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# Using Water Isotope Tracers to Develop the Hydrological Component of a Long-Term Aquatic Ecosystem Monitoring Program for a Northern Lake-Rich Landscape

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## Abstract

Arctic lake-rich landscapes are vulnerable to climate change, but their remote locations present a challenge to develop effective approaches for monitoring hydroecological status and trends. Here, we structure the hydrological component of an aquatic ecosystem monitoring program that addresses concerns of Parks Canada (Vuntut National Park) and the Vuntut Gwitchin First Nation about changing water levels of Old Crow Flats (OCF), Yukon, Canada, a 5600-km$^2$ thermokarst landscape recognized nationally and internationally for its ecological, historical, and cultural significance. The foundation of the monitoring program is 5 years (2007–2011) of water isotope data from 14 lakes situated in catchments that are representative of the land-cover and hydrological diversity of OCF. Isotopic compositions of input water ($\delta_I$) and evaporation-to-inflow (E/I) ratios, calculated using the coupled-isotope tracer method, provide key hydrological metrics for each lake over the 5-year sampling interval. From these time series, we identify monitoring lakes that are sensitive to changes in snowmelt, rainfall, and evaporation, and demonstrate the use of the Mann-Kendall test for determining statistically significant trends in the roles of these hydrological processes on lake-water balances. These approaches will serve to identify lake hydrological responses to climate change and variability from ongoing water isotope monitoring by Parks Canada, in partnership with the Vuntut Gwitchin Government, Wilfrid Laurier University, and the University of Waterloo.

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## Introduction

Shallow thermokarst lakes contribute significantly to Arctic biodiversity with abundant microbial, planktonic, and benthic communities, aquatic plants, and fish (Schindler and Smol, 2006; ABEK, 2008; Vincent et al., 2008; Rautio et al., 2011). These freshwater ecosystems also provide important habitat that supports populations of migratory birds and other wildlife, and are integral to the traditional lifestyle and cultural heritage of indigenous circum-Arctic communities (Wrona et al., 2006; White et al., 2007). Arctic landscapes are particularly sensitive to accelerating climatic warming and change, and are undergoing pronounced ecosystem modifications (Smol et al., 2005; Schindler and Smol, 2006; Prowse et al., 2009). For example, remote sensing techniques have documented widespread hydrological changes during recent decades, including decreases in the abundance and size of lakes in Alaska (Yoshikawa and Hinzman, 2003; Riordan et al., 2006), Siberia (Smith et al., 2005; Karlsson et al., 2012), and Canada (Labrecque et al., 2009; Carroll et al., 2011), likely driven by increases in susceptibility of thermokarst lakes to sudden drainage events (Frohn et al., 2005; Hinkel et al., 2007; Wolfe and Turner, 2008; Marsh et al., 2009; Pohl et al., 2009; Jones et al., 2011) and evaporation (Labrecque et al., 2009; Turner et al., 2010). Increases in water surface area have also been observed in some other regions of Alaska (Jorgenson and Shur, 2007), Siberia (Smith et al., 2005), and northern Quebec (Payette, 2004) owing to thawing permafrost. Yet, not all lakes have shown changes in surface area during recent decades (Rover et al., 2012). Although models predict declines in the areal extent of pan-Arctic wetlands (Avis et al., 2011), accelerated rates of permafrost thaw within the continuous permafrost zone and increases in precipitation may also lead to increases in total surface area of lakes in some regions (Plug et al., 2008; Arp et al., 2011). Thus, shallow lakes in circumpolar regions exhibit, and will likely continue to display, variability in their hydrological responses to climatic changes and local controls on lake water balances (Roach et al., 2011; Wolfe et al., 2011a; Jepsen et al., 2012).

Climate warming has not only resulted in profound hydrological transitions but also regime shifts in the biological communities of many high-latitude lakes (Schindler and Smol, 2006; Carroll et al., 2011; Karlsson et al., 2011). Changes in lake water balances due to thawing permafrost (Hobbie et al., 1999; Kokelj et al., 2005, 2009; Frey and McClelland, 2009) and enhanced evaporation (Smol and Douglas, 2007) influence water quality (changes in water clarity and water chemistry, including nutrient supply and nutrient cycling) that has cascading effects on aquatic biological communities (MacDonald et al., 2012a; Kokelj and Jorgenson, 2013). Thus, there is a growing need for improved comprehensive science-based monitoring programs to adequately assess spatial patterns and rates of change of the hydroecological conditions of these northern landscapes.



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To address the complexities of climate change in northern landscapes and the concerns about rapidly changing lake levels, and the associated effects on ecological integrity, a multidisciplinary project entitled ''Environmental change and traditional use of the Old Crow Flats in northern Canada (Yeendoo Nanh Nakhweenjit K'atr'ahanahtyaa)'' was initiated in 2007 to study the physical and biological components of the ecosystem as part of the International Polar Year (IPY) program (Wolfe et al., 2011b). Old Crow Flats (OCF) is the largest, most significant wetland in Yukon and is cooperatively managed by the Vuntut Gwitchin First Nation (VGFN), Parks Canada (Vuntut National Park, established in 1995), and the North Yukon Renewable Resource Council. The IPY project aimed to leave a legacy for the northern community of Old Crow, and research is currently focused on establishing long-term monitoring programs to detect and quantify ecosystem change, increase understanding of the mechanisms driving changes, and inform decisions and policies underpinning effective ecosystem stewardship.

In recognition of the need for long-term monitoring, the Canada National Parks Act (2000) states that a set of ecological integrity objectives and indicators need to be developed for each national park. Science-based monitoring and reporting programs are required to effectively measure the state of ecosystems and determine how they are changing over time. Monitoring plans are based on the systematic gathering of data and information from a set of indicator variables with the purpose of establishing baseline conditions and detecting changes over time (Vaughan et al., 2001; Mezquida et al., 2005; Lovett et al., 2007). Ecological monitoring in national parks is a response to the fundamental question: ''What is the state of the park ecological integrity, and how is it changing?'' (Parks Canada, 2011:8). Information capturing an assessment of park ecological integrity is conveyed to the Canadian public every 10 years in State of the Park reports (SoPR). In 2009, the first SoPR for Vuntut National Park was released, which rated the overall ecological integrity of Vuntut National Park as ''good.'' The report used a wide range of ecosystem indicators, yet there is currently no method to adequately assess the conditions of the aquatic ecosystem within OCF, despite the fact that surface water (mainly shallow thermokarst lakes) in OCF covers ~25% of the landscape (Parks Canada, 2009). Since shallow thermokarst lakes are an important landscape feature, a science-based monitoring program is essential to improve understanding and quantification of the hydroecological conditions within OCF and identify how they are changing over time.

Here, we advocate the use of water isotope tracers as a practical monitoring tool to track hydrological conditions because they are sensitive, diagnostic, broadly applicable, and samples are easily obtained during fieldwork. Previous studies have shown that the water balance of shallow northern lakes strongly influences limnology and aquatic ecology, which can be identified using water isotope tracers (Sokal et al., 2008; Balasubramaniam, 2012; Wiklund et al., 2012). Although the hydrogen and oxygen isotope composition of water is well understood as it passes through the hydrological cycle (Clark and Fritz, 1997; Edwards et al., 2004), it has been underutilized as an indicator variable for hydrological monitoring programs. While wetland hydroecological monitoring programs are lacking in general, long-term investigation on lentic systems tends to rely on instrumentation techniques (e.g., lysimeters, gauged inflows and outflows) that are labor-intensive and expensive (Gilvear and Bradley, 2000) and are generally not feasible to implement at a large spatial scale in remote northern landscapes. Alternatively, leading-edge isotopic analysis techniques can be used to generate key process-based insight of lake hydrological conditions and drivers at the landscape scale (Brock et al., 2007; Wolfe et al., 2007; Turner et al., 2010).

To effectively detect, describe, and report on ecological integrity in national parks in a broad ecosystem context, multiple indicator variables are essential. A genuinely interdisciplinary and collaborative monitoring program for the OCF aquatic ecosystem is currently being developed, and this paper focuses on establishing a method for assessing hydrological changes using water isotope data collected from 2007 to 2011. We provide a 5-year time series of calculated lake-specific input water isotope compositions ($\delta_I$) and evaporation-to-inflow (E/I) ratios, key metrics that will serve as the foundation of the hydroecological monitoring program. $\delta_I$ values determine the dominant source water type (snowmelt versus rainfall) that influences lake water balances and distinguishes isotopic-based hydrologic regimes. E/I ratios indicate lake sensitivity to evaporation. We also demonstrate how researchers, a northern community, and a government agency can effectively collaborate to develop a long-term monitoring program that will continue to evaluate the status and trends of the aquatic ecosystem in response to climate change.

## Study Area

Old Crow Flats (68°N, 140°W) is a large (5600 km$^2$) landscape dominated by shallow thermokarst lakes that is recognized as a Wetland of International Importance by the Ramsar Convention on Wetlands (1982) for its valuable wildlife habitat and cultural significance (Fig. 1). OCF represents a prominent region of Beringia that remained unglaciated during the Last Glacial Maximum. During this time OCF was inundated by Glacial Lake Old Crow, which left a thick deposit of fluvial and glaciolacustrine sediments, with the exception of an exposure of Carboniferous shale at Timber Hill (Hughes, 1972; Lauriol et al., 2002; Zazula et al., 2004). The shallow-water wetland is dissected by the deeply incised, broadly meandering Old Crow River, leaving the river valley 40–50 m below a plateau of ''perched'' lakes that are primarily thermokarst in origin and underlain by continuous permafrost (Yukon Ecoregions Working Group, 2004; Labrecque et al., 2009; Roy-Léveillée and Burn, 2011).

Vegetation in OCF has spatially complex patterns owing to variations in topography, drainage patterns, and ongoing thermokarst cycles (lake formation, expansion, and drainage) (Yukon Ecoregions Working Group, 2004). Land cover in OCF has been broadly categorized by Turner (2013) using Landsat imagery. A total of 37% of OCF is covered by dwarf shrub tundra vegetation. This terrain is characterized by ericaceous shrubs (e.g., Labrador tea, blueberry), herbaceous plants (e.g., arctic marsh grass, reed grass, water sedges, horsetails), and non-vascular plants (e.g., sphagnum mosses and lichens) that are commonly found in drained lake beds and low-center polygons (Ovenden, 1982; Ovenden and Brassard, 1989). Coniferous and deciduous forests (e.g., black spruce, white spruce), located in well-drained areas, account for

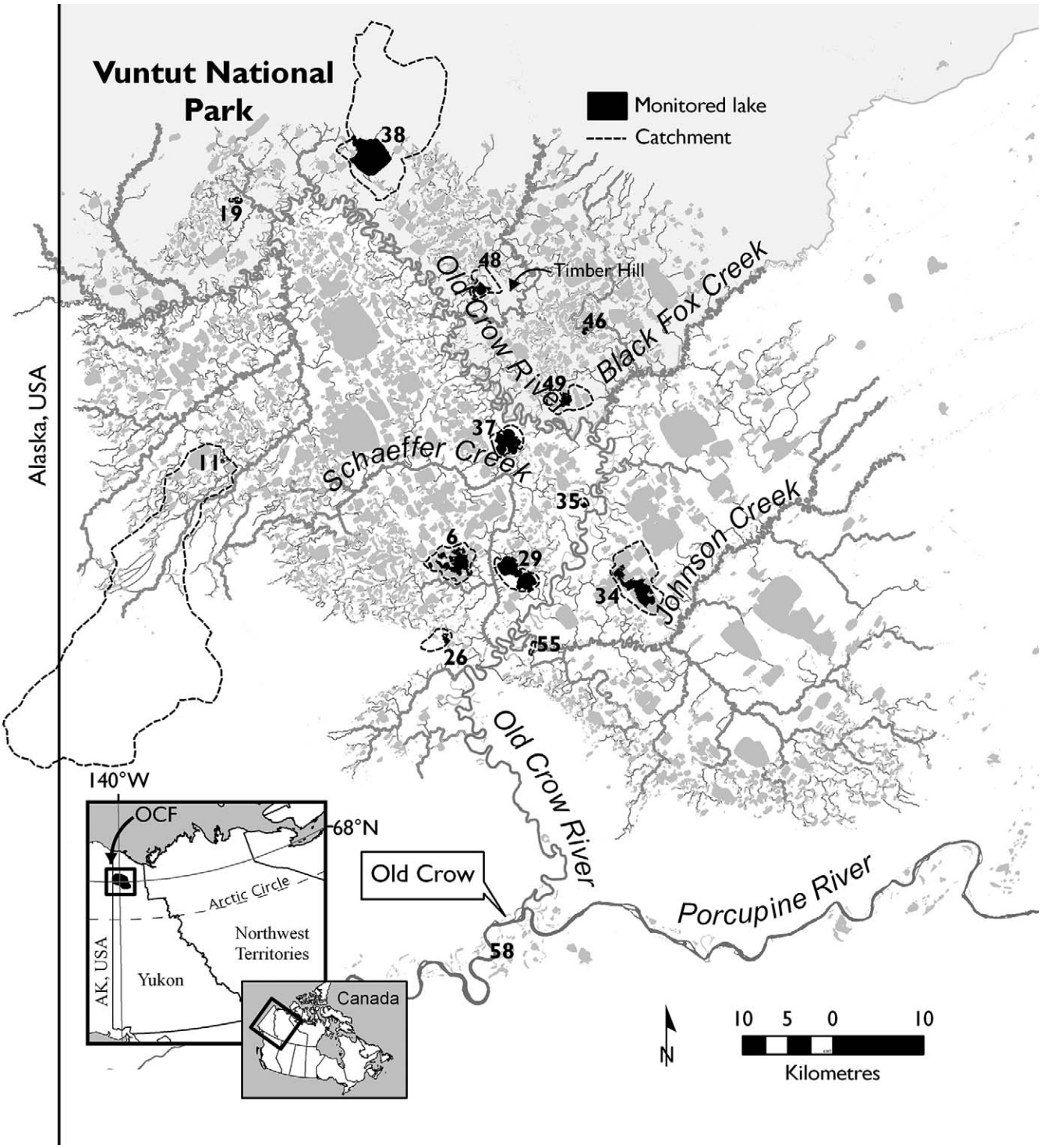


**FIGURE 1. Map showing the location of 14 lakes selected for the hydroecological monitoring program in Old Crow Flats (OCF), Yukon Territory. The shaded area north of Old Crow River represents Vuntut National Park, while the southern portion of OCF represents the Vuntut Gwitchin First Nation Special Management Area. Catchment areas are outlined for each lake (dashed lines). See Turner (2013).**

13% of the landscape. Tall shrub tundra (e.g., shrub birch, willows) covers 25% of the landscape. Shallow lakes located across OCF provide habitat for communities of pond weed, yellow pond lily, common duck weed, hornwart, watermilfoil, muskgrass, and bur-reed (Ovenden and Brassard, 1989; Yukon Ecoregions Working Group, 2004).

Water isotope tracers ($^{2}H$, $^{18}O$) have been used to classify lakes in OCF into hydrologic categories based on the dominant source of input waters and include snowmelt dominated, rainfall dominated, and evaporation dominated (Turner et al., 2010). These hydrological differences are driven by physiographic location and catchment characteristics including vegetation type (Turner, 2013).

Water balances of lakes in the southwestern area of OCF are primarily snowmelt dominated owing to the dominance of coniferous and deciduous trees that entrap and accumulate snow redistributed from dwarf shrub tundra areas by northeasterly winds. Furthermore, many of these lakes have catchments extending to upland areas that provide snowmelt runoff. Lakes classified as having rainfall-dominated hydrology are typically found in central and northeastern areas of OCF, and their catchments have a greater proportion of herbaceous plants, non-vascular plants, and dwarf shrubs. The physiography of snowmelt- and rainfall-dominated lakes located in more peripheral areas of OCF tends to provide adequate runoff from surrounding upland areas to offset evaporation. In contrast, rainfall-dominated lakes located in more central low-lying areas have smaller catchments, higher proportions of surface water, and short and sparse vegetation cover, and are more susceptible to evaporative drawdown. During prolonged dry periods, these rainfall-dominated lakes typically become evaporation dominated (Turner, 2013).

*MONITORING LAKES*

During 2007–2009, 58 lakes in OCF were repeatedly sampled for water isotope composition ($^{2}H$, $^{18}O$), water chemistry, and algal community composition and abundance as part of the broader IPY project. In collaboration with Parks Canada, 14 of these 58 lakes, which are representative of OCF, were selected for the hydroecological monitoring program (Fig. 2). These 14 lakes were selected to span a wide range of hydrological, limnological, and catchment characteristics (Tables 1 and 2), and attention was also given to jurisdictional location to ensure that lakes were distributed between Vuntut National Park (5 lakes) and the VGFN Special Management Area (9 lakes; Fig. 1). The remote location and difficult terrain of OCF renders most of these lakes inaccessible during the summer months without the use of a helicopter. In an attempt to mitigate future logistical challenges (primarily associated with cost of a helicopter charter), 5 of the monitoring lakes were also selected based on their proximity to the Old Crow River so they could potentially be accessed by boat during early spring. This was an

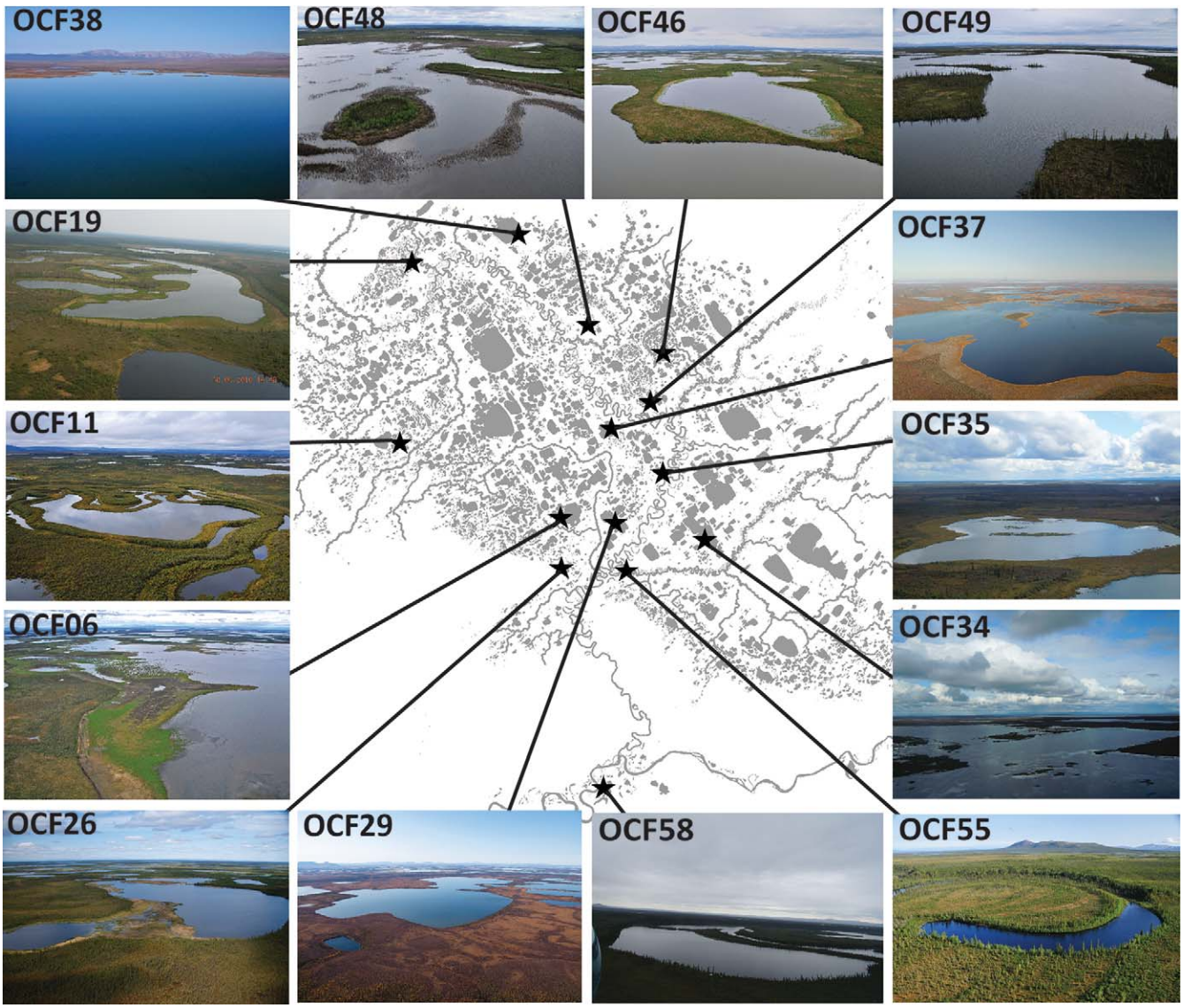


**FIGURE 2. Photographs of selected monitoring lakes and their locations within OCF.**

**TABLE 1**

**Selected hydrological and catchment characteristics for monitoring lakes. Hydrological categories are based on Turner et al. (2010) and vegetation cover is based on Landsat data explained in detail by Turner (2013).**

| Lake ID | Local Name | Latitude | Longitude | Hydrology | Depth (m) | Lake surface area (km) | Catchment area (km) | Wood-land (%) | Tall shrubs (%) | Dwarfed shrubs, herbs, non-vascular (%) | Barren (%) | Surface water (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OCF 11 | | 68°01′N | 140°34′W | Snowmelt | 0.78 | 0.07 | 395.19 | 10.6 | 53.8 | 27.7 | 1.9 | 4.3 |
| OCF 26 | | 67°50′N | 139°59′W | Snowmelt | 1.69 | 0.42 | 5.21 | 8.2 | 73.3 | 1.9 | 0.8 | 15.7 |
| OCF 55 | | 67°50′N | 139°45′W | Snowmelt | >5.0 | 0.02 | 0.59 | 3.2 | 63.6 | 29.3 | 0.5 | 3.4 |
| OCF 29 | John Charlie | 67°54′N | 139°48′W | Rainfall | 1.18 | 6.86 | 11.71 | 0.5 | 11.2 | 28.4 | 1.4 | 58.6 |
| OCF 34 | Netro | 67°53′N | 139°27′W | Rainfall | 1.54 | 6.11 | 29.16 | 5.1 | 25.0 | 36.5 | 1.0 | 32.1 |
| OCF 35 | | 67°58′N | 139°37′W | Rainfall | 1.16 | 0.14 | 0.80 | 6.1 | 29.3 | 43.0 | 1.9 | 19.7 |
| OCF 37 | Ts'iivii zhit | 68°05′N | 139°81′W | Rainfall | 1.19 | 5.14 | 8.84 | 3.6 | 22.7 | 13.5 | 2.1 | 58.2 |
| OCF 38 | Husky | 68°19′N | 140°08′W | Rainfall | 1.05 | 12.67 | 137.96 | 6.7 | 3.8 | 70.5 | 7.0 | 12.3 |
| OCF 48 | Hot Spring | 68°11′N | 139°52′W | Rainfall | 0.70 | 1.31 | 7.41 | 21.4 | 21.4 | 26.0 | 4.8 | 26.3 |
| OCF 49 | Marten | 68°04′N | 139°39′W | Rainfall | 1.24 | 1.15 | 10.75 | 6.9 | 20.3 | 24.9 | 3.0 | 44.6 |
| OCF 58 | Mary Netro | 67°32′N | 139°51′W | Rainfall | 2.55 | — | — | — | — | — | — | — |
| OCF06 | Zelma | 67°55′N | 139°56′W | Evaporation | 0.33 | 5.01 | 15.99 | 0.8 | 14.5 | 9.9 | 43.6 | 31.3 |
| OCF 19 | | 68°17′N | 140°31′W | Evaporation | 0.86 | 0.11 | 0.58 | 1.3 | 16.6 | 59.3 | 2.2 | 20.5 |
| OCF 46 | | 68°09′N | 139°36′W | Evaporation | 0.48 | 0.12 | 0.28 | 4.6 | 10.8 | 32.9 | 8.0 | 43.6 |

important selection criterion because Parks Canada normally conducts a spring boat trip into Vuntut National Park; thus, a proportion of lakes can still be monitored during years when helicopter-based sampling is not possible. However, a helicopter is necessary to sample these lakes in late summer/early fall due to the low water level of Old Crow River. Initially (2010), 13 lakes were chosen for the monitoring program. However, as a result of a spring boat trip conducted in 2011 to assess the feasibility of accessing lakes from Old Crow River, another lake (OCF37) was added to the monitoring program. Although not part of the data set reported by Turner et al. (2010), we also included Mary Netro Lake (OCF58) as a monitoring lake because it is close to the village of Old Crow, has cultural significance to the community, and is easily accessible.

Monitoring lakes represent the three major hydrological categories described by Turner et al. (2010): snowmelt dominated (3 lakes), rainfall dominated (8 lakes), and evaporation dominated (3 lakes) (Table 1). The lakes span OCF (see Fig. 1) and have varying catchment sizes (0.28 to 395.19 $km^2$) and surface areas (0.02 to 12.67 $km^2$; Table 1). All monitoring lakes are thermokarst in origin and are less than 2.5 m in depth, with the exception of OCF55, which is an oxbow lake >5.0 m deep. Catchments of the study lakes with snowmelt-dominated input waters mainly contain tall

**TABLE 2**

**The mean and standard deviation of selected limnological characteristics of monitoring lakes, grouped into hydrological categories. Values represent the average of samples collected in June and August during the 2010 and 2011 sampling campaigns.**

| Hydrology category | Snowmelt | | Rainfall | | Evaporation | |
|---|---|---|---|---|---|---|
| Lake (OCF#) | 11, 26, 55 | | 29, 34, 35, 36, 37, 38, 48, 58 | | 06, 19, 46 | |
| Mean/s.d. | Mean | s.d. | Mean | s.d. | Mean | s.d. |
| pH | 7.00 | 0.15 | 8.07 | 0.27 | 8.71 | 0.07 |
| Specific conductivity (μS/cm) | 44.78 | 5.41 | 175.03 | 29.84 | 258.00 | 58.65 |
| Alkalinity (meq/L) | 17.13 | 2.41 | 82.93 | 17.51 | 100.55 | 2.67 |
| Dissolved organic carbon (mg/L) | 19.41 | 2.74 | 12.64 | 4.93 | 17.93 | 5.34 |
| Dissolved inorganic carbon (mg/L) | 4.30 | 0.68 | 18.57 | 3.85 | 21.48 | 0.70 |
| Calcium (mg/L) | 5.63 | 0.40 | 22.00 | 2.33 | 32.29 | 5.08 |
| Magnesium (mg/L) | 1.89 | 0.30 | 7.44 | 1.76 | 11.53 | 2.87 |
| Potassium (mg/L) | 1.08 | 0.49 | 1.77 | 0.82 | 3.07 | 0.96 |
| Silica (mg/L) | 0.95 | 0.18 | 0.86 | 0.57 | 0.64 | 0.29 |
| Total nitrogen (mg/L) | 0.65 | 0.10 | 0.74 | 0.18 | 1.15 | 0.24 |
| Total dissolved phosphorus (μg/L) | 24.65 | 9.16 | 11.07 | 4.59 | 18.69 | 3.26 |
| Total phosphorus (μg/L) | 42.83 | 14.39 | 33.21 | 12.97 | 42.62 | 11.02 |
| Chlorophyll-*a* (μg/L) | 4.41 | 1.37 | 4.05 | 1.83 | 3.50 | 1.54 |
| Total suspended solids (mg/L) | 4.85 | 3.90 | 9.83 | 13.51 | 9.03 | 5.72 |

shrubs (mean 63.6% of catchment area) and have small proportions of dwarfed shrubs, herbs, and non-vascular plants (mean = 19.7%; Table 1). In contrast, the catchments of study lakes with rainfall-dominated and evaporation-dominated hydrology have lower proportions of tall shrubs (mean = 19.1% and 14.0%, respectively) and higher proportions of dwarf shrubs, herbs, and non-vascular plants (mean = 34.7% and 34.0%, respectively; Table 1). Barren areas of exposed rock, sand, and fire scar make up a small proportion of land cover within lake catchment areas, with the exception of OCF06 where barren lands accounted for 43.6% of the catchment area (based on a Landsat image from 2007). This high proportion of barren land around OCF06 is due to the drainage event that occurred in June 2007, as well as the drainage of two neighboring lakes (Wolfe and Turner, 2008; Turner et al., 2010). Since then, a large proportion of the exposed sediments has become re-vegetated by grasses and sedges.

Monitoring lakes span a wide range of limnological conditions that are associated with hydrological categories (Table 2). Snowmelt-dominated lakes tend to have neutral pH, whereas rainfall-dominated and evaporation-dominated lakes are more basic. Snowmelt-dominated lakes have relatively low conductivity and low concentrations of major ions (Ca, K, Mg, Na, $SiO_2$), rainfall-dominated lakes have intermediate ion content, and evaporation-dominated lakes have high values. Dissolved inorganic carbon (DIC) concentration displays a similar pattern among the hydrological categories and is relatively low in snowmelt-dominated lakes and high in evaporation-dominated lakes. Although lakes in OCF are covered by ice for up to 9 months of the year, they are highly productive and are meso-eutrophic to eutrophic based on total phosphorus (TP) concentration (Table 2).

### *METEOROLOGICAL CONDITIONS*

According to 1971–2000 climate normals at Old Crow airport (Station ID 2100800 and 2100805), average annual temperature is –9.0 °C and fluctuates substantially between summer and winter months. Average annual total precipitation is 265.5 mm, 60% of which falls as rain (165.5 mm) from May to September. Mean monthly air temperatures during the study period (2007–2011) were comparable to the 1971–2000 climate normals (Fig. 3, part a). Total annual precipitation between 2007 and 2011 was variable and was high in the last 2 years (417 mm and 625 mm in 2010 and 2011, respectively; Fig. 3). With the exception of very wet spring conditions, total precipitation during the ice-free months (May–September) of 2007 was below average (134 mm; 1971–2000 mean = 166 mm; Fig. 3, part b; Environment Canada, 2012). The 2007–2008 ice-covered months experienced extremely low snowfall and below-average winter cumulative precipitation (snow water equivalent (SWE) = 28 mm; 1951–2000 mean SWE = 100 mm; Environment Canada, 2012) and near-average cumulative rainfall during the 2008 ice-free season (178 mm). Winter snowfall in 2008–2009 was above average (SWE = 134 mm), followed by high ice-free season cumulative rainfall (212 mm). The ice-covered months during 2009–2010 experienced below-average snowfall (SWE = 75 mm) and the 2010 ice-free season had above-average cumulative rainfall (276 mm). Heavy snowfall during the fall of 2010 coupled with uncharacteristically high snowfall events in February 2011 contributed to very high winter precipitation in 2010–2011 (SWE = 359 mm). Cumulative ice-free season rainfall reached 347 mm by September 2011, which is ~200% greater than the long-term mean. Overall, precipitation during 2007 and 2009 was similar to the long-term mean, 2008 was relatively dry, and precipitation during 2010 and 2011 exceeded the long-term mean (Fig. 3, part b).

## Methods

### *WATER ISOTOPE SAMPLING AND ANALYSIS*

Monitoring lakes were sampled for the analysis of water isotope tracers in June, July, and September from 2007 to 2009, as reported in Turner et al. (2010) and Turner (2013), and on 10 June and 25 August 2010 and 5–17 June and 12 September 2011. The initial 3 years of fieldwork included mid-season sampling in July to more fully characterize the hydrological behavior of lakes within OCF, which was used as a basis for establishing the monitoring program. All monitoring lakes were sampled with the aid of a helicopter equipped with pontoons, except for Mary Netro Lake (OCF58), which was always sampled from a canoe following river travel by motorboat and a short hike to the lake, and 5 lakes (OCF29, 35, 37, 49, and 55) that were sampled from a canoe during a spring boat trip in 2011. Water samples were collected from 10 to 15 cm below the surface at the approximate center of each lake. A hand-held GPS system was used to ensure that samples were collected at the same location in each lake (within a maximum distance of 150 m) during subsequent sampling trips. Samples for water isotope analysis were collected in 30-mL high-density polyethylene bottles and transported to the University of Waterloo Environmental Isotope Laboratory for evaluation of oxygen and hydrogen isotope composition.

Isotopic compositions are expressed as variations in the relative abundance of the rare (heavy) isotope species of water with respect to the common (light) isotope species. These ratios are conventionally expressed as a delta (δ) value, reported as per mil (‰). Reported isotopic compositions reflect the difference between the ratio of the sample and the ratio of a known standard, such that $\delta^2H$ or $\delta^{18}O = 1000\ ([R_{sample}/R_{standard}] - 1)$, where R is the ratio of $^2H/^1H$ or $^{18}O/^{16}O$ in the sample and standard. The international standard for water is the Vienna Standard Mean Ocean Water (VSMOW), and results are normalized to −55.5‰ and −428‰, respectively, for Standard Light Antarctic Precipitation (Coplen, 1996). Maximum analytical uncertainties for $\delta^{18}O$ and $\delta^2H$ are ±0.2‰ and ±2.0‰, respectively.

A constant volume Class-A evaporation pan was deployed at the Old Crow airport from 2007 to 2009, as reported by Turner et al. (2010) and Turner (2013), and it was monitored by staff of the Vuntut Gwitchin Government (VGG). We continued to monitor the evaporation pan at the Old Crow airport again from June to August 2010, with the assistance of VGG staff. The evaporation pan was operated over 4 years to simulate a terminal basin (i.e., closed-drainage) at isotopic and hydrologic steady-state, where inflow is equal to evaporation ($\delta_{SSL}$). The source of evaporation pan input water was from the Old Crow airport, which is supplied by groundwater from below the permafrost zone. Water within the pan was maintained at a constant volume, and water samples were collected weekly for isotopic analysis.

Lake hydrological conditions were evaluated using a reference

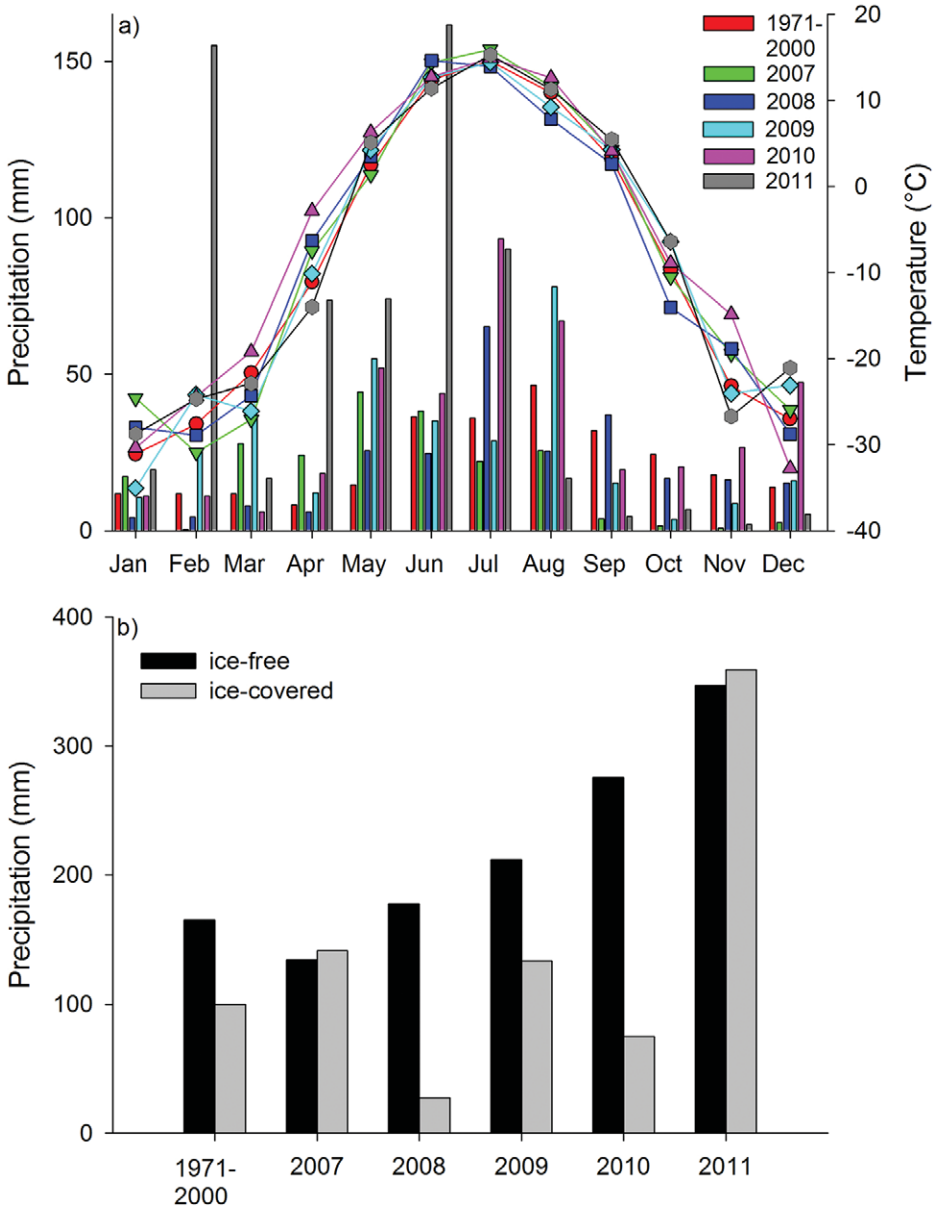


**FIGURE 3. (a) Mean monthly air temperature (°C; lines) and total monthly precipitation (mm; vertical bars) recorded at the Old Crow weather station (Station ID: 2100800 and 2100805) from 2007 to 2011 compared to climate normals (1971–2000) (Environment Canada, 2012). (b) Total precipitation (mm) during the ice-free months (May–September) and the ice-covered months (October–April) from 2007 to 2011, including climate normals (1971–2000).**

isotopic framework in $\delta^{18}O$-$\delta^{2}H$ space (Fig. 4) and the linear resistance model of Craig and Gordon (1965) (see Appendix). A key feature of the isotopic framework is the Global Meteoric Water Line (GMWL), which describes the isotopic composition of precipitation on a global scale, such that $\delta^{2}H = 8\delta^{18}O + 10$ (Craig, 1961). At regional scales, precipitation can plot in a linear trend along a Local Meteoric Water Line (LMWL) similar to the GMWL. Substantial isotopic information on local precipitation is required to define the LMWL, but if this is unavailable, the GMWL can generally provide a useful baseline of precipitation isotope composition (Edwards et al., 2004). Surface water that has undergone evaporation deviates away from the GMWL due to mass-dependent fractionation (i.e., preferential evaporation of water molecules containing lighter isotopes). As a result, lake water isotope compositions plot in a linear trend referred to as the Local Evaporation Line (LEL), which typically has a slope of 4–6. Key reference points along the LEL include the amount-weighted mean annual precipitation ($\delta_P$, at the GMWL-LEL intersection), the limiting steady-state isotope composition ($\delta_{SSL}$), and the theoretical limiting isotopic enrichment ($\delta^*$) of a desiccating basin under ice-free season conditions (Fig. 4; see Appendix).

In high-latitude areas, strong seasonal variation in the isotope composition of precipitation is characterized by snowfall that is generally depleted in heavy-isotope content and rainfall that is isotopically enriched (Clark and Fritz, 1997). Consequently, the isotopic composition of lake water ($\delta_L$) will shift above and below the LEL depending on the relative influence that these source waters have on lake hydrological conditions. Thus, $\delta_L$ values that plot above the LEL generally receive greater proportions of rainfall, whereas $\delta_L$ values that plot below the LEL reflect greater influence of snowmelt. To quantitatively assess lake water balances, we used lake water oxygen and hydrogen isotope compositions to derive the isotopic composition of lake-specific input water ($\delta_I$) and to calculate evaporation-to-inflow (E/I) ratios (Appendix). These esti-

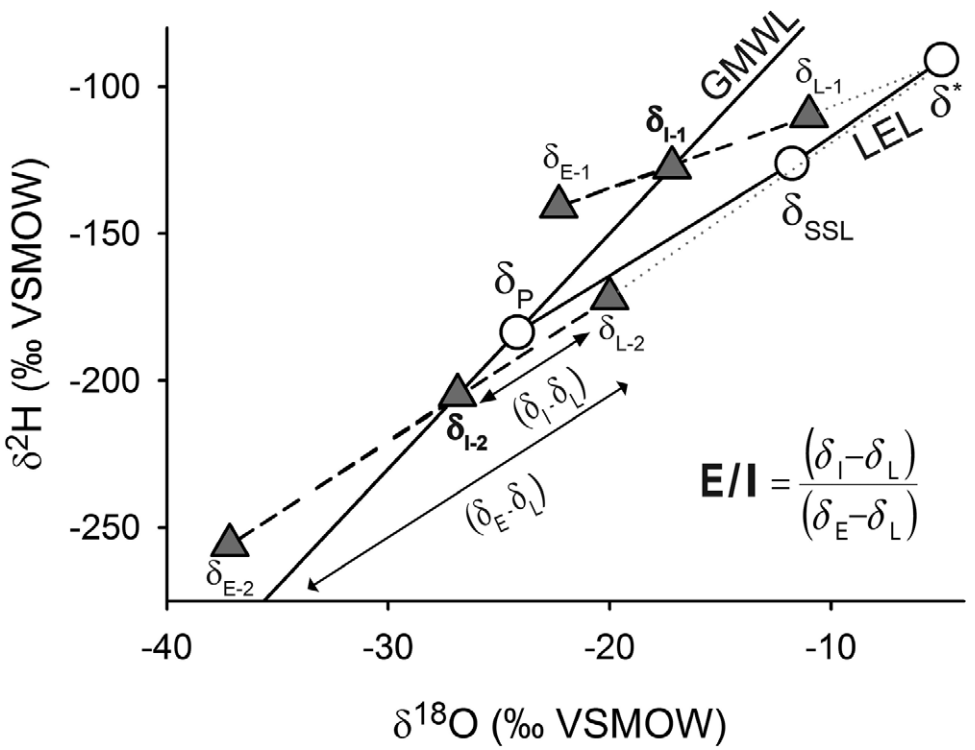


**FIGURE 4. Schematic $\delta^{18}O$-$\delta^2H$ diagram illustrating two hypothetical lakes (lake 1 and lake 2) that each plot along a lake-specific evaporation line and intersect the Global Meteoric Water Line (GMWL), which provides an estimate of $\delta_I$. Key isotopic framework labeling features in relation to the Local Evaporation Line (LEL) include amount-weighted mean annual precipitation ($\delta_P$), the limiting steady-state isotope composition where evaporation is equal to inflow ($\delta_{SSL}$), and the limiting isotopic enrichment ($\delta^*$) of a desiccating basin under thaw season conditions. Parameters that are used in isotope mass-balance models to derive evaporation-to-inflow (E/I) ratios include the lake water isotope composition ($\delta_L$), input water isotope composition ($\delta_I$), and the isotopic composition of evaporated vapor from the lake ($\delta_E$). See Appendix for further details. VSMOW = Vienna Standard Mean Ocean Water.**

mates were based on the coupled-isotope tracer method, which assumes conservation of mass and isotopes during evaporation (explained in detail by Yi et al., 2008). The isotopic composition of all lakes within a geographic area under similar atmospheric conditions, regardless of hydrological complexity, will converge towards $\delta^*$ because a water body approaching desiccation is dependent on atmospheric conditions (temperature and relative humidity) and is independent of hydrological conditions ($\delta_L$, $\delta_I$) (Yi et al., 2008). Thus, $\delta_I$ values for each water sample collected from each lake can be estimated by calculating lake-specific LELs and extending $\delta_L$ to the intersection of the GMWL (see Appendix; Fig. 4). According to mass conservation, the isotopic composition of evaporated vapor from a lake ($\delta_E$) will lie on the extension of the LEL, to the left of the GMWL. Using these key water isotope budget components ($\delta_L$, $\delta_I$, $\delta_E$), lake hydrological conditions can be quantified in terms of evaporation-to-inflow (E/I) ratios that consider the mass-balance ratio between the isotopic composition of lake-specific input water and the evaporative flux from the lake (see Equation in Fig. 4 and Appendix). An E/I ratio of 0.5 represents lakes in which 50% of the inflow has evaporated, and we identify that an E/I ratio $>0.5$ defines evaporation-dominated lakes (modified from Turner et al., 2010). An E/I value of 1 is equal to the terminal basin steady-state limiting composition ($\delta_{SSL}$) in which evaporation is equal to inflow. Although we recognize that E/I ratios $<1$ can also occur under transient non-steady conditions, as in the evaporation pan prior to establishment of isotopic steady-state (see below), a calculated E/I ratio $>1$ provides a clear threshold to identify lakes having a negative water balance and thus experiencing net evaporative drawdown. $\delta_I$ values and E/I ratios reported by Turner et al. (2010) and Turner (2013) were re-calculated to reflect the 4-year average monitoring framework, as described below.

*TREND ANALYSIS*

The Mann-Kendall test, originally derived by Mann (1945), developed by Kendall (1975), and modified by Hirsch et al. (1982) and Hirsch and Slack (1984), was used to detect monotonic trends in $\delta_I$ values and E/I ratios over time (see Appendix). The Mann-Kendall test is non-parametric and is commonly applied to detect trends in hydrologic time series data because it is highly robust to departures from normality, missing values, and seasonal cycles (Helsel and Hirsch, 1992). It is not, however, robust against serial dependence, although a modified test that performs the Mann-Kendall trend test for individual seasons separately and then combines the results accounts for serial correlation (Hirsch and Slack, 1984; Yue and Wang, 2004). We apply both the Mann-Kendall and the Seasonal Kendall trend test to the 5-year data set of $\delta_I$ values and E/I ratios. The seasons were defined as early (June) and late (September) based on the proposed frequency of future monitoring. Thus, results from July 2007–2009 are not included in the Seasonal Kendall test. Trend analysis was completed using software developed by Helsel et al. (2006).

## Results and Interpretation

*DEVELOPING AN ISOTOPIC FRAMEWORK*

In all 4 years of evaporation pan deployment, rapid isotopic enrichment occurred during the first 4 weeks as cumulative evaporation increased and the pan water equilibrated with atmospheric

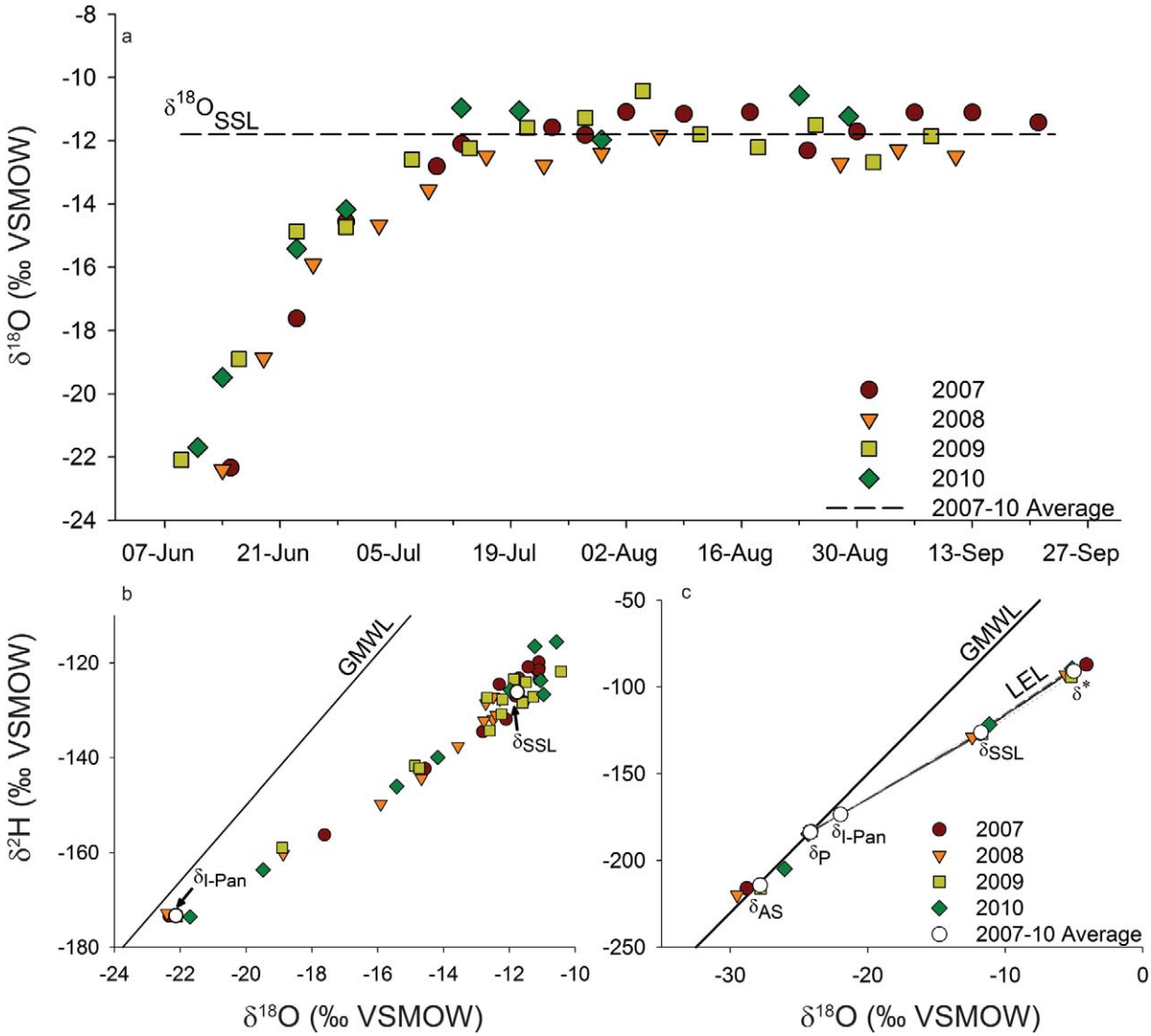


**FIGURE 5. (a) Isotopic evolution of $\delta^{18}O$ of water sampled from an evaporation pan maintained at the Old Crow airport from June to September, 2007–2010. (b) Evaporation pan evolution is consistent among years and cluster around an average $\delta_{SSL}$ ($-11.8‰$ for $\delta^{18}O$ and $-126‰$ for $\delta^2H$). (c) A four-year mean LEL ($\delta^2H = 4.7\delta^{18}O - 71.2$) was extended through the isotopic composition of pan input water ($\delta_{I\text{-}Pan}$) to the Global Meteoric Water Line (GMWL).**

conditions (Fig. 5, part a). After the fifth week of operation each year, similar and relatively constant $\delta^{18}O$ and $\delta^2H$ values were obtained, yielding robust estimates of $\delta_{SSL}$ (mean $\delta^{18}O_{SSL} = -11.8‰$ and $\delta^2H_{SSL} = -126‰$; standard deviation (s.d.) = 0.5 and 3.2, respectively; Table 3). The isotopic composition of evaporation pan input water was very consistent each year (mean $\delta_{I\text{-}pan} = -22.1‰$ for $\delta^{18}O$ and $-173‰$ for $\delta^2H$; s.d. = 0.3 and 0.3, respectively) and plotted close to the GMWL (Fig. 5, part b). Based on the 4-year mean $\delta_{SSL}$ and $\delta_{I\text{-}Pan}$ values, the LEL ($\delta^2H = 4.7\ \delta^{18}O - 71.2$) was extended to the GMWL to provide an estimate of $\delta_P$ ($\delta^{18}O_P = -24.3‰$ and $\delta^2H = -185‰$; s.d. = 0.4 and 3.2, respectively). The equation provided by Gonfiantini (1986; see Appendix) was used to calculate $\delta^*$ for each year (mean $\delta^* = -4.9‰$ for $\delta^{18}O$ and $-90‰$ for $\delta^2H$; s.d. = 0.6 and 3.8, respectively; Fig. 5, part c). Although an evaporation pan was not maintained in 2011, framework results likely did not deviate substantially since the flux-weighted temperature and relative humidity for 2011 ($T = 287.0$ K, $h = 67.1\%$) were similar to mean values for 2007 to 2010 ($T = 286.8$ K and $h = 65.9\%$; s.d. = 0.8 and 3.0, respectively; Table 3).

### *MONITORING LAKE HYDROLOGICAL CONDITIONS WITH WATER ISOTOPES*

Lake water isotope compositions ($\delta_L$) obtained from the monitoring lakes during the 2007–2011 field campaigns are superimposed on the 4-year average isotopic framework developed from the evaporation pan data (Fig. 6). In general, the lake water isotope composition spans a broad range ($\delta^{18}O_L = -25.8‰$ to $-8.7‰$, and $\delta^2H_L = -200‰$ to $-100‰$) among the monitoring lakes and between the sampling periods, but distinct trends are evident. Lakes with values that are positioned below the LEL reflect a

**TABLE 3**

**Flux-weighted ice-free season temperature and relative humidity based on WLU meteorological station set up at Old Crow airport and parameters used to construct an average isotopic framework for long-term monitoring based on 2007–2010 evaporation pan data.**

| Parameter | 2007 | 2008 | 2009 | 2010 | 2011 | Mean | Stand. Dev. |
|---|---|---|---|---|---|---|---|
| T (K) | 287.7 | 286.3 | 285.8 | 287.1 | 287.0 | 286.8 | 0.8 |
| h (%) | 62.6 | 64.0 | 66.5 | 69.4 | 67.1 | 65.9 | 3.0 |
| $\alpha^*$ ($^{18}$O, $^{2}$H) | 1.0103, 1.0910 | 1.0104, 1.0927 | 1.0105, 1.0934 | 1.0103, 1.0917 | — | 1.0104, 1.0922 | 0.0001, 0.0010 |
| $\epsilon^*$ ($^{18}$O, $^{2}$H) ‰ | 10.3, 91.0 | 10.4, 92.7 | 10.5, 93.4 | 10.3, 91.7 | — | 10.4, 92.2 | 0.1, 1.1 |
| $\epsilon_K$ ($^{18}$O, $^{2}$H) ‰ | 5.3, 4.7 | 5.1, 4.5 | 4.8, 4.2 | 4.3, 3.8 | — | 4.9, 4.3 | 0.4, 0.4 |
| $\delta_{AS}$ ($^{18}$O, $^{2}$H) ‰ | −28.8, −216 | −29.5, −220 | −27.8, −216 | −25.8, −203 | — | −27.8, −214 | 1.5, 7.7 |
| $\delta_{SSL}$ ($^{18}$O, $^{2}$H) ‰ | −11.8, −127 | −12.4, −129 | −11.7, −127 | −11.2, −122 | — | −11.8, −126 | 0.5, 3.2 |
| $\delta^*$ ($^{18}$O, $^{2}$H) ‰ | −4.1, −87 | −5.6, −93 | −5.2, −94 | −4.9, −87 | — | −4.9, −90 | 0.6, 3.8 |
| $\delta_P$ ($^{18}$O, $^{2}$H) ‰ | −24.1, −183 | −24.2, −184 | −24.1, −183 | −24.9, −190 | — | −24.3, −185 | 0.4, 3.2 |
| $\delta_{I\text{-pan}}$ ($^{18}$O, $^{2}$H) ‰ | −22.3, −173 | −22.4, −173 | −22.1, −174 | −21.7, −173 | — | −22.1, −173 | 0.3, 0.3 |
| Slope of LEL | 4.57 | 4.65 | 4.54 | 4.93 | — | 4.67 | 0.20 |

stronger influence of inputs from snowmelt relative to rainfall, and generally plot closer to the GMWL. In contrast, lakes that are more influenced by summer rainfall have higher values and are positioned above the LEL. $\delta_L$ values are lower in June and become higher by the end of the ice-free season, reflecting the seasonal isotopic evolution that is typical of high-latitude lakes as they receive isotopically depleted snowmelt in spring and subsequently undergo evaporative isotopic enrichment during the summer. This general seasonal cycle is evident in all 5 years, although the evolution is unique to each year because of inter-annual differences in the flux and isotopic composition of inputs (snowmelt and rainfall) and outputs (evaporation). For example, lakes in 2008 are much more isotopically enriched in July and September compared to other sampling years (Fig. 6), with some lakes plotting beyond $\delta_{SSL}$ because there was very low precipitation during the preceding 10 months (Fig. 3).

The influence of summer rainfall is most clearly revealed in 2010 and 2011 (Fig. 6, parts d and e) when lake water isotope compositions for August and September, respectively, deviated above the LEL in several lakes in response to substantial rainfall events in July and August of both years (Fig. 3). The influence of snowmelt, rainfall, and evaporation on lake water balances is summarized in Figure 6, part f, which shows the 5-year mean $\delta_L$ for each monitoring lake according to hydrological lake categories defined by Turner et al. (2010). Lakes that are classified as snowmelt dominated are located below the LEL close to the GMWL, whereas rainfall-dominated lakes plot above the LEL and are closer to $\delta_{SSL}$. An exception to this is one rainfall-dominated lake (OCF48) that plots within the isotopic range of snowmelt-dominated lakes. Turner et al. (2010) and MacDonald et al. (2012a) noted that this lake, in particular, oscillates between snowmelt- and rainfall-dominated categories owing to a high proportion of woodland and tall shrubs within the catchment area that entrap snow. OCF48 is also located close to Timber Hill, which may enhance shallow groundwater seepage through the active layer that is likely derived from snowmelt. Evaporation-dominated lakes are situated further along the LEL, and the 5-year average of one lake (OCF06) plots beyond $\delta_{SSL}$.

The relative role of snowmelt versus rainfall on lake water balances was quantitatively assessed by calculating lake-specific input water isotope compositions ($\delta_I$). As displayed in Figure 7, calculated $\delta_I$ values over the 5-year period show variation within and among lakes. Turner et al. (2010) distinguished snowmelt- versus rainfall-dominated lakes based on the position of $\delta_I$ relative to $\delta_P$, such that snowmelt-dominated lakes are defined by $\delta^{18}O_I \leq \delta_P$ and rainfall-dominated lakes are delineated by $\delta^{18}O_I > \delta_P$. Using this operational metric and considering the 5-year data set, rainfall is the main contributor to most monitoring lakes (OCF06, 19, 29, 34, 35, 37, 38, 46, 49, and 58), and snowmelt is a main contributor to only OCF11 and 55. A few lakes oscillate between rainfall and snowmelt categories (OCF26 and 48), and their average $\delta_I$ values are similar to $\delta_P$. Therefore, we recategorize these lakes as sourced by mean annual precipitation (''$\delta_P$ lakes'').

$\delta_I$ values for $^{18}$O were plotted versus time to explore temporal trends in lake-specific input water for each monitoring lake (Fig. 8). The 5-year mean of $\delta_I$ values for each lake was calculated and compared to the 4-year mean of $\delta_P$ (−24.3‰) that delineates the threshold between snowfall- and rainfall-dominated isotope-based hydrologic regimes (Fig. 8). Seasonally, $\delta_I$ values in June are typically lower than in July and September owing to the decreasing supply of snowmelt and increasing influence of rainfall during the ice-free season. Standard deviations (reported in Table 4, part a) reveal lakes that have relatively low, moderate, and high variability in $\delta_I$ values during the 5-year data set. OCF29, 38, 48, 55, and 58 show very little variability in $\delta_I$ values, with standard deviations that range from 0.6 to 0.7. Most of the monitoring lakes (OCF11, 26, 34, 35, 37, and 49) display moderate variation in $\delta_I$ values (s.d. = 0.9 to 1.1). Lakes OCF06, 19, and 46 exhibit pronounced seasonal and inter-annual variation in $\delta_I$ values, with standard deviations >1.5.

A Mann-Kendall test showed statistically significant increasing monotonic trends at OCF11, 26, and 49 (OCF11: $S = 48$, $p = 0.004$; OCF26: $S = 44$, $p = 0.003$; OCF49: $S = 38$, $p = 0.011$) and an emerging trend in OCF29 ($S = -8$, $p = 0.088$). A Seasonal Kendall test also showed emergent trends at OCF11 ($S = 12$, $p = 0.057$) and OCF29 ($S = 11$, $p = 0.079$), but no significant trends for any of the monitoring lakes (Table 4, part a). From 2007 to 2009, both OCF11 and 26 have depleted $\delta_I$ signatures that are below $\delta_P$ and shift to $\delta_I$ values that are above $\delta_P$ in 2010 and 2011. An independent samples *t*-test of $\delta_I$ values from 2007–2009 and

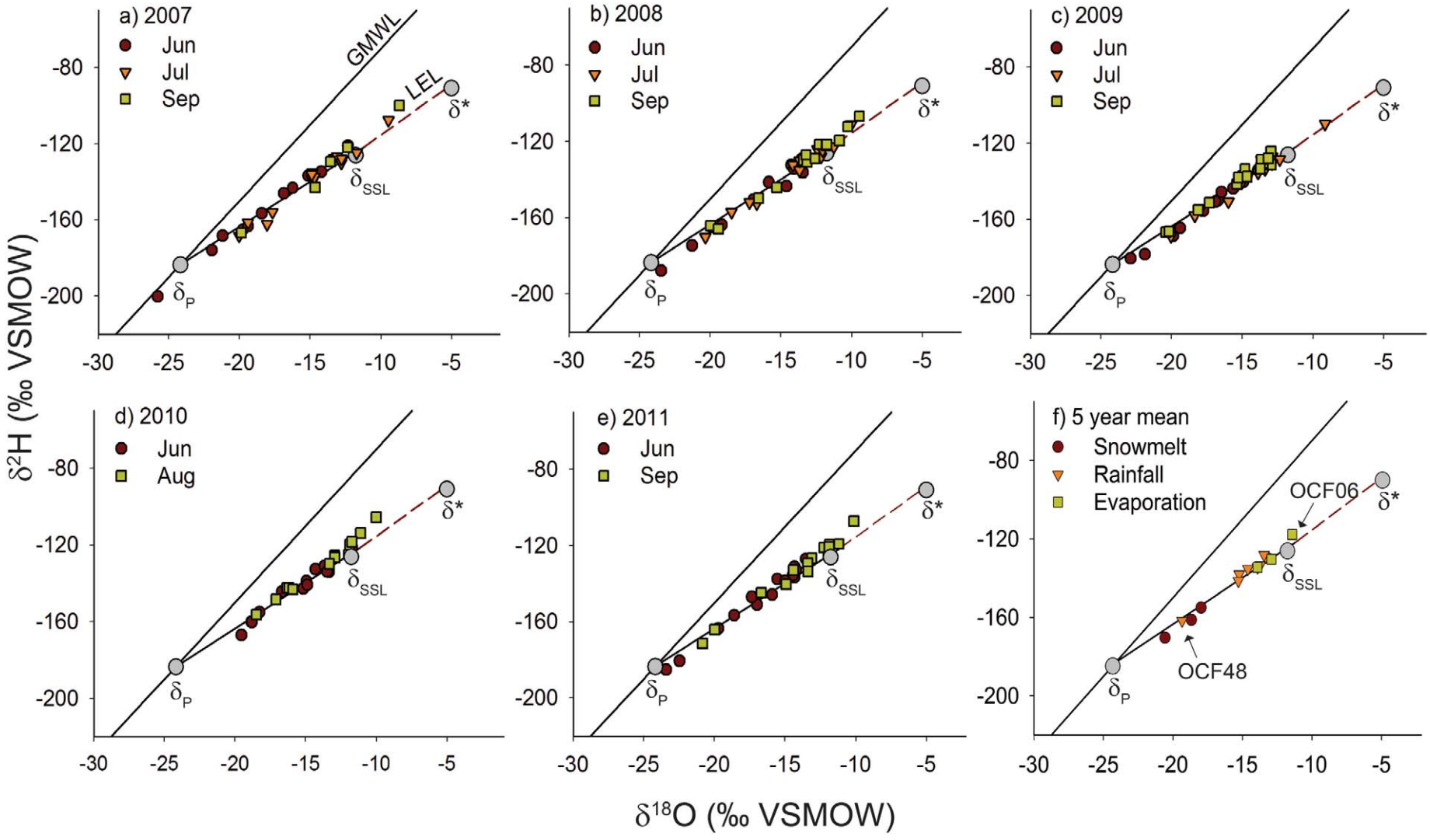


**FIGURE 6. Isotopic composition of monitoring lakes ($\delta_L$) superimposed on the four-year mean monitoring isotopic framework for each sampling year: (a) 2007, (b) 2008, (c) 2009, (d) 2010, (e) 2011, and (f) the five-year mean for each lake distinguished by the hydrological categories designated by Turner et al. (2010).**

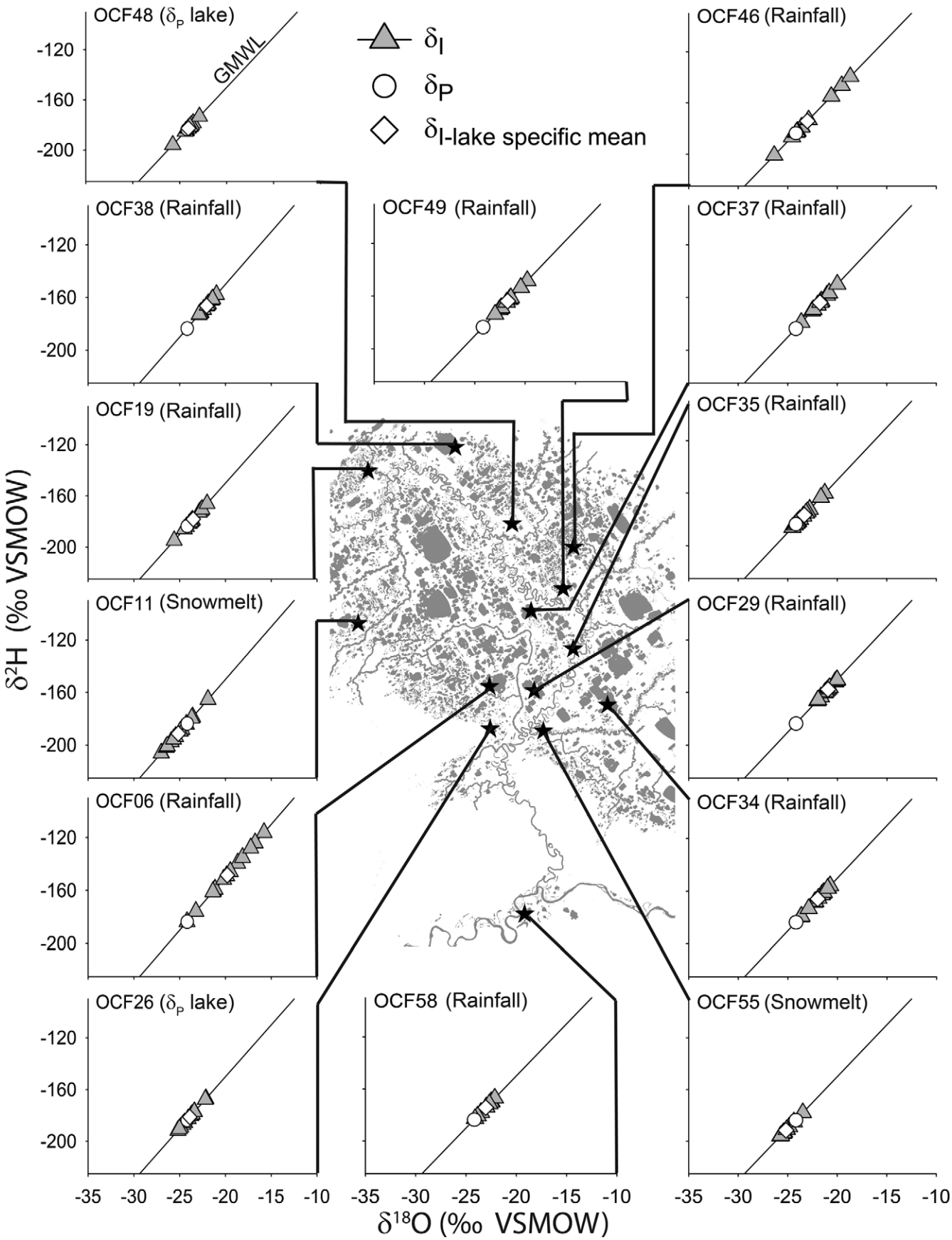


**FIGURE 7. Calculated input water isotope composition ($\delta_I$) for each monitoring lake from 2007 to 2011.**

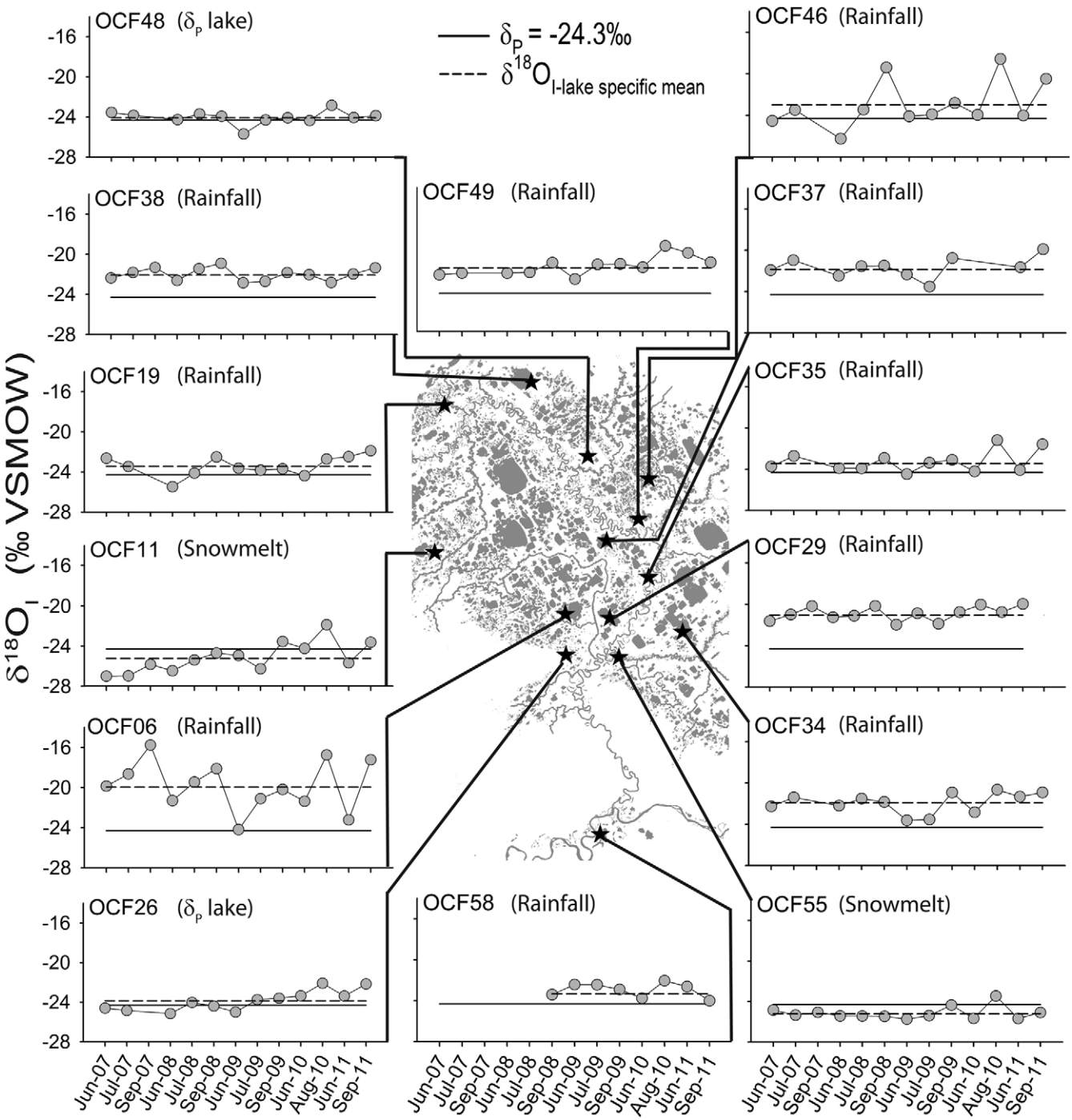


**FIGURE 8. Temporal distribution of the oxygen isotope composition of input water ($\delta_I$) for each monitoring lake from 2007 to 2011. Solid lines represent the four-year average amount-weighted mean annual precipitation ($\delta_P$), and the dashed lines represent mean $\delta_I$ values for each lake from 2007 to 2011.**

2010–2011 shows a statistically significant difference between the means of 2007–2009 and 2010–2011 for these lakes (OCF11: $t = -3.034$, $p = 0.013$; and OCF26: $t = 4.699$, $p = 0.001$).

The importance of evaporation to lake water balances was quantitatively assessed by calculating evaporation-to-inflow (E/I) ratios using lake-specific input water ($\delta_I$) and the evaporative flux ($\delta_E$) determined for each lake. Temporal trends for E/I were assessed and 5-year mean E/I values were used to determine lakes that are evaporation dominated (E/I $\geq$ 0.5; Fig. 9). Overall, E/I ratios vary substantially among the lakes, ranging from 0.03 in June (mean E/I June = 0.34), due to high input of snowmelt and rainfall in spring, to 1.55 by the late ice-free season (mean E/I August/September = 0.53), because of the influence of evaporation. Based on mean E/I values, OCF06, 19, 37, 46, 49, and 58 are evaporation-dominated lakes, and OCF29 is very close to the 0.5 threshold (mean E/I = 0.49). OCF46 and 19 had E/I ratios that

**TABLE 4**

**General statistics and summary statistics of the Mann-Kendall and Seasonal Kendall trend tests for (a) $\delta^{18}O_I$ values and (b) E/I ratios.**

(a) $\delta^{18}O_I$ values

| | | | Mann-Kendall trend test | | | Seasonal Kendall trend test | | |
|---|---|---|---|---|---|---|---|---|
| Lake | Mean (‰) | Standard Deviation | Mann-Kendall Z | S | *p*-value | Mann-Kendall Z | S | *p*-value |
| OCF06 | −19.67 | 2.50 | −0.427 | −8 | 0.665 | −1.212 | −8 | 0.225 |
| OCF11 | −25.11 | 1.01 | 2.867 | 48 | **0.004** | 1.905 | 12 | *0.057* |
| OCF19 | −23.40 | 1.51 | 1.029 | 16 | 0.304 | 0.596 | 4 | 0.551 |
| OCF26 | −23.86 | 1.02 | 2.949 | 44 | **0.003** | 1.391 | 8 | 0.164 |
| OCF29 | −20.87 | 0.68 | 1.708 | −8 | *0.088* | 1.759 | 11 | *0.079* |
| OCF34 | −21.92 | 1.00 | 1.303 | 29 | 0.193 | 0.993 | 6 | 0.321 |
| OCF35 | −23.26 | 1.03 | 0.206 | 20 | 0.837 | −0.199 | −2 | 0.843 |
| OCF37 | −21.66 | 1.01 | 0.716 | 4 | 0.474 | 1.139 | 5 | 0.255 |
| OCF38 | −21.99 | 0.63 | −0.183 | 9 | 0.573 | 0.000 | 0 | 1.000 |
| OCF46 | −22.92 | 2.26 | 1.303 | 20 | 0.193 | 0.993 | 6 | 0.321 |
| OCF48 | −24.05 | 0.66 | −0.480 | −4 | 0.684 | 0.000 | 0 | 1.000 |
| OCF49 | −21.64 | 0.92 | 2.537 | 38 | **0.011** | 1.391 | 8 | 0.164 |
| OCF55 | −25.15 | 0.64 | −0.671 | −12 | 0.749 | −0.520 | −4 | 0.603 |
| OCF58 | −22.95 | 0.70 | −0.619 | −6 | 0.732 | 0.000 | −1 | 1.000 |

(b) E/I ratios

| | | | Mann-Kendall trend test<br>Seasonal Kendall trend test | | | | | |
|---|---|---|---|---|---|---|---|---|
| Lake | Mean | Standard Deviation | Mann-Kendall Z | S | *p*-value | Mann-Kendall Z | S | *p*-value |
| OCF06 | 0.80 | 0.34 | −0.671 | −12 | 0.749 | −0.173 | −2 | 0.863 |
| OCF11 | 0.30 | 0.20 | 0.061 | 2 | 0.951 | 0.000 | 0 | 1.000 |
| OCF19 | 0.75 | 0.20 | −0.617 | −10 | 0.731 | −0.199 | −2 | 0.843 |
| OCF26 | 0.25 | 0.06 | −0.480 | −8 | 0.684 | −0.596 | −4 | 0.551 |
| OCF29 | 0.49 | 0.11 | 0.488 | 9 | 0.625 | 0.352 | 3 | 0.725 |
| OCF34 | 0.42 | 0.10 | 1.029 | 16 | 0.304 | 0.199 | 2 | 0.843 |
| OCF35 | 0.44 | 0.14 | 1.029 | 16 | 0.304 | 0.569 | 4 | 0.551 |
| OCF37 | 0.56 | 0.15 | 0.179 | 3 | 0.858 | 0.000 | 1 | 1.000 |
| OCF38 | 0.36 | 0.10 | −1.037 | −18 | 0.850 | −1.559 | −10 | 0.119 |
| OCF46 | 0.61 | 0.25 | −0.069 | −2 | 0.527 | 0.199 | 2 | 0.843 |
| OCF48 | 0.18 | 0.07 | 0.891 | 14 | 0.373 | 0.993 | 6 | 0.321 |
| OCF49 | 0.62 | 0.14 | −0.069 | −2 | 0.527 | −0.199 | −2 | 0.843 |
| OCF55 | 0.16 | 0.05 | 0.183 | 4 | 0.855 | −0.520 | −4 | 0.603 |
| OCF58 | 0.58 | 0.12 | 0.000 | 0 | 0.500 | −0.569 | −3 | 0.613 |

Significant ($p < 0.05$) trends are reported in bold.
Emerging ($p < 0.1$) trends are reported in italics.

exceeded 1 in July and September 2008, respectively. OCF06 had E/I ratios that exceeded 1 in July and September of 2007 and 2008, as well as July 2009.

Monitoring lakes exhibit differences in both intra- and inter-annual variation of E/I ratios that can be described by standard deviations (Table 4, part b). Similar to $\delta_I$ values, we grouped monitoring lakes into three categories based on mean E/I values and the amount of variation in E/I ratios: low, moderate, and high. OCF26, 48, and 55 display very low E/I values (mean $\leq$ 0.25) and low variation in E/I ratios (s.d. $<$ 0.10). Other lakes, including OCF29, 34, 35, and 38, have moderate mean E/I values (0.35 to 0.50) and display moderate variation about the mean (s.d. = 0.10 to 0.14). OCF11 has a low mean E/I value (0.30), yet a large standard deviation (s.d. = 0.20). Lakes that are classified as evaporation dominated (OCF06, 19, 37, 46, 49, and 58) have high mean E/I values ($>$0.5) and large standard deviations (s.d. = 0.12 to 0.34). A Mann-Kendall and Seasonal Kendall test showed no significant or emerging trends in E/I ratios during the 5 years of this study.

## Discussion

Northern landscapes are logistically challenging to monitor, yet land managers and scientists recognize that long-term, science-based monitoring is necessary to evaluate how these ecosystems are responding to climate change. Implementation of sustainable long-term monitoring approaches involves coordination among multiple authorities and stakeholders to systematically gather information. To achieve this, we developed and implemented the first phase of a hydroecological monitoring program in partnership with Parks Canada, with support from the Vuntut Gwitchin First Nation

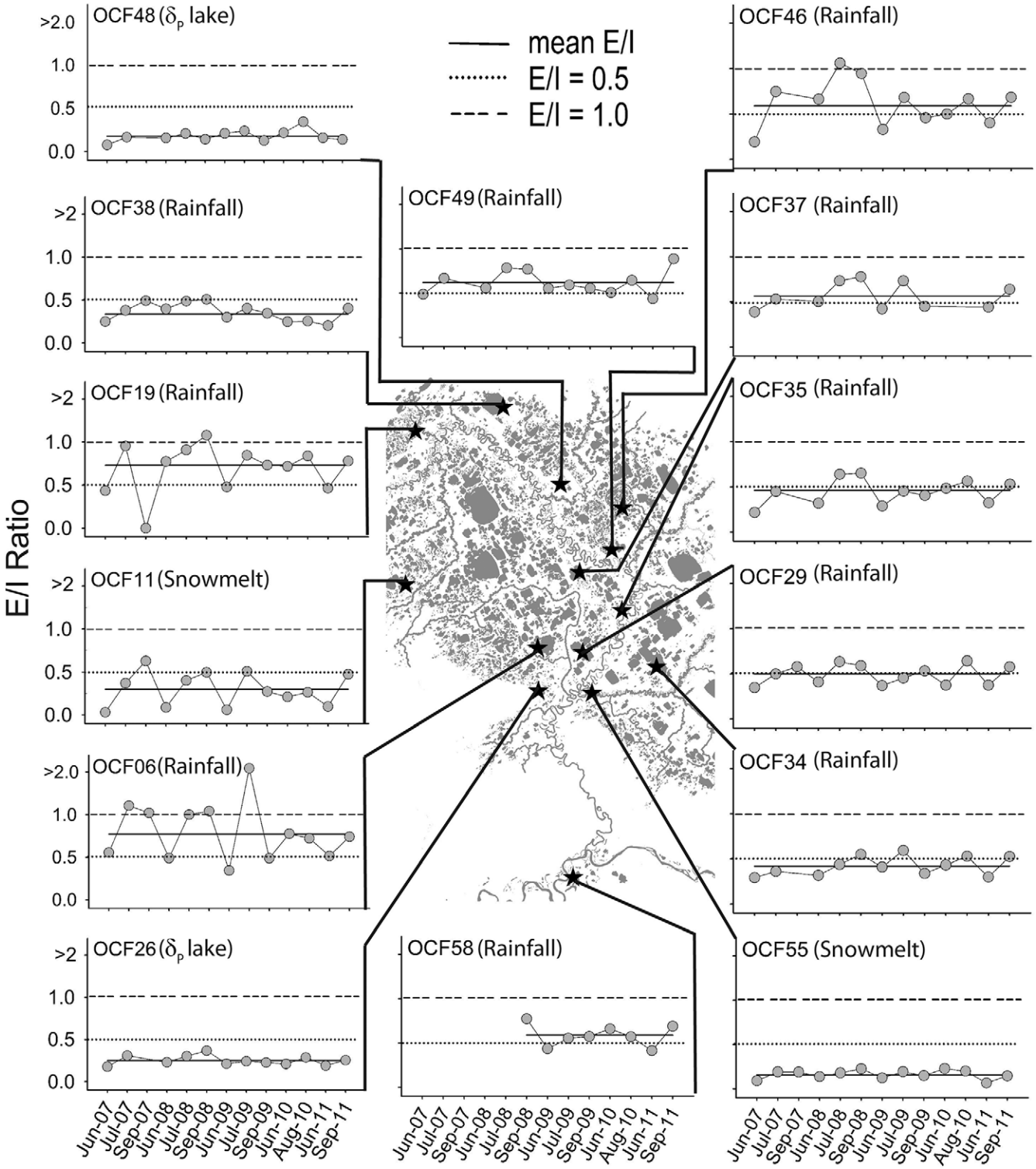


**FIGURE 9. Temporal distribution of evaporation-to-inflow (E/I) ratios during 2007–2011. An E/I ratio >0.5 represents the threshold for evaporation-dominated lakes and is designated by a dotted line. The dashed line at E/I = 1 represents $\delta_{SSL}$.**

and the North Yukon Renewable Resource Council. A key component of these efforts includes a commitment that future water isotope monitoring (to be conducted by Parks Canada in partnership with the Vuntut Gwitchin Government, Wilfrid Laurier University, and the University of Waterloo) will occur to provide hydrologic information for Vuntut National Park State of the Park reports.

Climate warming is already pronounced in the Arctic (Vincent et al., 2011) and has the potential to cause major regime shifts in high-latitude inland ecosystems (Karlsson et al., 2011), the most critical threshold being the integrity of lake basins and the presence or absence of water (Vincent et al., 2008). Northern lake-rich landscapes are showing different responses to ongoing climate change

over space and time (Avis et al., 2011; Carroll et al., 2011; Karlsson et al., 2011; Roach et al., 2011; Rover et al., 2012). Thus, ongoing monitoring that is capable of capturing the diversity of hydrological trajectories is needed to adequately assess the ecological integrity of high-latitude aquatic ecosystems. The approach presented here utilizes leading-edge water isotope tracer techniques as an effective monitoring tool to evaluate landscape-scale hydrological change in a northern thermokarst landscape. Water isotopes are sufficiently affordable and logistically feasible to incorporate into a sustainable long-term hydroecological monitoring program. Key information from this work includes 5-year characterization of lake hydrological conditions, which will be compared to results of future sampling campaigns to evaluate multiple potential hydrological pathways in response to changes in climate.

Each lake selected for this study represents an individual ''monitoring station'' that records the relative importance of hydrological drivers of lake-water balance conditions. Since hydrological fluxes from groundwater are generally negligible in continuous permafrost landscapes (Woo et al., 2000), and glaciolacustrine sediments underlying the OCF landscape have a low hydraulic conductivity, the main components of thermokarst lake water balances can be characterized using the isotopic metrics $\delta_I$ and E/I, which evaluate the relative importance of input source water types (snowmelt and rainfall) and losses (evaporation), respectively. The $\delta_L$ data collected from 2007 to 2011 show that the monitoring lakes encompass a broad range of isotopic signatures and, thus, capture the diverse hydrological conditions in OCF (Fig. 6). This highlights the range of hydrological variation in OCF and reinforces the notion that lakes will likely undergo multifaceted hydrological changes over time (Turner, 2013).

Ideally, samples for water isotope analysis should be collected during the early, mid, and late ice-free season, yet given the logistical constraints of northern monitoring, this is not necessarily feasible. $\delta_I$ values and E/I ratios calculated for July and September are statistically different from each other based on a Wilcoxon signed-rank test ($\delta_I$: 2007 $n = 28$, $p = <0.001$; 2008 $n = 56$, $p = <0.001$, 2009 $n = 58$, $p = 0.002$; and E/I: 2007 $n = 28$, $p = <0.001$; 2008 $n = 56$, $p = 0.12$; 2009 $n = 58$ $p = <0.001$, respectively). However, collecting samples during the early and late ice-free season captures the full scope of seasonal isotopic evolution, and, therefore, we consider this sample frequency adequate to assess changes in hydrological conditions. Furthermore, lakes that experience high E/I ratios in July generally maintain elevated E/I ratios when sampled again in September, thus the importance of vapor loss can still be determined by collecting samples at the beginning and end of the ice-free season.

### *AN ISOTOPIC FRAMEWORK FOR LONG-TERM MONITORING*

A framework to evaluate the isotopic evolution and water balance of monitoring lakes was based on 4 years of evaporation pan data and flux-weighted temperature and relative humidity. The similarity of flux-weighted temperature and relative humidity during the 5-year sampling period and the agreement between isotopic frameworks developed from evaporation pan data for each year (Fig. 5, part c; Table 3) clearly demonstrates that our approach is robust and repeatable. A meteorological station deployed within OCF at John Charlie Lake (OCF29), located approximately 50 km north of Old Crow airport, revealed that temperature and relative humidity recorded at the Old Crow airport by Environment Canada and within OCF were very similar over a 3-year period (Turner, 2013). Thus, temperature and relative humidity recorded by Environment Canada at the Old Crow airport are suitable for interpreting water isotope results for future monitoring in OCF. Although we have shown that the 4-year average isotope framework is appropriate for characterizing lake water balances during 2007–2011, we recommend that isotope monitoring of an evaporation pan be conducted every 5 years to ensure that the framework remains reflective of hydroclimatic conditions.

### *FUTURE CONSIDERATIONS OF ONGOING WATER ISOTOPE MONITORING*

We present data collected over 5 years of varying meteorological conditions (Fig. 3) and show that lakes within OCF vary substantially in temporal patterns of dominant source-water types ($\delta_I$). $\delta_I$ values can be used to identify lakes that are sensitive to changes in relative inputs from snowmelt versus rainfall. Despite experiencing both ''dry'' and ''wet'' conditions, some lakes in OCF (29, 38, 48, 55, and 58) displayed very narrow ranges in $\delta_I$ values over the 5-year time period. In contrast, OCF06, 19, and 46 displayed considerable temporal variations in $\delta_I$ values throughout the data set. This suggests that some lakes will be more sensitive to changes in snowmelt and rainfall than others, which may result in altered lake hydrological conditions on a local scale. Increases in summer rainfall, winter rain events, and decreases in winter snowpack influence the source water composition of lakes, and can potentially shift the water balance of snowmelt-dominated lakes toward rainfall-dominated lakes. Derksen and Brown (2012) recently showed evidence of pan-Arctic losses in snow cover extent, and continued reductions in snow cover extent and snow depth may also contribute to a shift towards rainfall-dominated lakes. Reductions in ice cover extent and increasing temperatures have also been associated with changes in Arctic vegetation (Jia et al., 2009), and Turner (2013) revealed a strong association between individual lake $\delta_I$ values and catchment characteristics such as terrestrial land cover and the ability that trees have to entrap snow and minimize snow redistribution. Hence, monitoring trends in $\delta_I$ values over time may also reveal hydrological changes associated with an increase in shrub coverage that may shift lake water balance from rainfall dominated to snowmelt dominated. Complete and partial lake drainage events, due to increased rates of thermokarst erosion and lateral expansion as temperature (Pohl et al., 2009) and precipitation rise (Wolfe and Turner, 2008), will also influence vegetation dynamics. Mackay and Burn (2002) showed that vegetation grows rapidly on the exposed organic-rich sediments of recently drained lake basins in a successional pattern from grasses and sedges, to willow and other shrubs, to alder trees and tall willows >2.0 m. For example, the margins of OCF06, a lake that drained in 2007, have become revegetated by grasses, sedges, and other water-tolerant plants. Thus, the edges of partially drained and completely drained lake beds will eventually be colonized by tall shrubs that will help trap snow and enhance winter snowpack thickness. Though not all areas in the Arctic are experiencing increases in tree growth (Osterkamp et al., 2000), local land users have observed increases in shrub size and coverage in OCF (ABEK, 2007).

Lakes in OCF have high surface-area-to-depth ratios, making them susceptible to climate-induced losses in lake area due to increased evaporation rates. In this study, we used calculated E/I ratios to evaluate the importance of evaporation and temporal trends on lake water balances. Lakes that possess low E/I values and low variability are the least sensitive to vapor loss, whereas lakes with high E/I values and greater variability are more responsive to evaporation. OCF26, 48, and 55 represent lakes that are, currently, not sensitive to vapor loss. In contrast, OCF06, 19, 37, 46, 49, and 58 have mean E/I ratios that surpass 0.5, indicating that evaporative water loss exceeds 50% of the lake input. This is not to suggest that these lakes are drying up, as they still maintain positive water balances. Rather they will be more sensitive to evaporative drawdown under shifting meteorological conditions that enhance rates of evaporation. Rainfall-dominated lakes are most susceptible to becoming evaporation dominated, and they are typically shallow, have small lake surface areas, small catchment areas, or have recently experienced a drainage event. Furthermore, vegetation within the catchments of evaporation-dominated lakes typically includes high proportions of low-lying tundra vegetation that do not act as a barrier to wind-driven snow redistribution and thus generate less spring snowmelt (Turner, 2013). Snowmelt-dominated lakes are less vulnerable to water vapor loss as demonstrated during the dry 2008 ice-free season. On the other hand, 3 lakes exceeded an E/I ratio of 1 during the 2008 ice-free season (OCF06, 19, and 46), signifying that these lakes had a negative water balance and are the most susceptible to dry conditions. If prolonged dry conditions such as these become more frequent, lakes may cross the evaporation-dominated threshold. Several shallow lakes in the High Arctic have completely desiccated, while others have experienced reduced water levels attributed to increased evaporation/precipitation ratios associated with climatic warming (Smol and Douglas, 2007). This underscores the importance of continued isotope monitoring to calculate E/I ratios, which identify lakes and areas in OCF that are sensitive to water-level changes due to evaporation.

To determine if hydrological conditions (i.e., $\delta_I$ values and E/I ratios) are changing over time, the Mann-Kendall trend test was applied to detect statistically significant increasing or decreasing trends. Three lakes (OCF11, 26, and 49) display a statistically significant increasing trend in $\delta_I$ values, indicating that rainfall inputs became a greater influence on water balances for these lakes during the monitoring period, although this trend is not significant when the Seasonal Kendall trend test is applied. This may be a result of a small sample size ($\leq$5 years of data) or the strong influence of July data. Despite the lack of significant trends according to the Seasonal Kendall test, Figure 8 clearly shows that both OCF11 (snowmelt dominated) and OCF26 (a $\delta_P$ lake) have $\delta_I$ values below the snowmelt/rainfall threshold from 2007–2009 and above the threshold in 2010–2011 with means that are different. This is likely due to above-average precipitation during the ice-free season of 2010 and 2011. While we are cognizant that this represents a small data set, the test suggests that the water balances of these lakes may transition from snowmelt-dominated to rainfall-dominated isotopic-based hydrologic regimes due to increases in precipitation during the ice-free season. There were no discernible trends in E/I ratios, although prolonged ice-free conditions and warmer temperatures may lead, in the future, to enhanced evaporative isotopic enrichment, which can only be determined by long-term monitoring and future trend tests.

The time series of $\delta_I$ values and E/I ratios presented here provide baseline hydrologic data that, in conjunction with the determined threshold values for snowmelt- and rainfall-dominated lakes ($\delta_P = -24.3‰$) and evaporation-dominated lakes (E/I $> 0.5$), can be used to identify and evaluate fluctuations in the hydrological status of lakes in OCF in response to ongoing climate change. The outcome of this work will contribute directly to ecological integrity assessments. Parks Canada uses thresholds as a mechanism to evaluate ecological integrity and determine the ''condition'' of the ecosystem (Parks Canada, 2011). The condition of the ecosystem is rated as good, fair, or poor based on a healthy composition and abundance of native species or biological communities, rates of change, and supporting processes (Parks Canada, 2011). While the hydrological monitoring methods presented here do not provide direct assessments of ecosystem health, they do provide a useful tool that can define isotopic-based thresholds and effectively evaluate the status and trends of lake hydrological conditions in OCF. Furthermore, $\delta_I$ values and E/I ratios are ecologically relevant hydrological variables that influence nutrient chemistry (Table 2) and likely aquatic communities (e.g., macrophytes and algae). These metrics will provide Parks Canada, the Vuntut Gwitchin First Nation, and the North Yukon Renewable Resource Council with quantitative data that will provide insight to the hydroecological responses to changes in climate conditions.

## Conclusions

This paper advocates that long-term hydroecological monitoring of high-latitude wetlands is essential to adequately determine changes in ecological integrity, and that routine surveillance of these landscapes should be incorporated into stewardship and management activities. There is substantial evidence showing that the Arctic is in a state of hydrological transition, the direction of which is varied (Hinzman et al., 2005; Rowland et al., 2010; Vincent et al., 2011). Thus, long-term data sets and monitoring are essential to identify and understand the hydrological status and trends of northern freshwater landscapes. We demonstrate that water isotope tracers are a useful monitoring tool that can be used to assess future vulnerabilities of a suite of representative lakes in OCF to changes in input waters (snowmelt versus rainfall) and evaporation. $\delta_I$ values distinguish snowmelt- and rainfall-dominated lakes, with $\delta_P$ representing a threshold between the two isotopic-based hydrologic regimes. Lakes that display considerable variation in $\delta_I$ values (OCF06, 11, and 46) are more sensitive to changes in snowmelt and rainfall, which may result in altered lake hydrological conditions. Transitions in $\delta_I$ values from snowmelt-dominated to rainfall-dominated hydrology, or vice versa, may be a result of changes in cumulative summer rainfall, winter rain, and changes in winter snowpack associated with precipitation levels as well as landscape vegetation that entraps snow. A Mann-Kendall test, used to identify monotonic trends over time, revealed that 3 lakes (OCF11, 26, and 49) display statistically significant increasing trends in $\delta_I$ values and that OCF11 and 26 may be transitioning from snowmelt dominated to rainfall dominated, although a longer data set is required to be conclusive. Lake sensitivity to vapor loss was monitored using hydrological thresholds established from E/I ratios such that E/I

ratios > 0.5 signify lakes that are evaporation dominated with positive water balances, and E/I ratios > 1 indicate lakes that are evaporation dominated with negative water balances. Six lakes (OCF06, 19, 37, 46, 49, and 58) surpassed the 0.5 threshold and are evaporation dominated. Three of these lakes (OCF06, 19, and 46) cross the significant evaporation threshold (E/I > 1), representing lakes that are vulnerable to desiccation. Despite the substantial variability in precipitation and meteorological conditions during the 5-year study period, the water balances of OCF29, 48, and 55 showed marked hydrological resiliency. While these trends are subject to the limitations inherent in a 5-year data set, they highlight the diversity of hydrological conditions in OCF and reinforce the notion that lakes will undergo multiple pathways and trajectories over time that can be captured using water isotope tracers. Water isotope tracers are diagnostic indicator variables of changes in source water and evaporation, which can be coupled with remote sensing studies and climate records to support explanations of root causes of future hydrologic transitions here, and potentially elsewhere.

Changes in hydrological conditions will likely have implications for water chemistry and aquatic ecology, potentially altering the structure and function of lake ecosystems. In recognition of the value and need for coordinated hydrological and ecological monitoring to systematically observe the status and trends of aquatic ecosystems, we are working towards integrating the hydrological monitoring program with an ecological monitoring program, protocols of which were described by MacDonald et al. (2012b). Northern ecosystem monitoring remains challenging. Yet, here we reveal how collaboration between researchers, a northern community, and a government agency can develop a long-term monitoring strategy that will serve to inform future policy and land-use management decisions. Furthermore, these approaches can be readily adopted by other national parks and agencies that have a vested interest in monitoring the hydrological status and trends of northern lake-rich landscapes.

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# APPENDIX

## Isotopic Framework Calculations

The equilibrium liquid-vapor isotope fractionation factor ($\alpha^*$) was derived from the equation given by Horita and Wesolowski (1994):

$$[\delta^{18}O]: 1000 \ln \alpha^* = -7.685 + 6.7123\left(\frac{10^3}{T}\right) - 1.6664\left(\frac{10^6}{T^2}\right) + 0.35041\left(\frac{10^9}{T^3}\right) \quad \text{(A1)}$$

$$[\delta^2H]: 1000 \ln \alpha^* = 1158.8\left(\frac{T^3}{10^9}\right) - 1620.1\left(\frac{T^2}{10^6}\right) + 794.84\left(\frac{T^3}{10^3}\right) + 2.9992\left(\frac{10^9}{T^3}\right) - 161.04, \quad \text{(A2)}$$

where $T$ represents the interface temperature (K). The equilibrium ($\boldsymbol{\varepsilon}^*$) and kinetic ($\boldsymbol{\varepsilon}_K$) isotope separation factors between liquid and vapor phases are given by (Gonfiantini, 1986):

$$\boldsymbol{\varepsilon}^* = a^* - 1 \quad \text{(A3)}$$

$$[\delta^{18}O]: \boldsymbol{\varepsilon}_K = 0.0142(1-h) \quad \text{(A4)}$$

$$[\delta^2H]: \boldsymbol{\varepsilon}_K = 0.0125(1-h) \quad \text{(A5)}$$

Isotopic composition of atmospheric moisture over the ice-free season ($\delta_{AS}$) was calculated using the isotopic composition of a terminal lake at steady-state and input water derived from the evaporation pan data (Gibson et al., 1999):

$$\delta_{AS} = [(\delta_{SSL} - \boldsymbol{\varepsilon}^*)/a^* - \boldsymbol{\varepsilon}_K - \delta_P(1 - h + \boldsymbol{\varepsilon}_K)]/h. \quad \text{(A6)}$$

The limiting non-steady state composition of a water body approaching complete desiccation ($\delta^*$) was calculated from the equation given by (Gonfiantini, 1986):

$$\delta^* = \frac{h \cdot \delta_{AS} + \varepsilon_K + \varepsilon^*/\alpha^*}{h - \varepsilon_K - \varepsilon^*/\alpha^*} \quad \text{(A7)}$$

Note that all calculations are expressed in decimal notation.

## Calculations for E/I Ratios

The isotopic composition of evaporative flux and individual lake input water was calculated based on isotope mass-balance equations and the coupled isotope tracer method (Yi et al., 2008). This involves balancing the volume of evaporative flux, $\delta_E$, with outflow ($\delta_L$) to yield input water ($\delta_I$). Outflow is isotopically equal to lake water because liquid outflow does not fractionate (Gibson and Edwards, 2002). Thus, considering isotope-mass balance, hydrogen and oxygen isotope data can be quantified in terms of an evaporation-to-inflow (E/I) ratio:

$$E/I = \frac{(\delta_I - \delta_L)}{(\delta_E - \delta_L)}, \quad \text{(A8)}$$

where $\delta_E$ represents the isotopic composition of the vapor derived from an evaporating lake, defined as (Craig and Gordon, 1965):

$$\delta_E = \frac{(\delta_L - \varepsilon^*)/\alpha^* - h \cdot \delta_{AS} - \varepsilon_K}{1 - h + \varepsilon_K}. \quad \text{(A9)}$$

## Trend Analysis

The Mann-Kendall is a rank-based method that compares the relative magnitude between data points to test if values tend to increase or decrease with time. The presence of an increasing or decreasing trend over time was calculated using the trend statistic. The Mann-Kendall test statistic is defined by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(Xj - Xk) \quad , \quad \text{(A10)}$$

where $Xj$ and $Xk$ are the sequential data values, n is the number of data points, and

$$Sgn(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 \quad if & \theta = 0 \\ -1 & \theta < 0. \end{cases} \quad \text{(A11)}$$

The mean variance of $S$ given the possibilities of ties is:

$$Var(S) = n(n-1)(2n+5) - \sum_t \frac{t(t-1)(2t+5)}{18}, \quad \text{(A12)}$$

where $t$ is the extent of any given tie and $\Sigma_t$ is the summation over all ties. The standard normal variate $Z$ is defined by:

$$Z = \begin{cases} \dfrac{S-1}{(Var(S))^{\frac{1}{2}}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{(Var(S))^{\frac{1}{2}}} & if\ S < 0 \end{cases} \quad \text{(A13)}$$

In a two-sided test, the $H_o$ (no trend) is accepted if the absolute value of Z is $\leq Z_{\alpha/2}$.