Journal of Great Lakes Research 42 (2016) 248–255

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

The under-ice soundscape in Great Slave Lake near the city of Yellowknife, Northwest Territories, Canada

S. Bruce Martin [a,*], Peter A. Cott [b]

[a] JASCO Applied Sciences, 202-32 Troop Avenue, Dartmouth, NS B3B 1Z1, Canada
[b] Cumulative Impact Monitoring Program, Environment and Natural Resources, Government of the Northwest Territories, Box 1320, Yellowknife, NT X1A 2L9, Canada

ARTICLE INFO

Article history:
Received 25 November 2014
Accepted 20 August 2015
Available online 17 October 2015

Communicated by Bruce Hanna

Index words:
Soundscape
Under-ice
Fish vocalization
Great Slave Lake
Burbot
Lota lota

ABSTRACT

Most recent research and monitoring of under-water “soundscapes” has focused on marine systems in open water conditions. Here we present the first long-term assessment of the diel and seasonal patterns of a freshwater aquatic soundscape under-ice cover. Acoustic data recorded in Yellowknife Bay, Great Slave Lake in Canada's Northwest Territories, measured the under-ice soundscape near an ice road and airport. From December to late January, the soundscape consisted of geophony from ice cracking and anthrophony from snowmobiles, aircraft, and road vehicles. In late January, burbot spawning calls began and added a localized biophony source to the soundscape that increased the total sound pressure level due to an increase in sound levels in the 10–425 Hz frequency band. The median 1 min root-mean-square sound pressure level (rms SPL) in the period without burbot biophony was 90.3 dB re 1 μPa. The measured hourly rms SPL was negatively correlated with air temperature in the 200–800 Hz band but positively correlated with average hourly wind speed in the 800–8000 Hz band. The nightly mean rms SPL was 88 dB re 1 μPa and increased to 96 dB re 1 μPa in late afternoon. This diel cycle had a strong positive correlation with the number of minutes per hour where ice-road vehicles were detected. Further work is recommended to quantify the soundscape in deep-water areas of large lakes and to include particle motion. Such information will enable the assessment of cumulative impacts of anthrophony and geophony on aquatic biota.

Introduction

A soundscape results from the overlap of *biophony* (sounds from organisms), *anthrophony* (sounds created by human activities), and *geophony* (sounds not from biological or man-made sources) (Krause, 1987; Pijanowski et al., 2011; Farina, 2014). The framework proposed by Jennings and Cain (2013) divides the description of a soundscape into the measured properties of the sound with the mixture and evolution of the sources that created the sound. A fully described soundscape includes the number of sources, the evolution of the sounds in time, the proximity of the sources, whether they are identifiable or dominant, in the foreground or background, and, where possible, the direction of the sources.

Much is known about the generation and propagation of geophony sound sources in the ocean under sea ice (see Roth et al., 2012 for an excellent review). One of the most important sources of under-ice noise is broadband impulsive noise from ice fracturing or cracking (Ganton and Milne, 1965; Milne and Ganton, 1964; Zakarauskas et al., 1990). Less is known about the geophony of freshwater lakes, especially under ice. Mann et al. (2009) provide a short-term background spectrum for a sheltered bay in Kennady Lake more than 4 km from the Gahcho Kué diamond mine, in the Northwest Territories (NWT), Canada. They measured a nearly flat spectral density of ~45 dB re 1 μPa^2/Hz from 100 to 8000 Hz. Below 100 Hz, the spectral density decreased to 35 dB re 1 μPa^2/Hz at 10 Hz, with the exception of a small 50 dB re 1 μPa^2/Hz at ~50 Hz.

Whether a sound in the soundscape is a signal or noise depends on the context of the receiver (Farina, 2014). Mann et al. (2009) demonstrated that aircraft and snowmobiles generate under-ice noise at levels that may cause behavioural reactions in fish. Anthropogenic noise can also mask communications between fish (Popper et al., 2014). The behavioural effects and masking are of concern if they affect critical life functions such as spawning. Increased activity under ice in response to noise disturbance could be especially detrimental under hypoxic conditions which are known to occur in shallow ice-covered lakes (e.g., Stewart et al., 2015, this issue). Behavioural and masking effects on a freshwater gadoid fish burbot (*Lota lota*) are of concern since Cott et al. (2014), this issue recently demonstrated that this species vocalizes under ice-cover during their spawning period.

This study presents the under-ice soundscape recorded over 80 days at one location in Yellowknife Bay of Great Slave Lake next to the city of Yellowknife, NWT, Canada. The primary motivation for the recording was to determine if burbot, as in closely related marine gadoid species,

* Corresponding author.
E-mail address: bruce.martin@jasco.com (S. Bruce Martin).

http://dx.doi.org/10.1016/j.jglr.2015.09.012

vocalize during mating (Cott et al., 2014, this issue), which occurs in winter under ice cover (Scott and Crossman, 1973; McPhail and Paragamian, 2000). To test the hypothesis that they vocalize pre-spawn, burbot were placed under the ice in a large net enclosure (hereafter the Lota-tron), and their vocalizations were monitored using an underwater sound recorder (Cott et al., 2014, this issue). The recorder was calibrated so that the data could also be used for soundscape analysis and to provide an understanding of the acoustic environment in which burbot call.

This is the first report of the under-ice soundscape for fresh water environments. The biophony, geophony, and anthrophony contributions to the soundscape are quantified using special purpose automated detectors. The major sound sources are identified, as well as diel and weekly trends in sound levels. This study provides insight into the levels of natural and anthropogenic sounds that enter under-ice aquatic ecosystems and how a sudden onset of biological sound production changes the local soundscape. These data may be used to establish ecological baselines and to better assess the cumulative impacts of the anthropogenic noise.

Methods

Site description

Acoustic data were recorded continuously from 15 December 2009 to 6 March 2010 in Great Slave Lake, near Yellowknife, NWT, Canada (Fig. 1). Yellowknife is NWT's largest urban centre with over 20,000 residents. A 6 km long ice road spans from Yellowknife to the community of Dettah located along the east side of Yellowknife Bay. The road is open approximately 110 days per year and supports 540–1100 vehicles per day (Northwest Territories Transportation, 2013). An Autonomous Multichannel Acoustic Recorder (AMAR G2, JASCO Applied Sciences) was placed in the 'the Lota-tron', a 10 m × 10 m × 10 m net frozen into the surface ice of the lake. The Lota-tron housed burbot close to the recorder. The water depth at the Lota-tron was 9.5 m with a nearly flat bottom. The ice was over 50 cm thick at the time of deployment and increased to over 1 m thick during the study. Details of the Lota-tron study can be found in Cott et al. (2014, this issue). The Lota-tron was almost directly in-line with a Yellowknife airport runway (Fig. 1).

Acoustic recordings

The AMAR sampled continuously at 16,000 samples per second. It was positioned within the Lota-tron, approximately 1 m off the lakebed from 15 December 2009 to 6 March 2010, spanning the burbot spawning period in Yellowknife Bay (Cott et al., 2014). The AMAR was fitted with an M15B hydrophone (GeoSpectrum Technologies Inc., −160 dB re 1 μPa/V sensitivity) and set with an input voltage gain of 6 dB. The complete recording system was calibrated before deployment and after retrieval with a 42 AA pistonphone calibrator (G.R.A.S. Sound & Vibration A/S) at 250 Hz. The AMAR had a broadband noise floor of 80.6 dB re 1 μPa and a spectral density noise floor of 46 dB re 1 μPa^2/Hz from 50 to 1000 Hz and 36 dB re 1 μPa^2/Hz above 3000 Hz. The recorder had a noise artefact at 4750 Hz, with a root-mean-square sound pressure level (rms SPL) of 94 dB re 1 μPa, which was removed with an equi-ripple notch finite impulse response filter during analysis (4650–4850 Hz, 1024 points). The recorder also created a short pulse of electrical noise lasting 0.01 s every 1.37 s while writing data from short-term memory to long-term storage. The memory writes increased the current consumed by the recorder, which modulated the battery pack voltage and injected noise into the hydrophone due to inadequate power supply rejection. This pulse created broadband energy to 50 Hz, with tone-like energy at 29, 37, and 210 Hz; the amplitude of the pulses increased as the battery pack was depleted. At the beginning of the deployment, the spectral density noise floor at 10 Hz was 50 dB re 1 μPa^2/Hz; at the end of the deployment the level at 10 Hz had increased to 70 dB re 1 μPa^2/Hz and decreased to the normal value of 46 dB re 1 μPa^2/Hz by 50 Hz. This increased the noise floor in the band of 10–40 Hz from 70 dB re 1 μPa to 79 dB re 1 μPa over the deployment period.

Data analysis

Acoustic analysis was performed in two stages using custom software (JASCO Applied Sciences). The first stage quantified the sound

Fig. 1. The Lota-tron project site near the city of Yellowknife, NT, Canada. The Lota-tron was approximately 600 m from the 6 km long Dettah ice road and directly below the flight path for the secondary runway of Yellowknife Airport located 6 km northwest.

levels in each minute of data, detected constant frequency tones (normally from anthropogenic sources), and detected burbot pulse vocalizations and ice cracking events in each 30-minute WAV file (detectors are described later). The second stage parsed the outputs of the first stage to determine the dominant sound source in each minute of data—anthrophony for vehicle minutes with detections, biophony for minutes with burbot detections, and geophony for all other minutes.

Quantifying the total sound levels

For each of the 115,390 min of data, 120 FFTs with 1 Hz resolution and 50% overlap were computed. The per-minute 1 Hz linear-mean power spectral density was stored, as well as the rms SPL, peak SPL, peak-to-peak SPL, and 1/3-octave-band SPLs. The 1 Hz power spectral density data are presented as spectrograms and the data were also sorted to create histograms of the power spectral density values, which were plotted as spectral probability densities (Merchant et al., 2013). The L_{95} through L_5 sound level statistic percentiles were overlaid on the spectral probability density data (L_{95} is the level exceeded by 95% of the 1-min samples, L_5 is the level exceeded by 5% of the samples, etc.). Histograms of the 1/3-octave-band SPLs were also computed and are presented. The daily sound exposure level was converted to an equivalent sound level (Leq; ISO, 2013), which is the metric typically used to assess potential for long-term hearing effects. Finally the per-minute SPL in four data analysis bands are plotted where the bands are based on the properties of the sources in the data set:

- 10–50 Hz: These frequencies are near or below the low-frequency cut-off for an environment with a depth of 8.5 m and should not propagate over long distances (Urick, 1983). This band will contain energy from burbot pulses at short ranges as well as sounds from vehicles. The noise floor of this band increased over the deployment.
- 50–200 Hz: This band contains energy from vehicles and burbot calls, as well as energy from ice cracks (Ganton and Milne, 1965).
- 200–800 Hz: This band contains the peak energy from ice cracks (e.g., Fig. 2), some energy from vehicles, and potentially wind-related noise (Ganton and Milne, 1965).
- 800–8000 Hz: This band is expected to contain some energy from ice cracks and wind-related noise (Ganton and Milne, 1965)

Ice cracking and burbot call detectors

Ice cracking sounds were present almost continuously throughout the study. These sounds were typically 0.05–1 second long pulses with broadband frequency content. The purpose of the ice-crack detector was to find minutes of data with a large number of loud ice cracks to exclude them from the vehicle detector (see below). Ice cracks were detected using a variation on the Teager–Kaiser energy operator (Kaiser, 1990). The raw time-series data were summed over a 2.5 ms window to create the detection time series. This detection time series was normalized, by dividing by its mean value in a 2 second window, before the Teager–Kaiser energy operator was applied:

$$\Psi(x(n)) = x^2(n) - x(n-1)x(n+1). \tag{1}$$

The normalization allowed for the definition of a constant detection threshold of 20 that is independent of the absolute data magnitudes. The energy time window of 2.5 ms matches the operator time scale to the expected onset time of the ice cracking. The analysis was performed on every minute of data. This detector identified minutes of data during which ice cracking was the dominant sound source. Ice crack detections where the rms SPL was below 90 dB re 1 μPa or the peak SPL was below 120 dB re 1 μPa were considered non-dominant sources and rejected. The thresholds were chosen based on the medians of the ambient sound level distributions.

Burbot calls are a unique bi-phase signal characterized by a rapid positive or negative pressure peak followed by a smaller peak of the opposite phase (Fig. 2 in Cott et al., 2014, this issue). The duration of the over- and under-pressure peaks is 20–150 ms, which is much longer than the zero-crossing interval in most acoustic events, such as vehicle sounds and ice cracks (also shown in Fig. 2). A custom zero-crossing detector searched for data where the duration between three successive zero crossings is 20–150 ms, allowing for a 1.5 ms 'transition' period as the signal crosses from the positive to negative peak or vice versa. The detector required the peak signal level to also exceed an empirical threshold of 112 dB re 1 μPa. If the ice crack detector detected two pulses, these sounds were identified as a burbot call and subsequently removed from the ice-crack count in post-processing.

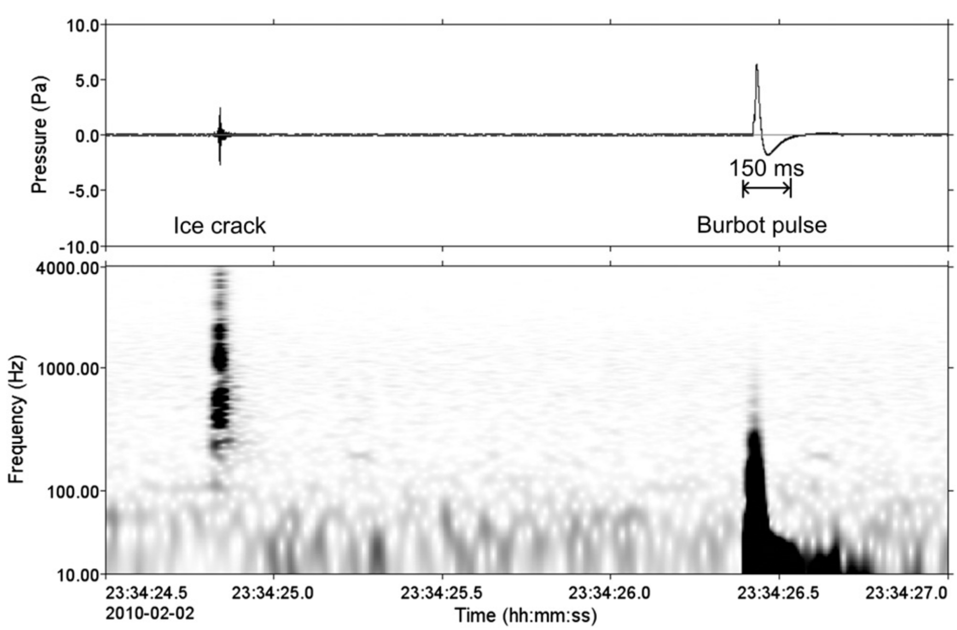

Fig. 2. Time series (top) and spectrogram (bottom) of an ice-crack and bi-phase calls from a burbot, Yellowknife Bay, Great Slave Lake, Northwest Territories, Canada. The long period without the time series crossing the 0 Pa line makes the burbot calls very unique. (Spectrogram FFT settings: 1 Hz resolution, 0.1 s of data, 0.005 s advance, Hamming window).

The performance of the ice crack and burbot call detectors was evaluated by verifying the detections against manual annotations. An analyst (BM) manually reviewed 960 min of data to determine if ice cracks and burbot calls increased the sound levels. Thirty minutes of data were annotated every 25 h for 1–14 January, 23 January, 29 January, and 1–16 February 2010. The 25-hour step was chosen to ensure that data was evaluated for each hour of the day. The dates were chosen to evenly select periods with and without burbot calling. For each minute, only the presence or absence of ice cracks and burbot calls was annotated because the number of calls per minute could exceed 250. Accuracy of detectors is based on the total number of minutes with true-positive, false-positive, and false-negative detections. For the ice crack detector, the precision is 0.80, the recall is 0.99, and the F-score is 0.89 (scores closer to 1 are better, Davis and Goadrich, 2006). For the burbot call detector, the precision is 0.94, the recall is 0.94, and the F-score is 0.94.

Vehicle detector

Vehicle noise was detected with an existing vessel detector after an optimal set of parameters was determined (Martin, 2013). The inputs to the vehicle noise detector were the 1 min rms SPLs, 1/3-octave-band rms SPLs, the number of 0.125 Hz tonals present and the number of ice cracks and burbot calls detected. The tonals are the signature of rotating machinery, such as car engines and wheels (Arveson and Vendittis, 2000; Mann et al., 2009). A vehicle noise band was defined to be 10–800 Hz by a manual inspection of the vehicle signatures in the spectrogram data. The rms SPL in the vehicle noise band was computed once per minute. Vehicles were detected for any minute of data when four conditions were met:

1. The rms SPL in the vehicle band had to be at least 1 dB above the median rms SPL in the vehicle band in a 20 minute window centred on the test time. This small threshold allowed the detector to distinguish the approach and departure of a vehicle and assign the energy to anthropogenic sources.
2. The rms SPL in the vehicle band had to be within 3 dB of the total broadband rms SPL.
3. At least five tonals were present.
4. Fewer than 20 ice cracks and burbot calls were present.

When these conditions were true for a period of at least 2 min and not more than 10 min, vehicles were detected, and the energy from that minute was assigned to anthropogenic sources.

The performance of the vehicle detector was evaluated by visually and aurally reviewing all data for a 24 hour period (19:00 on 17 January to 19:00 on 18 January 2010, UTC-7) and annotating all minutes during which vehicles were detected—324 min were annotated. The vehicle detector results were verified against these annotations: 256 detections were true positives, 48 were false positives, and 68 were false negatives. These values yield a precision of 0.84, a recall of 0.79, and an F-score of 0.82 for the detector. False negatives often occurred when the median rms SPL in the 20 minute background window was high compared to the rms SPL at the test time. Ice cracking with significant low-frequency components could also disrupt the tonal detector. In most cases, the ice noise was dominant; therefore, the energy in those minutes of data should not be attributed to anthropogenic sources. False positives were often caused by periods of extended ice noise with low-frequency components and with few cracks-per-minute, especially in low noise conditions. False positives also occurred during periods longer than 10 min with very low sound levels, which caused the background estimate to drop and lead to occasional false detections. Because these minutes were especially quiet, misclassification had a negligible effect on quantifying the contribution of anthropogenic sources to the total sound budget.

Correlations with environmental factors

The rms SPLs were correlated with hourly mean temperature and wind speed at the Yellowknife Airport (Environment Canada, 2009). The median hourly rms SPLs for each minute without vehicle or burbot detections were computed for the full bandwidth (10–8000 Hz) and each analysis band (50–200, 200–800, and 800–8000 Hz); 10–50 Hz was excluded due to the increase in noise floor overtime. Pearson correlation coefficients were computed for the SPLs with the wind speed, air temperature, and change in air temperature.

Results

The instantaneous soundscape in the Lota-tron was variable and could be dominated by geophony from ice cracking, but also

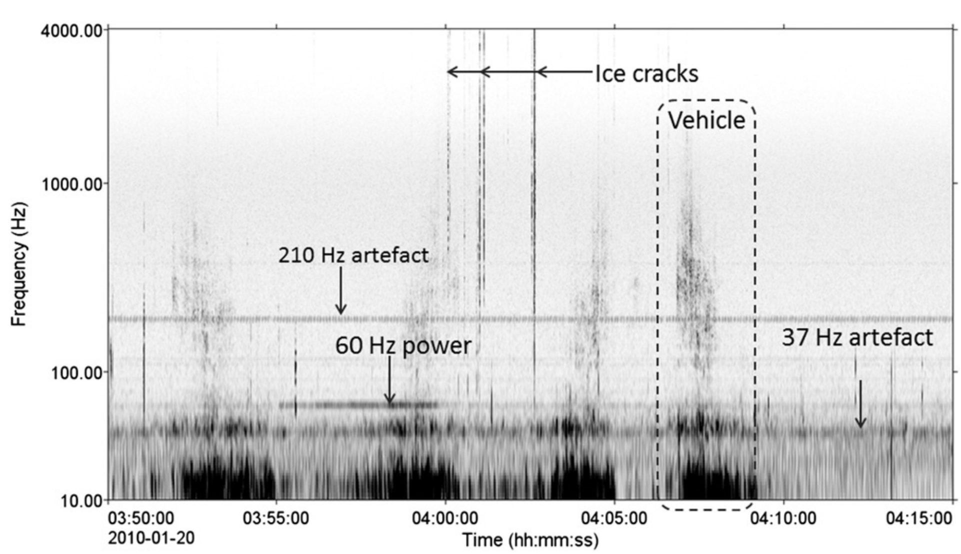

Fig. 3. Spectrogram of 30 min of data showing four vehicles on the Dettah ice road passing the study site in Yellowknife Bay, Great Slave Lake, Northwest Territories, Canada. A small number of ice cracks are also present, along with the tones from 60 Hz power generation on land and an unknown source at 37 Hz. FFT parameters: 1 Hz resolution, 0.5 s of data, 0.25 s advance, Hamming window.

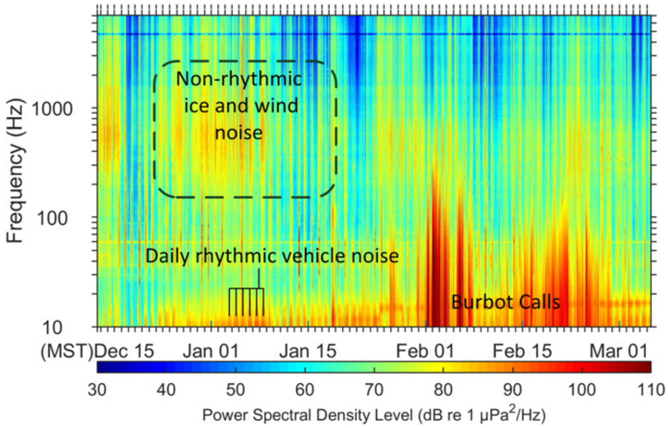

Fig. 4. Measured sound levels during the study, 15 December 2009 to 5 March 2010 in Yellowknife Bay, Great Slave Lake, Northwest Territories, Canada. Spectrogram created by choosing the one-minute averaged 1 Hz resolution spectra with the maximum energy each hour. The sound levels increase at the middle of each day (shown as the light-blue to yellow vertical bands) and decrease overnight (shown by the darker blue vertical bands). The high intensity (yellow to red colours) data below 200 Hz starting on 1 February 2010 is attributed to burbot calls. 60 Hz from on-shore power is visible throughout the recording period. The dark blue band at the top of the spectrogram is where the recorder artefact at 4750 Hz was removed. MST is mountain standard time.

anthrophony from vehicles on the Dettah ice road (e.g., Fig. 3), aircraft, snowmobiles, or people walking at the Lota-tron site. Biophony from burbot calls was a major sound source after 1 February 2010. The burbot were experimentally confined within the Lota-tron, which was in shallow water (8.5 m) with a flat bottom, an environment typical for burbot spawning (Cott et al., 2014). Because the burbot were confined to be close to the AMAR, we provide descriptions of the under-ice soundscape separately for the period before and after 1 February, with a focus on the period before 1 February because it is likely more representative of soundscapes from ice-covered shallow lakes in general.

The spectrogram of the full data set (Fig. 4) shows three types of noise: a rhythmic increase and decrease in noise due to vehicles, low frequency energy from burbot calls starting 1 February 2010, and non-rhythmic noise above 200 Hz from ice cracks and wind. The vehicle noise was strongest below 20 Hz; however, it contained energy up to 1000 Hz and on some days to 8000 Hz (Fig. 4). The sound level statistics show that Great Slave Lake can be a quiet environment when ice covered (Fig. 5). For the period without burbot calls (Fig. 5. (left)), the L_5 and L_{25} levels show increased sound levels in the band of 200–800 Hz. The effect of burbot calling on the soundscape can be seen in the L_5 sound levels during the period with calls (Fig. 5 (right)). The L_5 levels are 12 dB higher at 10 Hz and 9 dB higher at 100 Hz compared to the period without calls. The L_{50} (median) sound levels during the period with calls are 10 dB higher than the period without calls at 10 Hz and remain higher until 425 Hz; however, the period without calls has a spectral density up to 5 dB higher than the period with calls above 425 Hz.

Fig. 6 shows the statistical sound levels in the analysis bands. Fig. 6(a) shows the distribution of sound levels for each band, while Fig. 6(b) is the median sound levels for each 15 minute interval per week over the period of 15 December to 1 February. The median broadband SPL is 90.3 dB re 1 μPa (interquartile range 85.2–96.1). The 200–800 Hz and 800–8000 Hz bands have the highest median SPLs (82.4 and 84.7 dB re 1 μPa, respectively), while the 10–50 Hz and 50–200 Hz bands have the median SPLs 10 dB below the broadband. The quartile values for the peak SPL were 114.3–126.9–139.0 dB re 1 μPa for 15 December to 1 February and 120.9–129.0–137.2 dB re 1 μPa for 1 February to 5 March. The loudest event in the data set was an ice-crack with a peak SPL of 161 dB re 1 μPa at 15:31 on 11 February 2010.

The median in-band SPLs show a clear daily rhythm, with the lowest sound levels from 00:00 to 05:00, and the highest levels in the early afternoon (Fig. 6(b)). Sound levels are slightly reduced on Friday and Saturday nights, and the lowest sound levels occurred on Monday at 04:00. The daily increase in rms SPL during the afternoon is strongly correlated with vehicle detections, and negatively correlated with ice-crack detections (Fig. 7).

The environmental conditions were similar for the period before burbot calls and with burbot calls, except that the median temperature was 8.7° warmer during the period with burbot calls (Table 1, Fig. 8). Neither the temperature nor wind speed data shows any diurnal variation that correlate with the rms SPL rhythms (Fig. 6(b)). For both periods, there was a moderate positive correlation between the median hourly 1-min rms SPL above 800 Hz and the wind speed (Pearson correlation coefficients of 0.31, 0.21; the hourly rms SPL was not correlated with wind speed). Both periods also showed a moderate negative

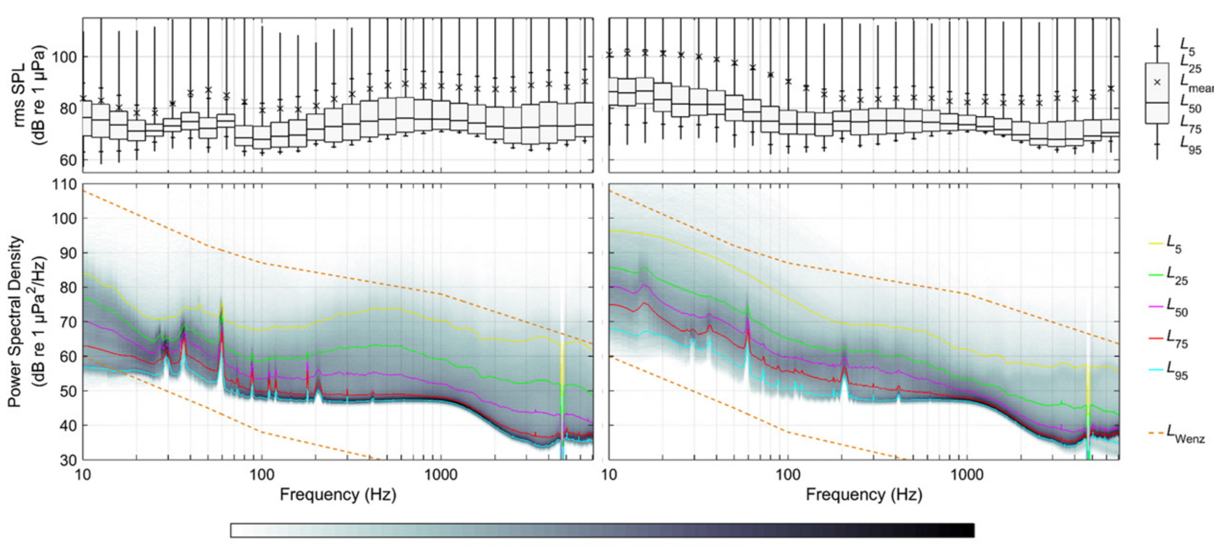

Fig. 5. Sound level statistics for Yellowknife Bay, Great Slave Lake, Northwest Territories, Canada 15 December 2009 to 5 March 2010: (Top panels) distribution of 1/3-octave-band levels and (bottom) relative spectral density levels for the period prior to the onset of burbot calling (on the left lower panel) and the period with burbot calls (on the right lower panel). The L_5 value is the power spectral density exceeded by 5% of the time periods. There is a tone at 60 Hz reaching up to 75 dB re 1 μPa²/Hz that also increases the median of the 63 Hz 1/3-octave-band by three dB. L_{95} is at the recorder noise floor for frequencies above 100 Hz; similarly the L_{75} is at the recorder noise floor above 500 Hz.

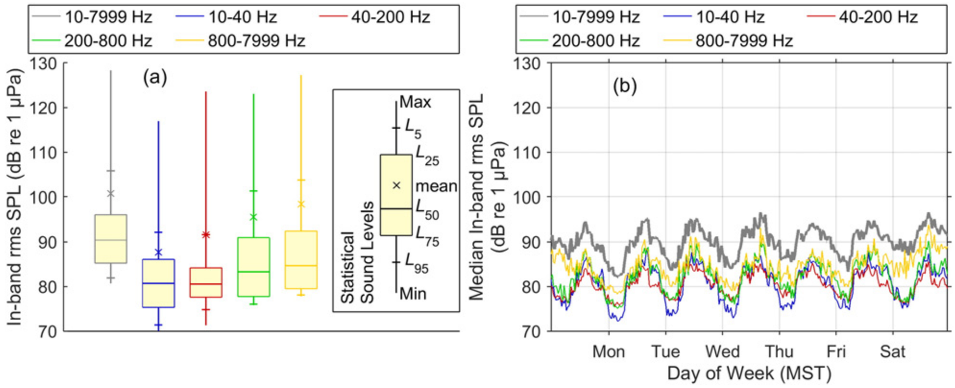

Fig. 6. Distributions of analysis band 1-min rms SPLs for the period 15 December 2009 to 1 February 2010, Yellowknife Bay, Great Slave Lake, Northwest Territories, Canada. (a) Box-and-whisker plot of the rms SPLs (Quartile ranges: 10–8000 Hz: 85.2–90.3–96.1; 10–40 Hz: 75.3–80.7–86.1; 40–200 Hz: 77.6–80.5–84.2; 200–800 Hz: 76.6–82.4–90.1; 800–8000 Hz: 79.5–84.7–92.4). (b) Median rms SPL for each band for each 15 minute interval of the week.

correlation between the temperature and the hourly rms SPL in the 200–800 Hz band (Pearson correlation coefficients −0.44, −0.42; Fig. 8) and the 800–8000 Hz band (Pearson correlation coefficients −0.39, −0.36); that is the SPL in this band increased at lower temperatures. This likely explains the increased sound levels above 200 Hz (Fig. 4) in the period without calls since the temperatures were colder in this period. We did not find correlations with the SPL in any band and the change in temperature.

An unexpected feature of the soundscape is a continuous 60 Hz tonal, possibly from electrical power generation on land (Figs. 1, 3, 4, 5). The tonal had a spectral density of up to ~75 dB re 1 μPa^2/Hz and elevated the 63 Hz 1/3-octave-band SPL above the adjacent bands by 5 dB for 75% of the study period (Fig. 3, 5). The second and third harmonics (120, 180 Hz) of 60 Hz were also present. Other constant tonals that also likely entered the water from shore were 37 Hz (and its third harmonic of 111 Hz), and 88 Hz (Fig. 5). The source of these tones is unknown.

Noise from three types of vehicles (ice road traffic, aircraft, and snowmobiles) were detected, all of which were easily recognized aurally. The most common was traffic on the Dettah ice road (Fig. 1), which had energy in the frequency bands of 10–30 and 200–1000 Hz (e.g., Fig. 3). Turbo-prop aircraft noise occurred several times per day and was distinguished by its tonal sounds showing rapid Doppler shifts. Typical rms SPLs for the aircraft were 95–110 dB re 1 μPa with peak SPLs of 120–130 dB re 1 μPa. Snowmobile noise was unique in its rapid frequency and intensity changes as the vehicles manoeuvered over the lake (Fig. 8). On 15 December 2009 and 18 January 2010, snowmobiles were known to be within 30 m of the AMAR for servicing of the Lotatron. The rms SPLs measured from those snowmobiles are typically less than 100 dB re 1 μPa with peak SPLs of 115–120 dB re 1 μPa. The sounds of walking, drilling, and hammering are also present (see Mann et al., 2009 for a description of these sounds).

The maximum daily Leq was 122 dB re 1 μPa measured on 2 February 2010, the principal source of which was burbot calls (Fig. 9). Geophony sources (ice cracking, wind noise) contributed the most energy to the soundscape before 1 February 2010, while the localized biophony source contributed the most after 1 February (Fig. 9). In general, the anthrophony sources had a lower mean 1 min rms SPL than the geophony sources.

Discussion

Comparisons to Arctic under-ice noise

There are many similarities, but also stark differences between the characteristics of under-ice sound in the shallow regions of a northern lake compared to the Arctic marine environment. The data indicates that noise from thermally induced ice cracking is negatively correlated with changes in air temperature and extended periods of low temperature, similar to the results of Ganton and Milne (1965) and Lewis (1994). The sound levels above 800 Hz increase with wind speed, which agrees with the findings of Ganton and Milne (1965); Makris and Dyer (1986) and (Lewis and Denner, 1988), that wind-driven movement of snow and ice-pellets on the surface, wind noise, and ice-fog contribute to noise above 1 kHz.

However, in our study the peak in ice-crack (thermal) noise was at 400–600 Hz, whereas Ganton and Milne (1965) reported a peak frequency for thermally induced noise of 100–200 Hz, and Makris and Dyer (1986) found a peak frequency of 300 Hz. While the mechanisms of thermal expansion are similar, the scales of the ice sheets are much different, the effects of multi-year ice keels are not present in Great Slave Lake, and the presence of brine pockets in first year sea-ice affects how and when ice-cracking related noise occurs (Vancoppenolle et al., 2007). The thickness of the ice likely also influences the peak frequencies. The ice at Great Slave Lake was ~1 m thick for most of this project; while Arctic marine ice is often close to 2 m (Ganton and Milne, 1965). The current results also show a difference in the magnitudes of noise created by environmental changes. Ganton and Milne (1965) reported a 40 dB change in the variance of the sound levels in the 200–800 Hz band during a 24-hour period when the temperature dropped ~15 ° C. A drop of 20 ° C on 23–25 January 2010 caused the variance in 1-min rms SPL to change from 15 (00:00–03:00 23 January) to 60 (05:00–08:00 25 Jan), a six dB change in variance. The hourly rms SPL increased also by approximately six dB over this period (Fig. 8).

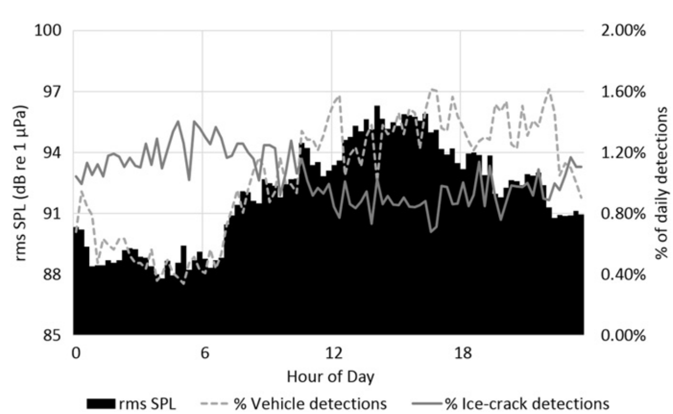

Fig. 7. Mean 15-minute rms SPL compared with pulse and vehicle detections per 15-minute interval (as percent of total) for the study period of 15 December 2009 to 1 February 2010, Yellowknife Bay, Great Slave Lake, Northwest Territories, Canada. Pearson correlation coefficients: SPL and vehicle detections, 0.89. The correlation coefficient of the ice-crack detections and temperature was −0.36.

Table 1
Means (standard deviation) of air temperature, change in air temperature, and wind speeds during the entire study (15 December 2009 to 5 March 2010) and the periods without burbot calls (15 December 2009 to 31 January 2010) and with burbot calls (1 February to 5 March 2010) at Yellowknife Airport, Northwest Territories, Canada.

Period	Air temp. (°C)	Change in temp. (°C)	Wind speed (km/h)
Entire study	−19.4 (8.5)	0.37 (0.33)	6.6 (6.4)
Without calls	−22.9 (6.9)	0.33 (0.26)	6.2 (6.2)
With calls	−14.2 (8.0)	0.43 (0.39)	7.1 (6.5)

The 8.5 m water depth at the Lota-tron site prevented sounds below 40 Hz from propagating (Urick, 1983). As a result, the geophony from ice-cracking in Yellowknife Bay did not appreciably increase the sound levels at 10–20 Hz, which contrasts with the results of Makris and Dyer (1986) and Zakarauskas et al. (1990) whose measurements were made in deeper waters and showed very high spectral density levels below 100 Hz.

Unexpected components of the soundscape

There were two especially surprising components in the data—energy between 10 and 30 Hz correlated with vehicles on the Dettah ice road and the 60 Hz power tonals. We propose that the 10–30 Hz noise associated with vehicles on the ice road energy is propagating through the ice and re-radiating into the water column.

The presence of tones at 60, 120, and 180 Hz is associated with North American power grids and is not an artefact of the recorder itself. Therefore, we believe that the 60 Hz was either present in the water column as a mechanical (acoustic) wave, or perhaps as an electro-magnetic field. The Lota-tron was approximately 800 m from the buildings at the end of 48th street in Yellowknife, which are very close to the shore. However, it is unlikely that 60 Hz would mechanically couple to the ice or water column from those buildings. We believe that it is more likely that 60 Hz magnetic fields induced a measurable electric field on the unshielded M15B hydrophone. The author's (BM) previous experience is that this hydrophone is extremely sensitive to such fields at long ranges from their source.

Potential impact of anthrophony on the resident fish

Several types of anthrophony were present in the data. The daily ebb and flow of traffic on the Dettah ice road near the study site added a rhythmic increase and decrease to the broadband sound levels of 8–12 dB each day. Aircraft were detected several times per day, and snowmobiles were present on numerous occasions. These sounds are not a normal part of the soundscape and have potential to impact resident fish populations.

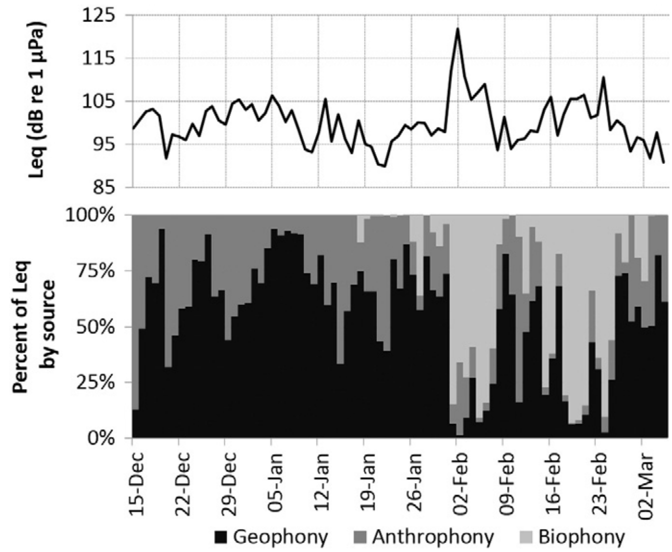

Fig. 9. Daily Leq for 15 December 2009 to 5 March 2010, Yellowknife Bay, Great Slave Lake, Northwest Territories, Canada: (top) daily equivalent sound pressure levels (Leq) values; (bottom) percent of the daily Leq by different sources.

The potential for sound from human activity to impact marine life is normally categorized into three levels of impact: 1) injury, 2) masking, and 3) behavioural disturbance. Currently recommended thresholds for potential injury to fish from continuous sounds like vehicles are an rms SPL of 170 dB re 1 μPa for 48 h to cause permanent injury and 158 dB re 1 μPa rms SPL for 12 h to cause a temporary threshold shift (only for fish with swimbladder adaptations for hearing; Popper et al., 2014). For fish without swimbladder hearing adaptations, there is a moderate chance of injury or temporary threshold shift at close ranges and a high probability of masking at close and intermediate distances to a high intensity source (Popper et al., 2014). The sound levels measured at the Lota-tron never approached these thresholds. Therefore we do not believe that the measured anthropogenic sounds have potential to injure or disturb the fish inhabiting Great Slave Lake.

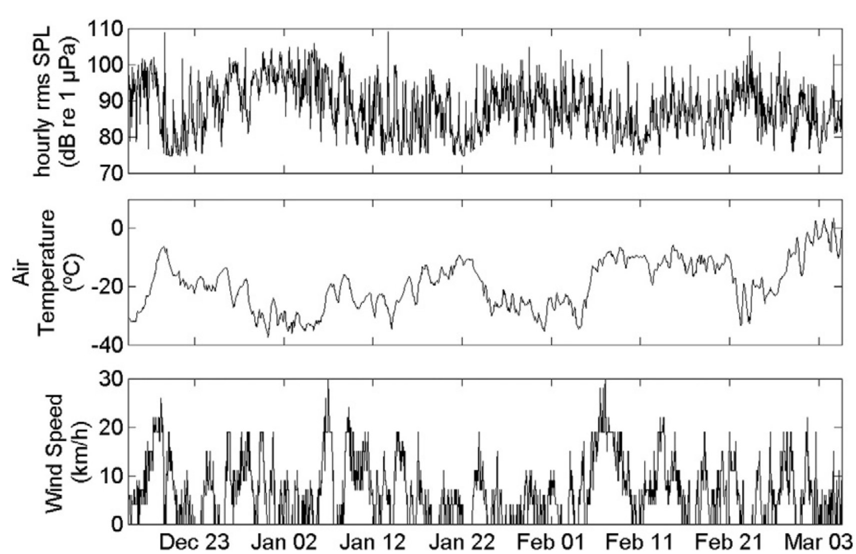

Fig. 8. Hourly rms SPL in the band 200–800 Hz at the Lota-tron as well as the air temperature, and wind speed at Yellowknife airport (Fig. 1) for 15 December 2009 to 5 March 2010, Yellowknife Bay, Great Slave Lake, Northwest Territories, Canada.

The data from this study also allowed for an evaluation of the potential for anthrophony to mask under-ice biophony, in this case the burbot mating calls that have evolved to occupy a unique niche in the soundscape. The relatively long duration between the zero-crossings is distinct from ice cracks. Even when burbot produce a frequency modulated series of calls (Cott et al., 2014, this issue), the apparent frequency is below the frequency of most ice cracking in this shallow water environment. The anthrophony at the Lota-tron included aircraft, snowmobiles, and the noise from the Dettah ice road. The anthrophony in the measured soundscape does not appear to conflict with the burbots' acoustic niche. At low frequency, the anthrophony tends to be a broadband rumble unlike the pulses and modulated tones of the burbot. Similar to results of Mann et al. (2009), the measured sound levels from anthrophony are likely only rarely detectable by burbot and other northern fish species because the levels are usually below their hearing thresholds (Cott et al., 2013; Mann et al., 2007). Further, the anthrophony sounds that exceeded the threshold of hearing generally lasted less than 1 min. The average number of minutes per day that the anthrophony detections exceeded 100 dB re 1 μPa rms SPL (1-min average) was 12.5, and the maximum number of minutes was 83 (31 December 2009). The 1-min rms SPL from anthrophony only once exceeded the burbot hearing threshold 130 dB re 1 μPa (Cott et al., 2013), for 5 min on 31 December 2009. Therefore, the potential for anthrophony to mask biophony is extremely low for ranges greater than 600 m from the ice road. The possibility of the ice road noise masking burbot calls will increase at ranges closer to the road.

The possibility that sound from the ice road is propagating through the ice and re-radiating into the water column implies that it may have a significant component of particle motion. A further study to measure the particle motion from burbot calls, the ice road, and thermal ice-cracking is needed to address this issue.

Conclusions

This study is the first to our knowledge to report on the long-term soundscape under the ice in fresh water, and the first to report on the long-term soundscape in a lake, whether ice-covered or ice-free (see Martin and Popper, In press, for an analysis of the long-term soundscape of the Hudson River). Geophony, specifically ice cracking pulses, was the most common sound source throughout the study; burbot spawning calls from late January thru mid-March introduced a local biophony source into the measured soundscape. The burbot calls increased the overall sound levels by increasing the sound levels in the band of 10–425 Hz. A diel pattern in the under-ice soundscape was observed. Ice cracking occurred more often at lower temperatures, which occur most commonly at night. The effects of human diel activity on the soundscape were evident, with vehicle detections occurring more often in the day.

Vehicle noise was detected from traffic on the Dettah ice road, aircraft approaching the Yellowknife Airport, and snowmobiles on the lake. Overall, the ice road traffic raised the median sound levels to 96 dB re 1 μPa during the peak traffic periods in the early evenings compared to 88 dB re 1 μPa at night. The anthrophony is not expected to be a significant source of masking for the burbot calls.

The soundscape measured in Great Slave Lake at Yellowknife Bay is likely representative of typical shallow lakes (<10 m) near a busy ice road. However, the soundscape in deeper waters will contain lower frequency sounds from all sources that propagate farther than in Yellowknife Bay. Long-term measurements in a large lake are recommended both in open water and under-ice. Similarly, measuring sound levels directly under an ice road is recommended to better characterize the actual effect of the road on soundscape. Future programmes should include particle motion sensors to evaluate if the low frequency energy that correlates with vehicles is re-radiating from the ice and if the magnitudes of the particle motion could disturb fish.

Acknowledgements

Thanks to the field team, Christopher Whitt and Chris Widdis (JASCO), and Rick Walbourne (Fisheries and Oceans Canada) for assisting Pete Cott with equipment deployment and retrieval. Thanks to Jeff MacDonnell and Del Leary for their assistance with data analysis. Thanks to Karen Hiltz and Nicole Chorney for assistance editing this manuscript. We thank the three anonymous reviewers for their comments and critiques, as well as the guest editor Bruce Hanna, as our manuscript was improved considerably as a result. Funding for this analysis was provided in part by the Program for Energy Research and Development (PERD), Fisheries and Oceans Canada, and JASCO Applied Sciences, Canada.

References

Arveson, P.T., Vendittis, D.J., 2000. Radiated noise characteristics of a modern cargo ship. J. Acoust. Soc. Am. 107, 118–129.
Cott, P.A., Johnston, T.A., Gunn, J.M., Higgs, D.M., 2013. Hearing sensitivity of the burbot. Trans. Am. Fish. Soc. 142, 1699–1704.
Cott, P.A., Hawkins, A., Zeddies, D., Martin, B., Johnston, T., Reist, J., Gunn, J., Higgs, D., 2014. Song of the burbot: under-ice acoustic signalling by a freshwater gadoid fish. J. Great Lakes Res. 40, 435–440.
Davis, J., Goadrich, M., 2006. The Relationship Between Precision–Recall and ROC Curves, Proceedings of the 23rd International Conference on Machine Learning. ACM, Pittsburgh, PA, pp. 233–240.
Environment Canada, 2009. Historical Climate Data. Government of Canada.
Farina, A., 2014. Soundscape Ecology: Principles, Patterns, Methods and Applications. Springer, Netherlands.
Ganton, J., Milne, A., 1965. Temperature-and wind-dependent ambient noise under midwinter pack ice. J. Acoust. Soc. Am. 38, 406–411.
[ISO] International Organization for Standardization, 2013. ISO 1999:2013 Acoustics—Estimation of Noise-induced Hearing Loss, Genevap. 23.
Jennings, P., Cain, R., 2013. A framework for improving urban soundscapes. Appl. Acoust. 74, 293–299.
Kaiser, J.F., 1990. On a Simple Algorithm to Calculate the 'Energy' of a Signal, International Conference on Acoustics, Speech, and Signal Processing. IEEE, pp. 381–384.
Krause, B., 1987. Bioacoustics, habitat ambience in ecological balance. Whole Earth Rev. 57.
Lewis, J.K., 1994. Relating Arctic ambient noise to thermally induced fracturing of the ice pack. J. Acoust. Soc. Am. 95, 1378–1385.
Lewis, J.K., Denner, W.W., 1988. Higher frequency ambient noise in the Arctic Ocean. J. Acoust. Soc. Am. 84, 1444–1455.
Makris, N.C., Dyer, I., 1986. Environmental correlates of pack ice noise. J. Acoust. Soc. Am. 79, 1434–1440.
Mann, D.A., Cott, P.A., Hanna, B.W., Popper, A.N., 2007. Hearing in eight species of northern Canadian freshwater fishes. J. Fish Biol. 69, 1–12.
Mann, D., Cott, P., Horne, B., 2009. Under-ice noise generated from diamond exploration in a Canadian sub-arctic lake and potential impacts on fishes. J. Acoust. Soc. Am. 126, 2215–2222.
Martin, B., 2013. Computing cumulative sound exposure levels from anthropogenic sources in large data sets. Proc. Meet. Acoust. 19, 010048.
Martin, B., Popper, A.N., 2015s. Short- and long-term monitoring of underwater sound levels in the Hudson River (New York, USA). J. Acoust. Soc. Am. (In press).
McPhail, J.D., Paragamian, V.L., 2000. Burbot biology and life history. burbot 11–23.
Merchant, N.D., Barton, T.R., Thompson, P.M., Pirotta, E., Dakin, D.T., Dorocicz, J., 2013. Spectral probability density as a tool for ambient noise analysis. J. Acoust. Soc. Am. 133, EL262–EL267.
Milne, A.R., Ganton, J.H., 1964. Ambient noise under Arctic-sea ice. J. Acoust. Soc. Am. 36, 855–863.
Northwest Territories Transportation, 2013. Northwest Territories Highway Traffic. Department of Transportation, Government of the Northwest Territories, p. 54 (Eds.).
Pijanowski, B.C., Villanueva-Rivera, L.J., Dumyahn, S.L., Farina, A., Krause, B.L., Napoletano, B.M., Gage, S.H., Pieretti, N., 2011. Soundscape ecology: the science of sound in the landscape. BioSci. 61, 203–216.
Popper, A.N., Hawkins, A.D., Fay, R.R., Mann, D.A., Bartol, S., Carlson, T.J., Coombs, S., Ellison, W.T., Gentry, R.L., Halvorsen, M.B., Løkkeborg, S., Rogers, P.H., Southall, B.L., Zeddies, D.G., Tavolga, W.N., 2014. Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. ASA Press.
Roth, E.H., Hildebrand, J.A., Wiggins, S.M., Ross, D., 2012. Underwater ambient noise on the Chukchi Sea continental slope from 2006–2009. J. Acoust. Soc. Am. 131, 104–110.
Scott, W.B., Crossman, E.J., 1973. Freshwater fishes of Canada. Fish. Res. Board Can.
Stewart, E.M., Coleman, K.A., Korosi, J.B., Thienpont, J.R., Palmer, M.J., Blais, J.M., Smol, J.P., 2015. Assessing Environmental Stressors on a Commercial Walleye Fishery from a Large Northern Ecosystem (Tathlina Lake) Using Water Chemistry and Paleolimnology. J. Great Lakes Res.
Urick, R.J., 1983. Principles of Underwater Sound. 3rd ed. McGraw-Hill, New York, London.
Vancoppenolle, M., Bitz, C.M., Fichefet, T., 2007. Summer landfast sea ice desalination at Point Barrow, Alaska: modeling and observations. JGR 112.
Zakarauskas, P., Chapman, D.M., Staal, P.R., 1990. Underwater acoustic ambient noise levels on the eastern Canadian continental shelf. J. Acoust. Soc. Am. 87, 2064–2071.