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# Alternative method for determining available winter water volumes from lakes to support small-scale projects

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## ABSTRACT

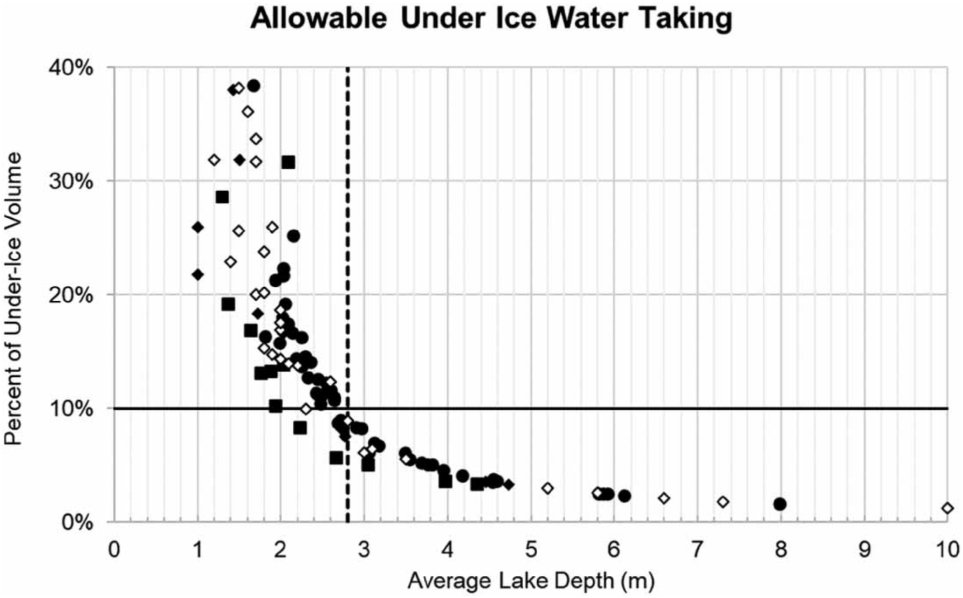
In Canada's Northwest Territories (NT), industrial activities conducted during the winter, such as ice road construction and exploratory drilling, require the use of water from ice-covered water bodies. Withdrawal in excess of 10% of available under-ice volume can threaten fish habitat or other users. The Land and Water Boards (LWBs) of the Mackenzie Valley require water licences for water withdrawal beyond regulated thresholds. Applicants must provide information including identification and location of proposed water sources, timing and proposed volume of water and winter water withdrawal must be limited to $<$10% of available volume to protect fish habitat under the ice. Many applicants are at early project stages and the necessary information on bathymetry and volumes of water is not readily available or requires expertise and effort that may not be feasible at the early stages of smaller projects. This paper describes the alternative method for determining available winter water volumes from lakes to support small-scale projects. A simple formula of 'allowable volume ($m^3$) = surface area ($m^2$) * 0.1 m' was developed and tested to provide a conservative estimate of under-ice volumes from easily available data which is protective in spite of uncertainties inherent in limited data.

**Key words:** bathymetry, habitat, volume estimation, winter water withdrawal

## HIGHLIGHTS

- Environmental impacts and mitigations.
- Environmental assessment.
- Water source volume estimations.
- Resource management.
- Water regulation.

## GRAPHICAL ABSTRACT




## INTRODUCTION

Water is required for a variety of activities during the development of industrial projects. These include domestic use to support remote camps, drilling, and process water and dust suppression. In northern regions, exploration continues in winter months and water may also be required to construct ice roads and overland winter (snow) roads to provide access to areas that cannot be accessed during the open water months (Cott *et al.* 2015). As a result, water is often removed from ice-covered water bodies for winter activities. Aquatic populations in lakes are at higher risk during the winter, as the removal of water will expose sensitive habitat in nearshore areas to freezing, the absolute loss of water volume reduces the volume of available overwintering habitat and reduces the available mass of dissolved oxygen available for aquatic life (Cott *et al.* 2008b; Leppi *et al.* 2016). Water level fluctuations, particularly in winter, can be detrimental to aquatic life including fish and their habitat by, for example, stranding (Nagrodski *et al.* 2012) and freezing eggs and larvae as water levels drop (Cott *et al.* 2008a). As a result, it is necessary to restrict the volumes of water that can be taken during winter. Although proponents may provide their own estimates for the licencing process, these are derived using unproven methods and can only be verified during operations, risking damage to aquatic habitats if the methods are not protective. There is therefore a need to develop and verify a method to determine appropriate limits for water withdrawal under ice that (a) can be easily used by proponents, (b) is acceptable to regulators, and (c) provides conservative estimates of available water to ensure that water withdrawal does not exceed 10% and aquatic life is protected.

## REGULATORY CONTEXT

Regulatory boards operate in the Northwest Territories (NT) of Canada under federal and territorial legislation and are responsible for issuing licences to regulate water use above certain thresholds. The Minister of Environment and Climate Change of the Government of the Northwest Territories (GNWT-ECC) is responsible for administering the Territorial *Waters Act* and approving Type A Water Licences[1] on territorial lands while the Land and Water Boards (LWBs) conduct the water licence processes and issue water licences. As a result, the parties often collaborate on the water licencing process.

As part of that process, the Boards are required to conduct a preliminary screening of proposed activities under the *Mackenzie Valley Resource Management Act* to assess potential environmental impacts related to development and ensure

[1] The NWT's *Water Regulations* have water licences that are categorized by Type A Water Licences, for more complex projects such as mining and oil and gas production that are more advanced and approved by the Minister and Type B Water Licences which are associated with lower threshold activities at early stages and are approved by the Land and Water Boards.

that appropriate mitigation measures are in place. Such screening includes the potential for water withdrawal to impair aquatic habitat. Mitigation may include specific volume thresholds, timing limitations, and other conditions that consider protection of the aquatic environment. Water licence applicants are required to provide information regarding proposed water uses, location of proposed water sources, timing and proposed volume of water to be used, and a comparison of the proposed water use volume to the available water for each proposed source.

Previous initiatives in the NT developed guidance on the amount of water that could be safely withdrawn without harming fish habitat, thus complying with the *Fisheries Act*. A withdrawal threshold of 10% of the under-ice volume was determined to be protective of fish habitat for lakes under maximum ice cover through a whole lake manipulation experiment (Cott *et al.* 2008b). Withdrawals beyond 10% resulted in decreases in dissolved oxygen below levels required to protect overwintering fish species (Cott *et al.* 2008b). The Department of Fisheries and Oceans Canada then established the *Protocol for Winter Water Withdrawal from Ice Covered Waterbodies in the Northwest Territories and Nunavut* (Fisheries and Oceans Canada (DFO) 2010, 'the Protocol') which outlined thresholds for the amount of water to be removed under ice in small lakes depending on location, lake depth, and ice cover. The Protocol also outlined the requirements to establish available water volumes by specifying minimum bathymetric information, depth criteria, and maximum expected ice cover for water sources. The Protocol has been considered best practice by several of the regulatory boards in the NT and in other jurisdictions including Alaska, Nunavut, and Saskatchewan (P.Cott, GNWT-ECC, pers. comm.). It is often included as a condition of water licences as a standard means to determine if appropriate information on water sources has been included with an application.

While this has become the standard, in recent years there has been some concern raised from industrial proponents, particularly smaller-scale mineral exploration companies, regarding the amount of effort required to complete the bathymetric field programs defined in the Protocol during a typical exploration project. The Protocol outlines specific field methods to gather the necessary information on the bathymetry of proposed water sources and requires each to be field verified either using a boat and depth-sounding equipment in the summer or ground-penetrating radar in the winter. Mineral exploration activities are mobile and transient in nature, however, with drill targets identified and revised depending on the results of geophysical exploration and exploratory drilling. As such, exploration companies are unable to confirm all potential water sources at the time of the Water Licence application, resulting in a need for operational flexibility in the field. In addition, exploration companies often have limited capital, expertise and resources to conduct extensive environmental field programs as required under the Protocol prior to commencing drilling activity. Therefore, the amount of time and financial commitment required to conduct these bathymetric surveys on all potential water sources in the field could delay the licencing process and limit the feasibility of conducting exploration projects.

The LWBs and the GNWT therefore initiated a project in 2019 to develop a simple method that could be applied to estimate available under-ice water volumes in small lakes in support of early-stage exploration or other small-scale activities. The intent was to determine if a simple method would provide a conservative and reliable volume estimate that could be used without requiring detailed bathymetry and which, if followed, would be supported by regulators as protective of fish habitat. The initial requirements were outlined in a request for proposal for an independent consultant, a report based on the methods outlined below (HESL 2021) and additional investigations and method verification by the authors.

## STUDY AREA

The method was a direct response to the needs of the water licencing process of the NT of Canada and so was developed using measured bathymetry from that region where the method would be applied and included data collected for both ice road and mineral exploration developments where water licences are required. Bathymetric methods are provided in the cited source material but, in general, echosounders were used to measure depth to bottom from the water or ice surface at set transects as per the DFO (2010) protocol. Data sets came from different areas across the NT and included two data sets from the Mackenzie River Delta region, two from the central interior of the NT, and one from the coastal central Arctic (Figure 1) to cover a range of landforms. Data sets and characteristics are described in Table 1.

Lake data sets from the NT and Nunavut were used because the guidance method would be used in the NT and, as such, data from the NT (and adjacent Nunavut) would include lakes from the area of application. The study lakes included a large range of lakes across the region and would therefore accurately reflect their range of characteristics. In addition, the project rationale was focused on the needs of project proponents, many of whom had readily accessible data sets from existing projects that had been prepared for the licencing process. Data sets used were the extent of those that were available to the team

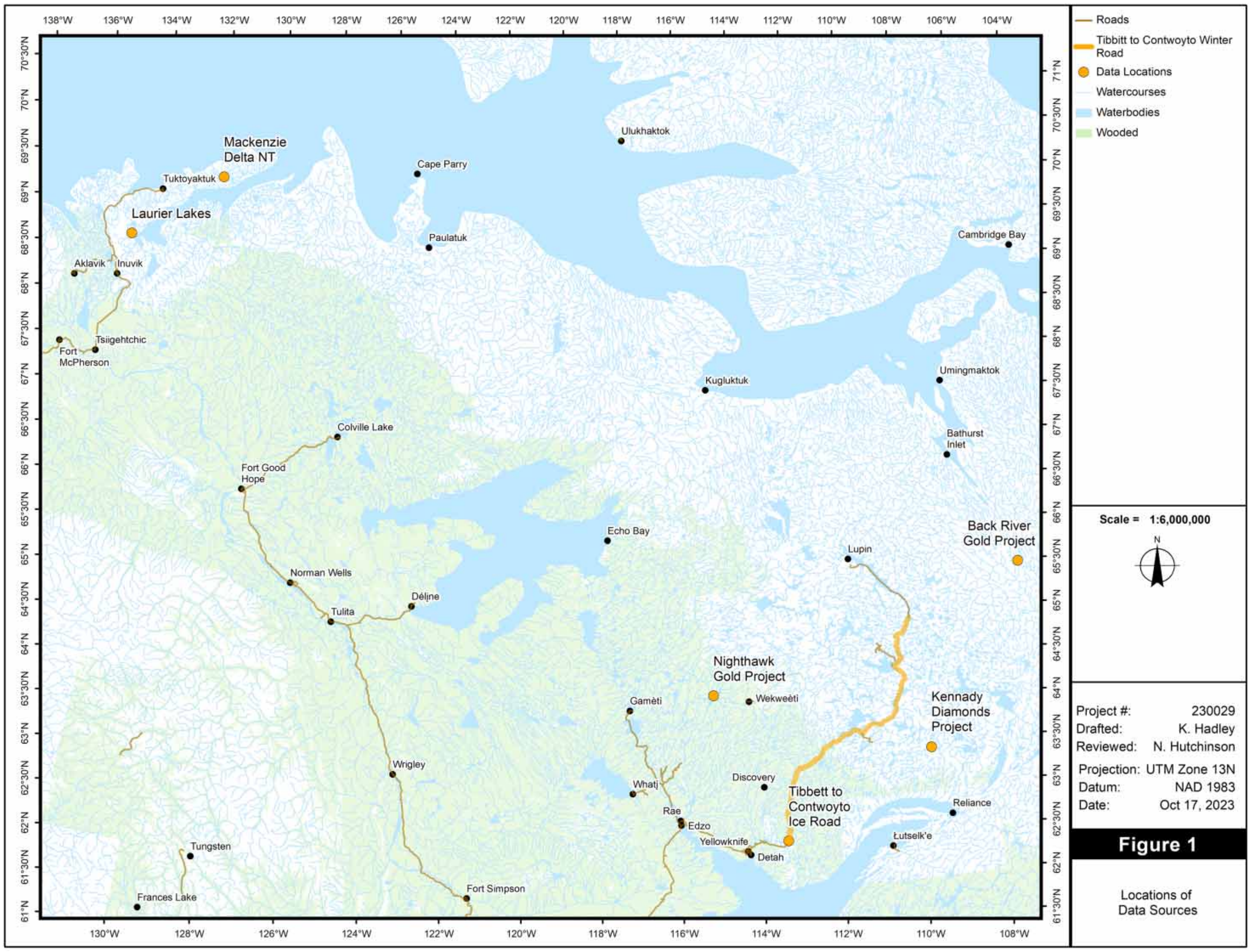



**Figure 1** | Northwest Territories showing locations of lake data sets.

during the time of the review and were not selected as a subset of a larger data set or in any other specific manner. The following lake data sets were used:

- The DFO data set (Cott *et al.* 2005) was collected from 37 lakes in the Mackenzie River Delta region of the northwestern NT by Fisheries and Oceans Canada to assist with the development of the original protocol for the protection of fish habitat. Average depths ranged from 0.5 to 5.3 m and bathymetry was collected in the ice-free season.
- The Golder Back River data set of 55 lakes was tested for initial model development using measured total lake volumes from the Back River Gold Project and then as a test data set for under-ice volume estimation assuming 2 m ice cover (Golder Associates 2018). Average depths in the 55 lakes ranged from 1.7 to 33.6 m and maximum depths from 3.5 to 64.45 m.
- A data set for 17 lakes along the Tibbett to Contwoyto Ice Road which extends 400 km NE of Yellowknife for which ice cover was measured (EBA 2013) was used for testing the model. Average water depths ranged from 0.8 to 4.3 m and maximum depths were not provided.
- A Kennady Diamonds mineral exploration data set of 28 lakes ~300 km NE of Yellowknife with an assumed ice depth of 2 m (Hunt 2020, pers. comm.) was used for testing the model. Eight lakes were <2 m maximum depth, assumed to freeze to the bottom and excluded from the analysis. Maximum depths of the remaining lakes ranged from 2.3 to 14.5 m and average depths from 0.4 to 4.7 m.
- A set of data for 59 lakes with an assumed ice depth of 2 m obtained by Wilfred Laurier University along the Inuvik – Tuktoyaktuk Highway (ITH) in the Mackenzie River Delta region was used for testing the model. Seven of these lakes were

**Table 1** | Lake sets used to develop and test estimation models

| Data set | Location | Number of lakes | Surface area (ha) | Volume 1,000 ($m^3$) | Average depth (m) | Maximum depth (m) |
|---|---|---|---|---|---|---|
| DFO data set (Cott *et al.* 2005) | Mackenzie Delta NT | 37 | 12.5–3,186 | 1,290–43,869 | 0.5–5.3 | 1.9–13.9 |
| Golder Back River | North-Central NU | 55 | 1.6–15,722 | 38–3,320,662 | 1.7–33.6 | – |
| Tibbett to Contwoyto Ice Road | Central NT | 17 | 0.3–500 | 33–6500 | 0.8–4.3 | – |
| Kennady Diamonds | Central NT | 28 | 0.4–90 | 1.8–3,804 | 0.2–4.7 | 1.3–14.5 |
| Wilfred Laurier University | Inuvik to Tuktoyaktuk Ice Road – NT | 59 | 0.8–236 | 10.3–6997 | 0.4–10 | 1.2–19.9 |

$<$1.8 m maximum depth and frozen to the bottom. Average depths of the remaining 52 lakes ranged from 0.9 to 10 m and maximum depths ranged from 2.2 to 19.9 m.

## METHODS

The volume estimation method was developed in four steps:

– A review of primary and technical literature established that there were no published methods that could be readily adapted to the purposes (see 'Literature Review').
– Candidate volume estimation methods were sought by canvassing government, industrial, and academic operators in the NT.
– Submitted methods were tested for their ability to estimate water volumes for a data set of lakes for which measured bathymetry was available (DFO data set – Cott *et al.* 2005; Table 1).
– The method that gave the best estimates of water volume for the DFO data set (Golder Nighthawk model) was then tested using four sets of lakes (Golder Back River, Tibbett to Contwoyto Ice Road, Kennady Diamonds, and Wilfred Laurier University, Table 1) for which under-ice water volumes had been established by measurement to provide confidence in the estimates generated by the preferred method and average depths for which the preferred method was protective.

## RESULTS

Detailed analyses and complete data sets are provided in Hutchinson Environmental Sciences Ltd (HESL 2021).

### Literature review

HESL (2021) completed a literature review which identified several potential approaches based on remote sensing or the use of a regional bathymetric data set and existing topographic maps:

- The HAB-2 model (Walther *et al.* 2011) estimated depths from aerial, high-resolution, film-based, true-colour imagery in the McKenzie River, Oregon. Equivalent photography was not available for the NT, the regional topography differed such that direct application of the model was not feasible and the model was intended for estimation of stream flow and could not be applied to lakes in the NT.
- Hamilton *et al.* (1993) used an aircraft-mounted Airborne Visible Infrared Imaging Spectrometer (AVIRIS) to measure depths in Lake Tahoe. Although such remote sensing technology could be usefully applied over large areas to generate regional data sets of lake bathymetry, within certain limits of transparency and depth to estimate volumes of water bodies, it did not provide a simple means that could be easily applied by proponents and required costly development of a regional lake bathymetry set using remote sensing and interpretation. The development of an empirical approach from available regional data sets (Table 1) was therefore preferred.

- Emmerton *et al.* (2007) used a data set of 81 lakes in the Mackenzie River Delta and used depth measured in summer and estimated ice thicknesses to develop a regional data set of lake volumes. The method was not carried forward for analysis as the assumed average depth of 0.818 m meant that all lakes would freeze to the bottom in winter with no available water.

These methods were limited for application in northern Canada and so were not carried forward.

## Assessment and analysis of potential methods

Water source volume estimation methods developed on the basis of operational experience were solicited from industrial proponents and regulatory bodies. In essence, all submitted methods were a variation on the same theme of attempting to make a coarse volume calculation based on known information, such as surface area, or by extrapolating relationships developed for a few lakes to apply to many. The project team used the submitted methods to estimate volumes and then compared these estimates to measured volumes from the DFO data set (Cott *et al.* 2005).

No under-ice volumes were included with the DFO data set so an initial screening of the alternative estimation methods was conducted by comparing the outputs of the various methods against 10% of the total lake volumes as a conservative first step. The two methods that provided accurate estimates of total water volume were then carried forward for the estimation of under-ice volumes. Additional methods submitted by two industrial operators were found to have an unacceptably high error rate and were not included in this discussion paper.

The Northwest Territories Power Corporation proposed two approaches:

- Total volume = (Area*Depth)/3, where depth = assumed maximum depth of 3 m and
- Total volume = (Area*Depth), where depth = assumed average depth of 1.5 m.

Both methods overestimated water volumes; in 10 and 4 of the 37 lakes, respectively, and the magnitude of the error exceeded that generated by other methods so these models were not carried forward.

TerraX Minerals used bathymetric contours for five lakes to generate a three-dimensional model to estimate lake volumes based on measured area and a power function where the average depth was assumed as ‘deep’ or ‘shallow’:

$$\text{Shallow lakes: Volume} = 6,843,654 * \text{Area}^{1.16939}$$

$$\text{Deep lakes: Volume} = 16,621,633 * \text{Area}^{1.17395}$$

Both models produced very large overestimates of lake volume such that the estimated takings of 10% exceeded the DFO threshold for all 37 lakes and ranged as high as 225 and 666% for the shallow and deep lake models, respectively, and so these models were not carried forward. Additional information on these can be found in HESL (2021). Models were also submitted that had been derived from the Golder Back River and Golder Nighthawk Projects and which provided more accurate estimates of volume and are discussed below.

### Golder Back River model

The Back River Project included the requirement for an ice road to service a proposed gold mine located inland of the Arctic Ocean in the central Canadian Arctic (Figure 1). The ice road required water use of 675 $m^3$/km. Golder (2018) developed bathymetric profiles and water volumes for 41 lakes from a digital elevation model (DEM) developed for 118 waterbodies and watersheds using photogrammetric interpretation of satellite imagery. The interpreted slope of the terrain surrounding each water body was used to derive the slopes entering the water bodies and extrapolated from there to estimate water depth from the blue and green satellite spectral bands which ‘*allow the identification of detailed lakebed topography to a* depth of 30 m’ (Golder 2018). No estimates of error or uncertainty of the bathymetry measurements estimates were provided. The error was derived by testing the lake volumes that were estimated by the model against volumes derived from the bathymetry (below).

Golder (2018) concluded that the withdrawal of 10% of the under-ice volume during winter resulted in a mean water level change of 0.183 ± 0.065 m for the 41 waterbodies that ranged in area from 2 to 93 ha (Table 1). They proposed a water level change of 12 cm or less (i.e., 0.183 – 1 SD) as a conservative threshold for protecting aquatic habitat during water withdrawals such that: ‘Allowable water taking ($m^3$) = Lake area ($m^2$) * 0.12 ’.

The model was applied to the DFO data set and the allowable volumes derived using the model were compared to the measured allowable volumes from the DFO data set. A target withdrawal of 10% of the total lake volume was used as a conservative test criterion of model accuracy to compare the two methods.

Withdrawal of 12 cm of water represented less than 10% of the total lake volume in 30 of the 37 lakes (81%) and exceeded 10% in 7 lakes (19%, Figure 2). All volumes which exceeded the 10% test threshold occurred for lakes <2 m in average depth. Volumes dropped to <5% of the total for all lakes >3.5 m depth.

### Golder Nighthawk model

The Golder Nighthawk model was submitted for the water licencing process for the proposed Nighthawk Gold Indin Project located 200 km north of Yellowknife in the NT (Figure 1). The method assumed a conservative estimate of 1 m of available water depth under 2 m of ice, such that the assumed average depth was 3 m. The submission stated that, in practice, an average depth of at least 3 m would be verified in the field prior to water extraction by a minimum of three measurements taken within 500 m of the water intake. The Nighthawk model assumed that (a) a maximum of 2 m of ice would form and (b) 10% of a minimum of 1 m of available water under the ice was conservative enough to protect overwintering aquatic life. The model was therefore stated as: 'Allowable water taking ($m^3$) = Lake area ($m^2$) * (10% of 1 m)'.

The 'Golder Nighthawk model' was applied to the measured volume of the 37 lakes from the DFO data set and the estimate was compared to the test threshold of 10%. Of the 37 DFO lakes, the estimated withdrawal volume was within the 10% volume threshold in 33 or 90% of the test lakes (Figure 3). The four lakes outside of the 10% threshold had average depths of 1.5 or less.

The Back River and Nighthawk models were variations of the same theme; the Back River model with an application of 12 cm of water level drop to the surface area (surface area × 0.12 m) or the Nighthawk model with an application of 10% of a conservative assessment of 1 m of lake volume (=surface area × 0.1 m) for lakes with an assumed ice depth of 2 m. The more protective threshold of a 10 cm water level decrease (Nighthawk model[2]) was chosen to increase confidence in the protection of fish habitat in the water sources. The 10 cm reduction increased the percentage of lakes protected from 81% (Back River model: 0.12 m) to 90% (Nighthawk model: 0.1 m).

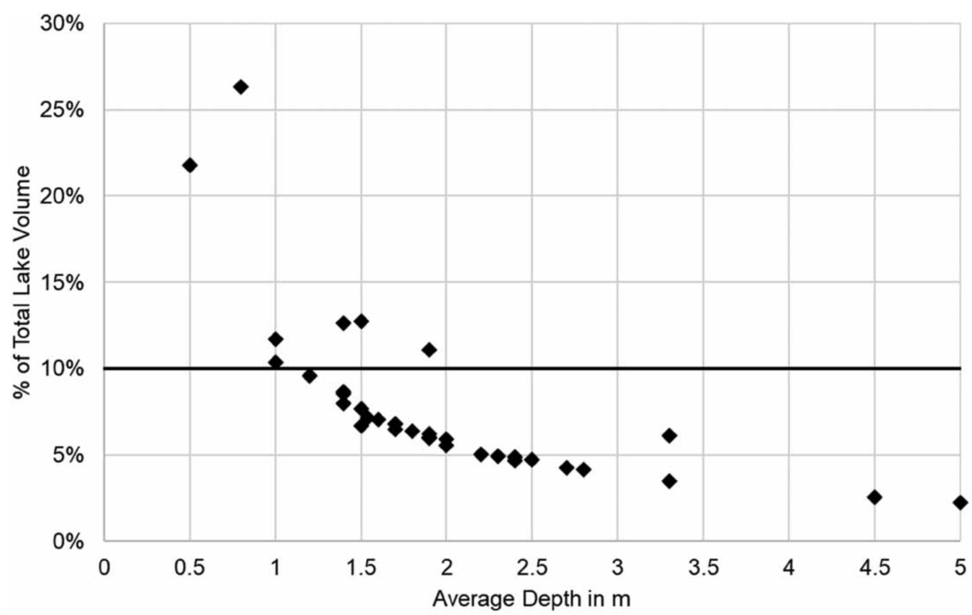



**Figure 2** | Percent of total lake volume taken: withdrawal of 12 cm water – Golder Back River model.

[2] We note that use of the Back River model with a 10 cm vs. a 12 cm withdrawal would be operationally equivalent to the Nighthawk model.

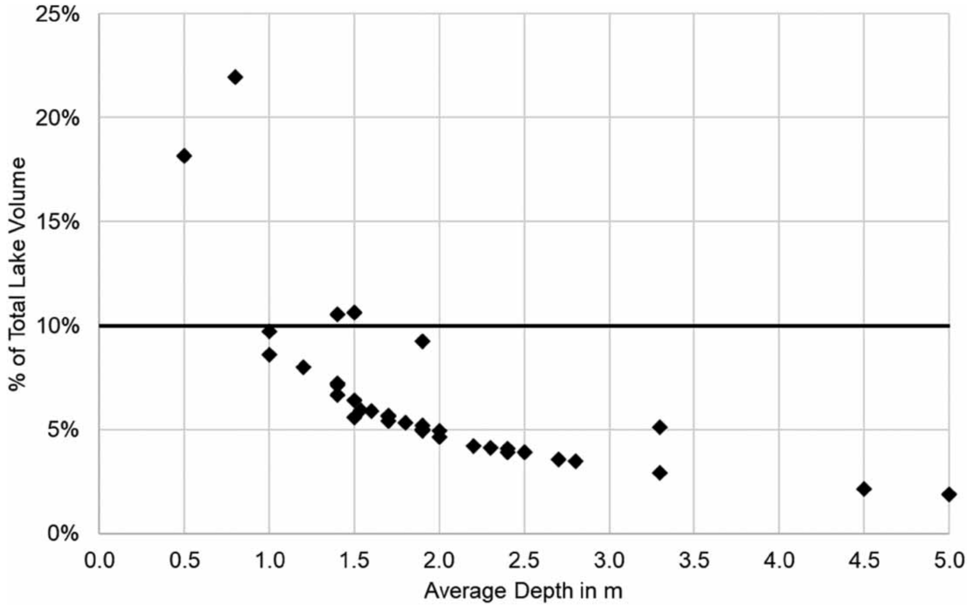



**Figure 3** | Percent of total lake volume taken: withdrawal of 0.1 m – Golder Nighthawk model.

Application of 10 cm of drawdown to the surface area (equivalent to 10% of 1 m of available water) was chosen as the preferred model as it maintained water losses at <10% for 90% of lakes in the DFO data set. The remaining 10% (4 of the 37 lakes) were shallow lakes with an average depth of 1.5 m or less in which the 0.1 m reduction resulted in the removal of 11–22% of the water. The Golder Nighthawk model was therefore chosen as the preferred means of estimating allowable water takings using the formula:

Allowable volume ($m^3$) = (Surface area ($m^2$) * 0.10 (m)).

## Under-ice volume estimation

The DFO (2010) protocol speaks to a requirement to take up to 10% of the water volume *under* ice. The Golder Nighthawk model was therefore tested using four independent bathymetric data sets from small lakes within the NT that included measured under-ice volumes to determine if the model derived for open water was protective under ice cover. Four data sets were obtained for which detailed bathymetry and ice cover were available (Figure 1; Table 1): the Golder Back River data set, recalculated with an assumed 2 m ice cover, the Tibbett to Contwoyto Winter Road data set, the Kennady Diamonds mineral exploration data set, and the Wilfred Laurier University data set for the Inuvik – Tuktoyaktuk Highway (ITH). Estimates of 10% of the under-ice volumes were calculated for each data set using the Golder Nighthawk model and compared to 10% of under-ice volumes from the measured bathymetry of each lake.

With the Back River data set, an allowable water withdrawal of 0.1 * surface area (SA) amounted to 1–38% of the under-ice volume and exceeded the limit of 10% in 27 of the 55 (48%) lakes. The lakes with exceedances had an average depth of 2.8 m or less (Figure 4).

With the Tibbett to Contwoyto Lake data set, the allowable water withdrawal amounted to 4–138% of the under-ice volume and exceeded the limit of 10% of the under-ice volume in 11 of the 17 (65%) lakes. The lakes with exceedances had an average depth of 2.1 m or less (Figure 5). Under-ice volumes exceeded 40% in 4 lakes which are outside of the range shown in Figure 5.

For the Kennady Diamonds data set, the allowable water withdrawal exceeded the entire under-ice volume in 16 of the 28 lakes that were <1 m in average depth (lakes of 1 m or less in depth are not shown in Figure 6) and exceeded the 10% limit in all but 4 of the remaining 10 lakes. The lakes with exceedances had an average depth of 2.1 m or less (Figure 6).

For the Wilfred Laurier University data set, the allowable water withdrawal exceeded the limit of 10% of under-ice volume in 48 of the 59 lakes (80%), of which 7 were lakes that were frozen to the bottom. The lakes with exceedances had an average depth of 2.6 m or less (Figure 7).

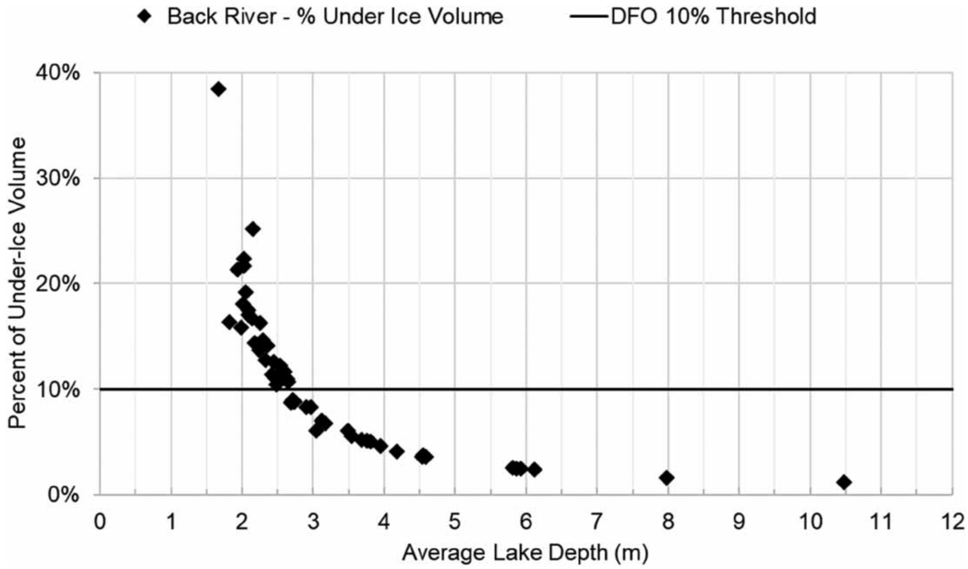



**Figure 4** | Comparison of the estimated under-ice volume against the DFO 10% threshold: Back River data set and Golder Nighthawk model.

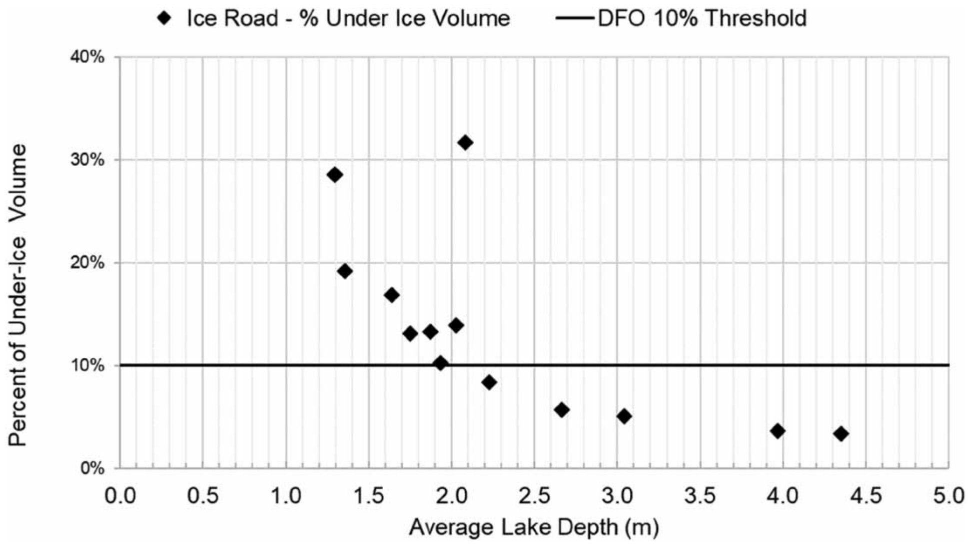



**Figure 5** | Comparison of the estimated under-ice volume against the DFO 10% threshold: Tibbett to Contwoyto Ice Road lake set and Golder Nighthawk model.

## DISCUSSION

A means to estimate available water volumes in small ice-covered lakes is required to ensure that water withdrawal requirements for small projects will not exceed 10% of the under-ice volumes of water necessary to protect fish habitat. The estimation method is intended to be used in the water licencing process as regulatory guidance and in the field so that estimates can be made reliably with existing data. The Nighthawk model (Allowable volume ($m^3$) = (Surface area ($m^2$)*0.10(m)) was proposed to meet this need.

A comparison of volume estimates made using the Nighthawk model to measure under-ice volumes in the 159 lakes from the four tested data sets showed that there is a significant risk of habitat loss associated with withdrawing 10 cm or more of under-ice water depth unless the average depth exceeds 2.8 m (Figure 8). Application of the Nighthawk model was protective

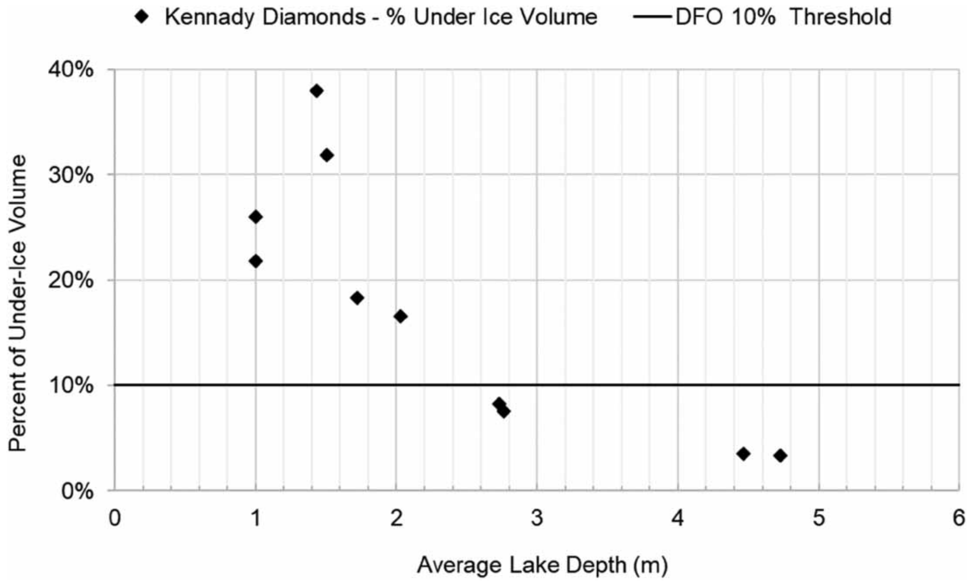



**Figure 6** | Comparison of the estimated under-ice volume against the DFO 10% threshold: Kennady Diamonds lake set and Golder Nighthawk model.

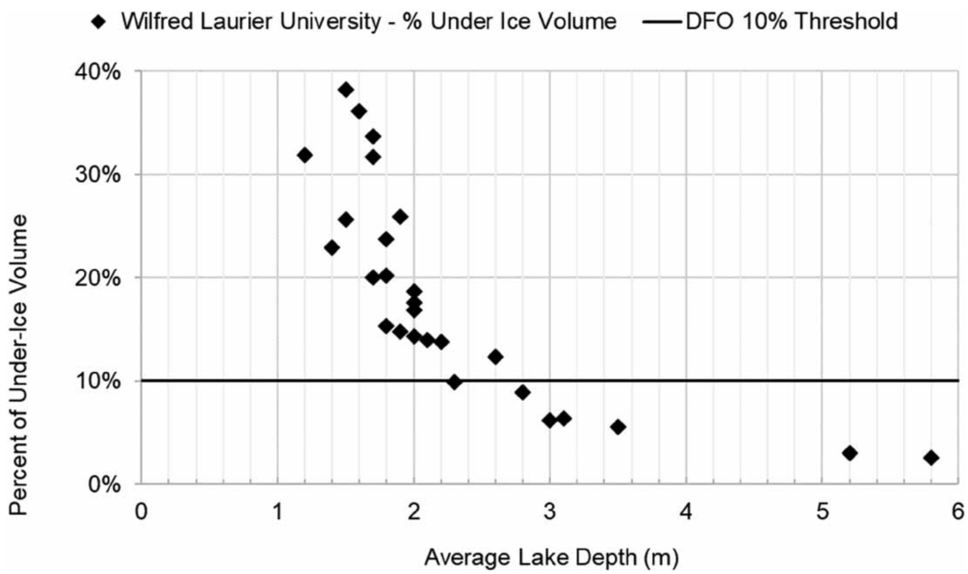



**Figure 7** | Comparison of the estimated under-ice volume against the DFO 10% threshold: Wilfred Laurier University lake set.

of only 48 out of 159 or 30% of the lakes and these lakes all exceeded 2.8 m in average depth. Fifteen of the 159 lakes were frozen to the bottom and would not be fish-bearing.

There will always be uncertainty associated with estimation methods when they are compared with measured bathymetric data but such detailed measurements are not generally feasible at the early stages of project development. We therefore recommend the alternative of an estimation along with measurements of surface area which can be easily obtained from topographic maps, satellite, or Google Earth© imagery.

Application of the estimation model (Allowable volume ($m^3$) = (Surface area ($m^2$)*0.10 ) based on measurement of surface area showed, however, that the protective threshold of 10% of under-ice volume could not be maintained when tested against measured bathymetry in 111 of the 159 (70%) lakes from four Arctic data sets. These 111 lakes were all less than 2.8 m in

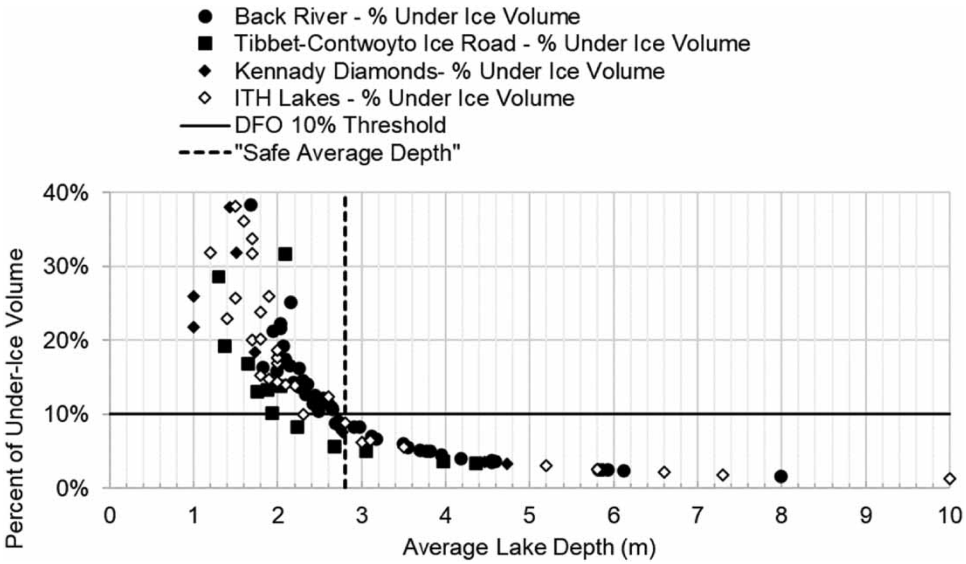



**Figure 8** | Comparison of the estimated under-ice volume against the DFO 10% threshold: all lake sets.

average depth and 15 were frozen to the bottom and would not support fish. There is therefore substantial risk of an over-estimation of water volumes for shallow lakes in the absence of accurate estimates of average depth.

The proposed estimation model would therefore require field verification of depth prior to initiating water use from under the ice. Golder (2019) proposed that an average depth of at least 3 m would be verified in the field prior to water extraction by a minimum of three measurements taken within 500 m of the water intake. Our analysis showed, however, that fish habitat would be protected if the average depth exceeded 2.8 m. We recommend that uncertainty be reduced by confirming average depth through measurements made in at least five locations within 20 m of the proposed withdrawal site to ensure that the minimum lake depth is 2.8 m. Efforts should be made to increase the number of field measurements where feasible. Although the stipulation of at least five data points is arbitrary, we recognize the need to strike a balance between operational feasibility and habitat protection such that some level of field verification is required.

Some potential for bias is inherent in the decision of where to locate a water intake. Proximity to shore would be a consideration to minimize the amount of pipe required and the potential that it could freeze. In most cases, field crews would have little information on the characteristics of a water source although the terrain surrounding the water body would provide some indication of the bathymetric slope of the water body. If five measurements near the intake exceeded 2.8 m in depth, then there is some assurance that this was typical for the lake.

There is also some risk inherent in developing empirical predictions of water volume from current data in an environment that is changing. Zhang *et al.* (2019) reported that the average annual temperature in northern Canada increased by 2.3 °C between 1946 and 2016 and projected increases of 1.9 to 2.7 °C by 2050 under models of decreasing (RCP2.6) and increasing (RCP8.6) carbon emissions. These increases will increase the rate of snow melt and evapotranspiration, changing the hydrologic dynamics of northern regions. Zhang *et al.* (2019) also predicted that annual precipitation would increase by 8.2–11.3% under the same emissions scenarios, adding additional uncertainty to hydrologic predictions.

While the intent of this study was not to address changing hydrology under a changing climate, we recognize that the empirical relationships described herein may be altered in a warmer future. Changes in water volumes of northern lakes will alter both the depth and surface area of water bodies, and potentially the relationships between them that informed the development of the estimation model we present. It is therefore important to encourage the acquisition of more data sets of measured bathymetry to test model accuracy over time as the climate changes. Future industrial development will add to the database of bathymetry as more ice roads and mines are built and acquisition of these data sets can be required as part of the licencing process as more advanced projects are undertaken. Future data sets should be compared with, and added to, the data sets used here to confirm the model presented or revise it as warranted. Additional research is also recommended to confirm if the threshold of a 10% reduction in water volume proposed by Cott *et al.* (2008b) and DFO (2010) provides adequate protection of fish habitat.

## CONCLUSION

Relationships between measured surface area and measured lake volumes were undertaken to develop a simple empirical model to predict how much water could be withdrawn for industrial purposes without threatening under-ice fish habitat. Guidance of 'Allowable volume ($m^3$) = (Surface area ($m^2$)*0.10 (m))' is therefore proposed to provide operators with the desired flexibility to make water use decisions in the field while being protective of fish habitat. The model was tested using 4 independent data sets of 159 lakes (Back River, Ice Road, Kennady Diamonds, and Wilfred Laurier University) and shown to be protective if the average lake depth exceeded 2.8 m. Verification of water depth by measurement at 5 points within 20 m of the water taking is therefore required to increase confidence in volume estimates and protection of aquatic habitat. The model will be implemented through the regulatory process of reviewing water licences for small-scale projects in northern Canada.

The warming climate will alter temperature, precipitation, and the hydrologic responses of the northern landscape. It is therefore important to verify and refine the proposed model through the acquisition of additional bathymetric measurements to test model accuracy as the climate changes.

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## DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: https://mvlwb.com/resources/lwb-policies-and-guidelines.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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