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Regional trends in evaporation loss and water yield based on stable isotope mass balance of lakes: The Ontario Precambrian Shield surveys

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ABSTRACT

Stable isotopes of water, oxygen-18 and deuterium, were measured in water samples collected from a network of 300 lakes sampled in six ~100 km^2 blocks (centred at 49.72°N, 91.46°W; 48.49°N, 91.58°W; 50.25°N, 86.62°W; 49.78°N, 83.98°W; 48.24°N, 85.49°W; 47.73, 84.52°W) within Precambrian shield drainages in the vicinity of Lake Superior, northern Ontario, Canada. Additional sampling was also conducted within the Turkey Lakes watershed (47.03°N, 84.38°W), a research basin situated in the Algoma region located 50 km north of Sault Saint Marie, Ontario. The studies were undertaken to gain a better understanding of hydrology and geochemistry of watersheds in the region in order to better predict acid sensitivity of lakes. The main objective of this paper is to describe the hydrologic variations observed based on stable isotope results. Evaporative isotopic enrichment of lake water was found to be systematic across the region, and its deviation from the isotopic composition of precipitation was used to estimate the evaporation/inflow to the lakes as well as runoff (or water yield) based on a simple isotope mass balance model. The analysis illustrates significant variability in the water yield to lakes and reveals a pattern of positively skewed distributions in all six widely spaced blocks, suggesting that a high proportion of lakes have relatively limited runoff whereas relatively few have greater runoff. Such basic information on the drainage structure of an area can be valuable for site-specific hydrologic assessments but also has significant implications for critical loads assessment, as low runoff systems tend to be less buffered and therefore are more sensitive to acidification. Importantly, the Turkey Lakes sampling program also suggests that isotope-based water yield is comparable in magnitude to hydrometric gauging estimates, and also establishes that uncertainty related to stratification can be as high as ±20% or more for individual lakes, although it likely has only a minor influence on regional survey results. While further analysis in gauged lake watersheds would be beneficial to constraining the accuracy of the method or calibrating it for operational use, it is nevertheless a powerful tool in its present form for lake-to-lake and regional runoff inter-comparisons.

1. Introduction

Lake hydrology in Canada has proven difficult to monitor due to the sheer number of lakes and vast areas that are remote and ungauged. Canada has an estimated 2 million lakes, covering roughly 7.6% (758,000 km^2) of Canada's total land area (Canada, Natural Resources Canada, 2016). This corresponds to 28% of the total lake area worldwide based on the area estimates of Tamrazyan (1974; 2.7×10^6 km^2). A more recent global lake area estimate was provided by Downing et al. (2006; 4.2×10^6 km^2) who used global models at enhanced spatial resolution to demonstrate that lakes smaller than 1 km^2 form a dominant proportion of lakes, and these have not been included in the traditional inventories. Including these smaller lakes, the projected number of lakes in Canada is undoubtedly much higher. Clearly there is a need for improved hydrologic characterization of lakes and surface waters in Canada, but also for basic information on the extent and distribution of surface water resources.

Use of conventional hydrometric methods for monitoring of lakes has been spatially limited as national networks in Canada have tended to focus on flowing waters (rivers) and mostly larger lakes due to the relative importance of these water bodies, and

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given limited resources. While some methods such as radar altimetry techniques have shown promise for remote hydrologic characterization of lakes, these methods remain immature (e.g. Smith and Pavelsky, 2009) and are therefore not a substitute for field-based assessment at the present time. The need for site-specific or regional hydrologic information to plan for hydroelectric or mining development, or to support research on water or climatic impacts, is still a pressing need. One promising approach that has been demonstrated for obtaining site-specific information in local and regional surveys is stable isotope mass balance. Previous studies have applied the stable isotopes of water for establishing hydrologic control in sustainable forest management studies (Prepas et al., 2001; Gibson et al., 2002), for mine-site evaporation and water-balance investigations (Douglas et al., 2000; Gibson et al., 1996, 1998; Gibson and Reid, 2010, 2014), for examining flood history of delta lakes (Yi et al., 2008; Brock et al., 2009; Wolfe et al., 2012), and for regional assessment of climate- or catchment-driven gradients (Gibson and Edwards, 2002; Turner et al., 2010; Brooks et al., 2014; Gibson et al., 2015a). A recent review of isotope mass balance and its application in various climatic regions is given by Gibson et al. (2015b). Several previous studies have also used isotope mass balance for estimating water yield as a component of critical loads assessments (Bennett et al., 2008; Jeffries et al., 2010; Scott et al. 2010; Gibson et al., 2010a,b). These studies have demonstrated regional patterns in water balance for areas of British Columbia, Alberta, Saskatchewan and Manitoba.

Here we provide an additional case study from application of isotope mass balance in Ontario, which contains approximately 18% of Canada's lake area (Canada, Statistics Canada, 2005). The study, designed to provide water yield estimates for a regional critical loads assessment carried out as part of Canada's National Acid Rain Program, demonstrates typical hydrologic characteristics of lakes in six blocks situated north of Lake Superior, in Canadian Shield watersheds with limited soil cover. As part of this analysis, a sub-study was also conducted at an acid rain research site, the Turkey Lakes watershed (see Jeffries et al., 1988), where the isotope method was similarly applied to estimate water balance for a variety of lakes which had well-defined stratification status. The objective of this paper is to describe the water balance results to illustrate hydrologic variability of lakes in the region, and to test assumptions in selected lakes about use of well-mixed isotope balance models, as information on thermal stratification is not always available for regional surveys. Influence of sampling date, stratification status and sampling strategy were also evaluated and are also discussed.

1.1. Study area

300 lakes, ranging in size from <1 to >5000 ha, were sampled in six different sampling blocks (L, M, N, O, P, and Q) during 2008 (Fig. 1a). Sampling blocks are 100 km × 100 km areas selected for intensive sampling. Rationale for selection of sampling blocks as part of Canada's national acid sensitivity program has been described previously by Jeffries et al. (2010). The northern blocks: L, N, O and P are characterized by boreal shield vegetation (dominated by white spruce, black spruce, balsam fir, and poplar) with mean annual temperature of between 1.5 and 3.0 °C and annual precipitation of between 670 and 740 mm based on interpolation from the North American Regional Reanalysis dataset (Mesinger et al., 2006). The southern blocks, M and Q, are situated near the northern margin of the Great Lakes-St. Lawrence forest type with old growth hardwood dominated by sugar maple and yellow birch. Mean annual temperature is 3.0–4.0 °C (Mesinger et al., 2006) with similar precipitation to the more northerly blocks. Blocks P and Q are situated on the north shore of Lake Superior and so are expected to have a somewhat cooler and wetter climate. Vegetation in the Turkey Lakes watershed is similar to that described for blocks M and Q.

1.2. Field methods

Within each selected block a stratified-random lake selection methodology was employed, as outlined in Jeffries et al. (2010). The method involves random selection of lakes within eight defined size classes (>1–2 ha, >2–5 ha, >5–10 ha, >10–50 ha, >50–100 ha, >100–500 ha, >500–5000 ha, and > 5000 ha). 5 lakes in the Turkey Lakes watershed (Fig. 1b), as described in detail by Jeffries et al. (1988, 2002), were also sampled and temperature stratification was measured at the time of sampling. Water samples for the block survey lakes were 2-L grab samples taken from a helicopter using a dipper at 1-m depth in a mid-lake location. Block sampling was carried out in early October 2008. At the conclusion of the flight, a portion of the samples were transferred to 30-mL high-density polyethylene (HDPE) bottles for isotopic analysis, with the majority of the sample being used for various geochemical analyses. The Turkey Lakes were sampled the subsequent year, between 14 October and 30 November 2009 using grab sampling, which involved collection in 2-L bottles, as well as integrated sampling of the epilimnion, metalimnion, hypolimnion, and bulk sampling (of the whole water column). Both integrated and bulk samples were collected using an Arnott tube sampler. Water was then transferred to 30 mL HDPE bottles. Temperature profiles were measured in the Turkey Lakes for several minutes at the time of sampling using a thermistor string, to identify if lakes were stratified or turned over.

1.3. Laboratory analysis

All isotope results were analyzed at the Alberta Innovates Technology Futures (AITF) lab in Victoria using a Thermo Scientific Delta V Advantage Dual Inlet/HDevice system. Results are reported in δ notation in permil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW) and normalized to the SMOW-SLAP scale, where SLAP is Standard Light Arctic Precipitation (see Coplen, 1996). Analytical uncertainty is estimated as the standard deviation of repeat measurements, which was ±0.06‰ for $\delta^{18}O$ and ±0.60‰ for $\delta^{2}H$ for 2008 and ±0.1‰ for $\delta^{18}O$ and ±0.44‰ for $\delta^{2}H$ for 2009. This was equal to or better than routine uncertainty of ±0.1‰ and ±1‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively reported by AITF and many other labs.

1.4. Theory

Site-specific hydrology was characterized using an isotope mass balance (IMB) model developed under the assumption of a well-mixed water body and steady-state conditions, which has been demonstrated previously for shallow lakes in northern Canada (Gibson et al., 2002, 2010a,b, 2015a; Bennett et al., 2008). The IMB is used to estimate evaporation/inflow based on the isotopic offset between the evaporatively enriched lake water compared to precipitation input. Then precipitation and evaporation estimates for the site are used to constrain the ungauged inflow to the lake and resulting outflows. The theoretical basis of this method has been described in detail by Gibson et al. (2015b) and a brief overview is presented below.

The annual water balance and isotope balance for a well-mixed lake or reservoir in isotopic and hydrologic steady state can be written, respectively as:

$$I = Q + E \quad (m^3 \cdot yr^{-1}) \tag{1}$$

$$I\delta_I = Q\delta_Q + E\delta_E \quad (‰ \cdot m^3 \cdot yr^{-1}) \tag{2}$$