = R \cdot \sin(\sim 15°) \sim= R/4$$

The formula for the truncated rectangular pyramid (*frustum of a pyramid*) is:

$$V = 1/6 \cdot h \cdot (a \cdot b + (a + c) \cdot (b + d) + c \cdot d)$$

where a and b are defined above using the *end range* for R, c and d replace a and b using the *start range* for R, and h is equal to the *end range – start range*.

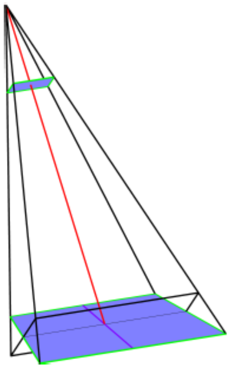
To calculate the volume when using an accessory spreader or concentrator lens, substitute the lens coverage value (e.g., 28°, 14°, 8°, 3° 1°) for the vertical field of view in the above equations, rather than using the shorthand term $R/4$.

This calculation may be done automatically (using a, b, c, d, and h) at:

http://www.aqua-calc.com/calculate/volume-truncated-pyramid

Note: These calculations assume the sonar is projecting energy into open water (e.g., the beam is not intersecting with the lake bottom or another surface).

Steps to calculate the volume for a frustum that would be reduced by intersecting the lake bottom:



These calculations assume the boundary is a uniform plane (flat) parallel to the surface of water. The blue trapezoid is the footprint on the bottom and does not account for bottom irregularities.

The rotation is made on an axis parallel to the long axis of the rectangular mask of the transducer.

The angle of the red axis from the horizontal is represented by θ.
In other words, when pointing straight down into the water,
$\theta = \pi \div 2 = 90°$

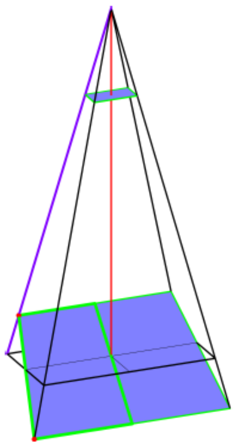
The distance on the (red) axis of the transducer is d.
The depth is then $d * \sin(\theta)$.

The complementary angle, φ, is calculated as:

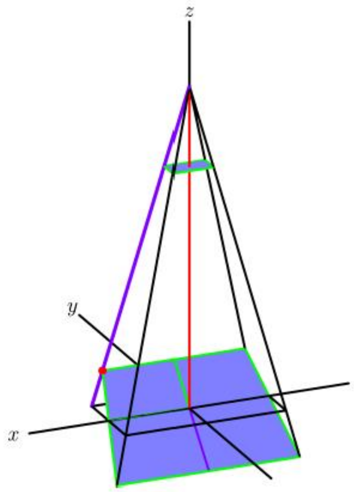
$$\varphi = \pi \div 2 - \theta$$

So that the depth is also d*cos(φ).

For ease of computation, the trapezoid is split into halves of equal area.



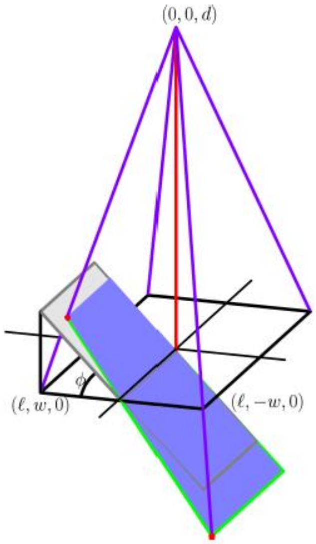
The frustum has x, y, and z axes. The x axis is parallel to the long side of the mask.



For computational convenience, the length of the rectangle (that is the bottom of the pyramid in the x-y plane) is denoted by $2l$ and its width by $2w$.

The four corners of the rectangle now have coordinates of the form $(\pm l, \pm w, 0)$. The apex of the pyramid has coordinates $(0,0,d)$.

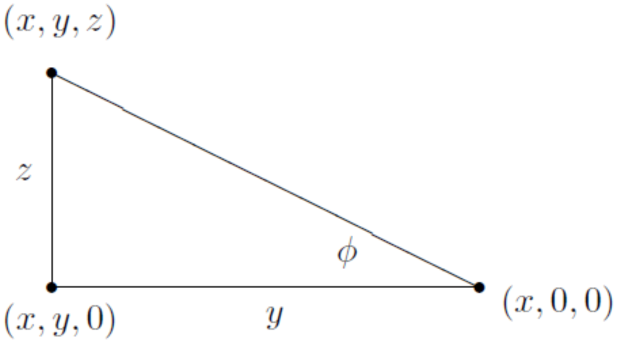
The next step is to find the coordinates of the red dot in the image to the right, that is, the point where the edge of the pyramid intersects the blue trapezoid. The angle "Φ" is the angle between the rectangle and the trapezoid (Φ, or Phi, is the complement of Theta, θ). The apex is labelled as (0, 0, d) and one corner of the pyramid is $(l, w, 0)$.



The points on the line through the apex and that corner are all of the form:

$$t(l, w, 0) + (1 - t)(0,0, d) = (tl, tw, (1 - t)d)$$

where t may be any real number.



How can we tell if a point is in the plane of the trapezoid? If (x, y, z) is on the plane, then drop a perpendicular to the rectangle to get the point $(x, y, 0)$ and a perpendicular to the x-axis to get $(x, 0, 0)$. This gives the following right triangle.

Hence the condition to be satisfied for $(x, y, z)$to be on the plane is

$$\frac{z}{y} = \tan(\varphi)$$

Putting the two conditions together, a point is on both the plane and the line (that is, it is one corner of the trapezoid) if

$$\frac{(1 - t)d}{tw} = \tan(\varphi)$$

$$(1 - t)d = tw * \tan(\varphi)$$

$$d - td = tw * tan\ (\varphi)$$

$$d = td + tw * \tan(\varphi)$$

$$d = t(d + w * \tan(\varphi)$$

$$\frac{d}{d + w * tan(\varphi)} = t$$

For convenience, we set
$k = d + w * tan(\varphi)$

We then have

$$t = \frac{d}{k}$$

And the point on both the trapezoid and the line is now

$$t(l, w, 0) + (1 - t)(0,0, d)$$

$$= \left(\frac{d}{k} l, \frac{d}{k} w, \left(1 - \frac{d}{k}\right) d \right)$$

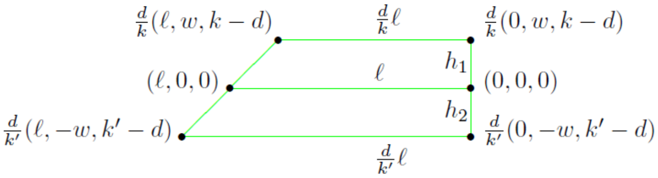
$$= \frac{d}{k}(l, w, k - d)$$

$$= t(l, w, k - d)$$

Now carry out the identical argument using the line through the apex at $(0, 0, d)$ and the corner at $(l, -w, 0)$.

The line now consists of the points with coordinates

$$t(l, -w, 0) + (1 - t)(0,0, d).$$



To be on both the plane of the trapezoid and the line, we have

$t` = \frac{d}{k`}$ where $k` = d - w * tan(\varphi)$

Which makes the corner of the trapezoid

$$\frac{d}{k`}(\mathrm{l}, -\mathrm{w}, \mathrm{k`} - \mathrm{d}) = \mathrm{t`}(\mathrm{l}, -\mathrm{w}, \mathrm{k`} - \mathrm{d})$$

So here is what the points and the side lengths of our (half) trapezoid look like:

Next we compute the height h_1

$$h_1^2 \ = \frac{d^2}{k^2}(w^2+(k-d)^2)$$
$$=\frac{d^2}{k^2}\left(w^2+w^2(tan)^2(\varphi)\right)$$
$$=\frac{d^2}{k^2}\left(w^2(sec^2(\varphi)\right)$$

And so

$$h_1 = \frac{d}{k}\left(w(sec(\varphi)\right)\text{=t } w \text{ *sec}(\varphi)$$

We can apply a similar argument to compute h_2

$$h_2 = \frac{d}{k`}\left(w(sec(\varphi)\right)\text{=t` } w \text{ *sec}(\varphi)$$

We conclude that the total area in the trapezoid above the rectangle (twice the area of the figure above) is

$$l(t+1)h_1 + l(t`+1)h_2 = l(t+1)\frac{d}{k}w*sec(\varphi)+l(t`+1)\frac{d}{k`}w*sec(\varphi)$$
$$= lw*sec(\varphi)(t(t+1)+t`(t`+1))$$

To get the volume, multiply this area by one-third of the height.

$$V=\frac{1}{3}\cos(\varphi)\,d\left(lw*sec(\varphi)\left(t(t+1)+t`(t`+1)\right)\right)$$
$$V \ = \ \frac{1}{3}\text{dlw}\left(t(t+1)+t`(t`+1)\right)$$

Volume calculated for the coverage of the DIDSON based on values of complementary angle $\varphi = \frac{\pi}{4}\ and\ \varphi = 0.$

φ	l	w	$k = d + w * tan(\varphi)$	$k = d - w * tan(\varphi)$	$t = \frac{d}{k}$	$t` = \frac{d}{k`}$	Volume
$\frac{\pi}{4}$	$\frac{d}{4}$	$\frac{d}{8}$	$\frac{9d}{8}$	$\frac{7d}{8}$	$\frac{8}{9}$	$\frac{8}{7}$	$\frac{512}{11907}d^3$
0	$\frac{d}{4}$	$\frac{d}{8}$	d	d	1	1	$\frac{1}{24}d^3$

Appendix 3: DIDSON customised user manual for data analysis

1 – Start the Sound Metrics DIDSON software

- Program will state "*Running in Demo Mode… Show this message again*". Select *No*.

2 – Open .ddf file

- *File* → *Open* → … then navigate to *.ddf file for analysis.
- The sonar images will be saved to the default directory of the field computer as DIDSON data files (*.ddf) with time stamps via the control software.

3 – Set parameters for analysis.

- *Processing* → *Show Parameters*.
- Adjust settings to help CSOT (Convolved Sample of Threshold) determine which frames contain data versus noise.
- Below are the settings used for post-processing the Lake Diefenbaker data:
    - *Set Min Cluster Area* = 100.
    - *Set Min Threshold (dB)* = 3.9.
    - When bottom was visible, adjusted *Range (m)* limits to exclude it.

4 – Create a CSOT file which eliminates all "empty" frames from *.ddf files.

- First select *Insert Prequel* so that frames are added before detections:
    - *Processing* → *CSOT* → *Insert Prequel*.
- Create CSOT file:
    - *Processing* → *CSOT* → *Export CSOT Frames*.

5 – Open CSOT file for analysis:

- *File* → *Open* → … then navigate to the CSOT file just created.

6 – Create an echogram:

- First select *Use Cluster Data*.
    - *Processing* → *Echogram* → *Use Cluster Data*.
- *Create Echogram*.
    - *Processing* → *Echogram* → *View Echogram*.

7 – The echogram presents the data showing defined 'streaks' where sound has been reflected off objects within the beam. Check each streak to see if it is a fish (i.e., appears to be swimming) or another object that is not a fish (i.e., moves in a fairly straight line at a constant speed with no undulation).

- Note: Ensure *Measure* is NOT selected in *Display Controls* on the left side menu.
- Hold down the left mouse button and drag over the section you want to view.
    - This will bring you to the video display and a video clip of the object you are interested in will play.
- To zoom in either right click to zoom to the *preset max zoom* or hold the right mouse button and drag across the area you wish to zoom in on.

8 – Once you have positively identified a fish, it is marked and measured:

- Left click the brightest part of the streak to place a fish mark.
- Right click the fish mark circle that you have just placed.
    - This will bring you to the video display and a short video clip of the fish will play.
- To pause the video playback, click the blue square icon in the top toolbar. To resume playback, click the blue square button again.
- While paused you can sift through the video section frame by frame using the blue arrows beside the pause button allowing you to select the best frame for fish measurement.
- To zoom into the subject hold the right mouse button and drag the box over the area of interest.
- Now you can either press the left mouse button on the head of the fish and drag to the tail of the fish or left click on the head and click along the fish until the tail. If unsatisfied with measurement double left click to start over.
- Once satisfied with the measurement press the ‘*f*’ key to enter the measurement into the log file.

9 – After all of the detected fish are measured or to save your current progress you must export echogram counts:

- *Processing* → *Echogram* → *Export Echogram Counts*.
- Site echogram counts and fish measurements were individually exported as separate *.csv files and later combined in a MS Excel database with unique site identifiers.

You can also save a jpg image of the echogram with marked fish:

- Processing → Echogram → Export Echogram as jpg.
- **Note**: Files are saved to same location as current CSOT file.

10 – To continue work from saved progress you can load the echogram file:

- File → Open → …
- Change dropdown menu *Files of Type* to *DIDSON Echogram Files* (*.ech).
- Then navigate to the *.ech file previously saved.

*Import *.txt files into Excel*

1 – Open created fish measurement *.txt file in Excel:

- In Excel open *.txt file:
    - File → Open → …
    - Change dropdown menu *Files of Type* to *Text Files* (*.prn; *.txt; *.csv).
    - Then navigate to the *.txt file previously saved (same location as CSOT file).

2 – In the *Text Import Wizard*:

Step 1 of 3:

- Select *Fixed width.*
- For *Start import at row* choose 24, which leaves out header data not needed.
- Leave *File origin* as MS-DOS (PC-8).

- Click Next.

Step 2 of 3:
- Follow instructions to create column breaks in the data.
- Click *Next*.

Step 3 of 3:
- Leave format as *General*.
- Click *Finish.*

3. Save file as *.xls format.
   - File → Save As → …
   - Change *Save as type* to *Microsoft Excel Workbook* (*.xls).
   - Click *Save.*