

Estimating Evaporation Using Stable Isotopes: Quantitative Results and Sensitivity Analysis for Two Catchments in Northern Canada

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The stable isotope-mass balance method can provide useful water balance information in ungauged catchments. The method has been used to evaluate evaporation and water balance at two contrasting sites in northern Canada. Areal weighted evaporative discharge from an 850 km² tundra catchment in south-central District of Keewatin is estimated to be about 7 % of total water discharge (≈ 16 mm/yr), compared to about 19 % (≈ 65 mm/yr) from a 300 km² forested watershed in the Upper Mackenzie Valley. Lakes in both watersheds exhibit broad ranges of evaporation/inflow ratios related to local water balance. The potential errors in the estimates are evaluated through consideration of possible variations in basin storage, humidity, and the isotopic composition of atmospheric vapour.

Introduction

Evaporation is commonly an important, yet poorly known water budget component, especially in parts of northern Canada where large areas of surface water are exposed to arid climatic conditions during the thaw season. Efforts to determine vapour loss from remote catchments using conventional techniques are hindered by the logistical difficulties of monitoring the spatial and temporal variability of meteorologic and hydrologic parameters throughout the year. As a result, information from such studies is often meaningful only for short periods of record (weeks or months), and may have limited value for assessment of longer-term hydrologic balance.

Recent field studies in northern Canada have demonstrated that stable isotope techniques can provide useful estimates of evaporation as a proportion of annual water budgets in ungauged catchments. The isotope-mass balance technique is not constrained by the need for extensive *in situ* measurements, but relies instead on natural isotopic labelling of water as it passes through the hydrologic cycle. It is particularly well-suited for investigations in remote areas, and offers significant potential to supplement the information obtained from conventional hydrometeorological monitoring as a tool to aid in understanding and managing local and regional water resources.

This article outlines the basis for the isotope-mass balance method, and presents the results obtained from field studies at two sites in the Northwest Territories, Canada. The results demonstrate the sensitivity of isotopic signals to varying water balance and highlight the inherent local variability of water loss *via* evaporation from the two catchments.

Background

The use of stable oxygen and hydrogen isotopes as tracers in hydrologic studies is based on naturally occurring variations in the relative abundance of two rare, heavy isotopic species of water ($^1\text{H}^2\text{H}^{16}\text{O}$ and $^1\text{H}^1\text{H}^{18}\text{O}$) with respect to the common light isotopic species ($^1\text{H}^1\text{H}^{16}\text{O}$), arising from phase changes and mixing as water passes through the hydrologic cycle. Isotopic composition is expressed in terms of $^2\text{H}/^1\text{H}$ and $^{18}\text{O}/^{16}\text{O}$ ratios, represented by δ values signifying the deviation in parts per thousand (‰) from a designated standard. Values here are cited with respect to SMOW (Standard Mean Ocean Water), such that $\delta_{\text{sample}} = (R_{\text{sample}}/R_{\text{SMOW}} - 1) 1000$, where $R = ^2\text{H}/^1\text{H}$ or $^{18}\text{O}/^{16}\text{O}$ ratio measured in sample and standard (see Fritz and Fontes 1980).

The oxygen and hydrogen isotope compositions of precipitation and surface waters in simple catchments typically define two distinct linear trends in $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ space (Fig. 1). Precipitation and other waters that have not undergone evaporation (such as most groundwaters) generally fall along a local meteoric water line (MWL) having a slope of about 8, usually lying close to the global meteoric water line of Craig (1961). Variations in the isotopic composition of precipitation, related mainly to temperature-dependent effects during condensation of atmospheric vapour and air-mass history, result in systematic seasonal shifts along the MWL, oscillating between isotopically heavy summer rain and isotopically light winter snow (see Dansgaard 1964). The isotopic composition of precipitation and the nature of local meteoric water lines in Canada were discussed in detail by Fritz *et al.* (1987).

Meteoric waters that have undergone evaporation display systematic enrichment in both ^{18}O and ^2H , resulting in divergence from the MWL along evaporation lines having slopes of less than 8 (often in the range 4 to 6). Surface waters in headwater

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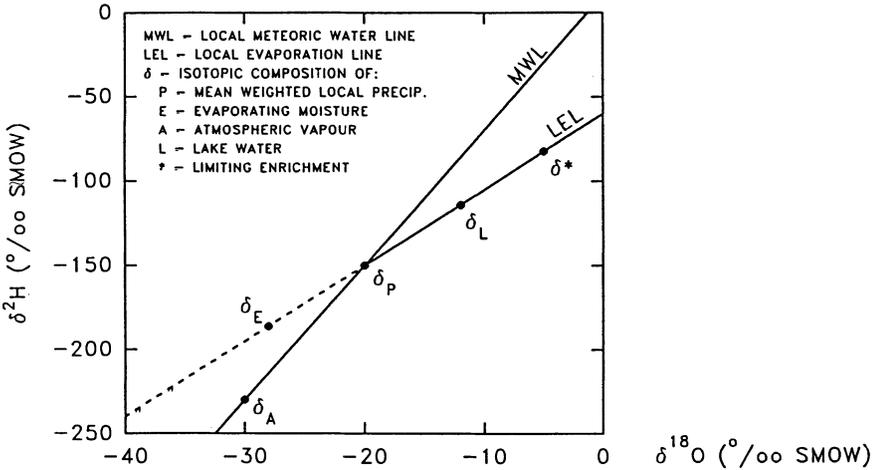


Fig. 1. Generalized $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ plot.

catchments commonly cluster along a single well-defined local evaporation line (LEL) with the intersection of the LEL and MWL providing a useful estimate of the weighted mean isotopic composition of annual precipitation in the catchment (δ_P in Fig. 1). Displacement along the LEL from δ_P varies within and between lakes in response to varying water balance.

Also shown in Fig. 1 are the isotopic compositions of ambient atmospheric vapour, δ_A , vapour derived from the evaporating water body, δ_E , and the limiting isotopic enrichment, δ^* , attainable only in the unusual case where the water body evaporates to near zero volume. δ_A is separated from δ_P by temperature-dependent isotopic fractionations related to differences in the equilibrium vapour pressures of $^1\text{H}^2\text{H}^{16}\text{O}$ and $^1\text{H}^1\text{H}^{18}\text{O}$, and hence plots on the MWL. The separation of δ_E from δ_L along the LEL is determined by a combination of temperature-dependent equilibrium effects plus transport-dependent kinetic effects arising as the different isotopic species pass from the lake into the overlying atmosphere (Craig and Gordon 1965). The slope of an LEL reflects the influence of varying local conditions (temperature, humidity, wind speed, fetch, *etc.*), naturally integrated over the evaporation season. Relative displacement along the LEL for a given evaporation rate is also characteristic of local conditions, as is the limiting enrichment.

Use of isotope-mass balance calculations to evaluate vapour outflow from a surface water body essentially reduces to solution of a two-component mixing problem. With reference to Fig. 1, this involves balancing the volume of lost vapour (of composition δ_E) with outflowing lake water (of composition δ_L) to yield input water (of composition δ_P), as shown by the following algebraic derivation.

Mass balance of a lake at hydrologic steady-state (*i.e.* undergoing evaporation while maintaining constant volume) is described by

$$I = O + E \tag{1}$$

where I is inflow, O is liquid outflow, and E is vapour outflow. The analogous isotope-mass balance equation using ^{18}O or ^2H as a tracer is

$$I \delta_I = O \delta_O + E \delta_E \tag{2}$$

For a well-mixed headwater lake receiving only local precipitation, δ_P and δ_L may be substituted for δ_I and δ_O , respectively. Substitution of Eq. (1) and rearrangement of Eq. (2) in terms of the ratio of vapour outflow to liquid inflow then yields

$$\frac{I}{E} = \frac{\delta_E - \delta_L}{\delta_P - \delta_L} \tag{3}$$

Although δ_P and δ_L can be obtained readily through sampling and analysis, determination of δ_E is complicated by the difficulty of selectively sampling evaporating moisture in the presence of ambient moisture (Zuber 1983). Nevertheless, δ_E may be estimated from evaporation pan experiments (Welhan and Fritz 1977; Allison *et al.* 1979), through calibration against an index lake of known water balance (Dinçer 1968), or from theoretical relations alone. According to the simplified form of the model of Craig and Gordon (1965) describing free-surface evaporation

$$\delta_E = \frac{\delta_L - h\delta_A - \epsilon}{1 - h} \tag{4}$$

where δ values represent the $\delta^{18}\text{O}$ or $\delta^2\text{H}$ of evaporate δ_E , lake water δ_L , and ambient atmospheric vapour δ_A ; ϵ is the isotopic separation between liquid and vapour, where $\epsilon = \epsilon^* + \epsilon_K$ incorporating both equilibrium ϵ^* and kinetic ϵ_K effects; and h is the relative humidity. Substituting for δ_E in Eq. (3) as suggested by Gat and Levy (1978) yields

$$\frac{I}{E} \equiv \frac{h}{1-h} \frac{\delta^* - \delta_L}{\delta_L - \delta_P} \tag{5}$$

where δ^* is the limiting isotopic enrichment under local hydrometeorological conditions, given by

$$\delta^* \equiv \frac{h\delta_A + \epsilon}{h - \epsilon} \tag{6}$$

Independent estimates of δ^* for oxygen and hydrogen can be obtained from Eq. (6), constrained by the slope of the observed LEL, to yield representative δ^* values.

Inflow/evaporation ratios obtained from isotope-mass balance determinations can be combined in turn with precipitation or hydrometric data to make volumetric estimates of vapour loss from a catchment or surface water body. Owing to seasonal variations in lake level and rates of runoff and evaporation, isotopic monitoring of ungauged catchments is best suited to longer-term studies encom-

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passing complete annual cycles (and hence approximating conditions of consistent water balance). Indeed, the main strength of the isotope-mass balance approach lies in the ability to derive useful water balance information in the absence of detailed hydrometeorological information.

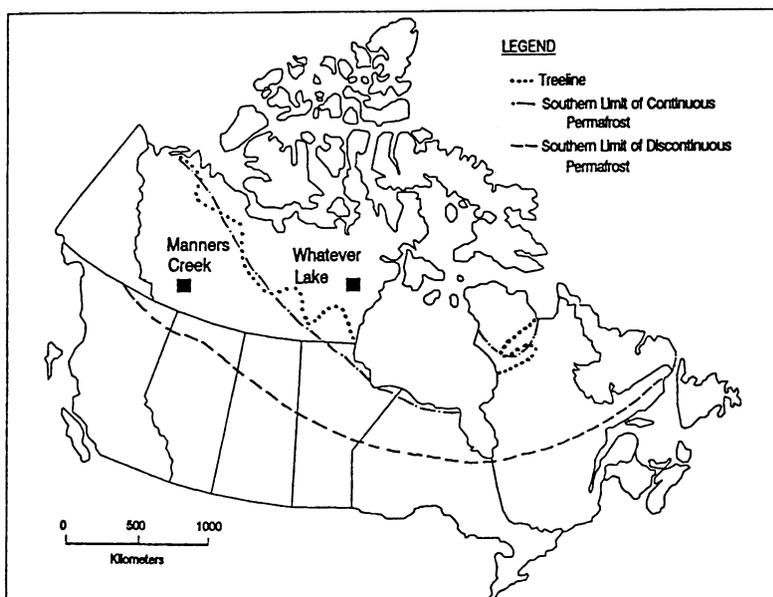


Fig. 2. Site locations showing permafrost distribution and the treeline boundary in Canada (redrawn from Prowse 1990).

Study Sites

Application of the stable isotope-mass balance method is demonstrated in the following comparison of results obtained from two catchments in widely differing climatic settings in northern Canada (see location map, Fig. 2).

Whatever Lake Watershed

Hydrologic and geochemical investigations were conducted during 1988 and 1989 in the Whatever Lake watershed (unofficial name) in the Barren Lands of south-central District of Keewatin ($64^{\circ}41'N$; $97^{\circ}03'W$). The studies were described comprehensively by Bursey (1990) and summarized by Bursey *et al.* (1991).

The site lies in the Kazan Upland, within the Churchill geological province of the Canadian Shield. The area is characterized by subdued bedrock topography, mantled discontinuously by thin overburden of glacial origin. The watershed is located in the Low Arctic Ecoclimatic Region (Ecoregions Working Group 1989),

having characteristic dwarf tundra vegetation and underlain by continuous permafrost beneath a 20 to 200 cm-thick active layer. The area receives between 200 and 300 mm of precipitation per year and has a mean annual temperature of about -12°C , based on meteorological records from Baker Lake, which lies about 170 km to the NNE (Environment Canada 1982, 1984). About 60 % of annual precipitation falls as rain in the late summer and early autumn, and the remainder is distributed as snow and rain throughout the rest of the year.

Studies were concentrated within a 3.5 km^2 headwater catchment, but included sampling throughout the 850 km^2 watershed tributary to Whatever Lake. Samples were obtained for isotopic analysis from residual snow banks, rain, permafrost, piezometers installed in the active layer, groundwater seeps, streams, and lakes, as well as from an evaporation pan monitored over several weeks in 1989. Isotopic data from natural sources clearly define both a MWL (described by $\delta^2\text{H} = 7.4\delta^{18}\text{O} - 5.7$) and a LEL (described by $\delta^2\text{H} = 5.5\delta^{18}\text{O} - 48$), as shown in Fig. 3. The intersection of the MWL and LEL provide estimated δ_P values for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively, of -21.6‰ and -166‰ .

Manners Creek Watershed

Detailed hydrologic studies were undertaken in 1989 and 1990 in the Manners Creek watershed, a high-boreal wetland in southern District of Mackenzie ($61^{\circ}52'\text{N}$; $121^{\circ}35'\text{W}$) near Fort Simpson. Aspects of these investigations have been reported, including isotope hydrology and water balance (Gibson 1991; *see also* Gibson *et al.* 1993), spring melt hydrology (Reedyk 1991), and hydrogeochemistry of groundwaters (Craig 1991). Studies are continuing at the site under the auspices of Environment Canada (National Hydrology Research Institute, Saskatoon).

The Manners Creek watershed is a headwater catchment, contributing to the Liard River near its confluence with the Mackenzie River. The watershed lies within the Interior Platform of western Canada, on the Great Slave Plain. The area is characterized by flat to gently undulating terrain, underlain by flat-lying glacial lake sediments and braid delta deposits capped discontinuously by peat (50 to 300 cm thick) and inactive aeolian sand dunes (Smith 1992). Permafrost underlies 10 to 25 % of the watershed, restricted primarily to areas underlain by thick peat and beneath north-facing slopes of tributary creeks having black spruce and sphagnum vegetation cover. South-facing slopes with aspen and alder, and well-drained uplands with white spruce, aspen and jack pine are generally free of permafrost (Rennie *et al.* 1981; Burgess 1988). Upland areas contain numerous shallow lakes, ponds and grassy fens. The Manners Creek watershed is typical of the High Boreal Ecoclimatic Region (Ecoregions Working Group 1989). Mean annual temperature of -4.2°C and annual precipitation of 355 mm were recorded at Fort Simpson airport, located less than 15 km from the field site (Environment Canada 1982, 1984). About 50 % of annual precipitation falls between mid-summer and lake freeze-up.

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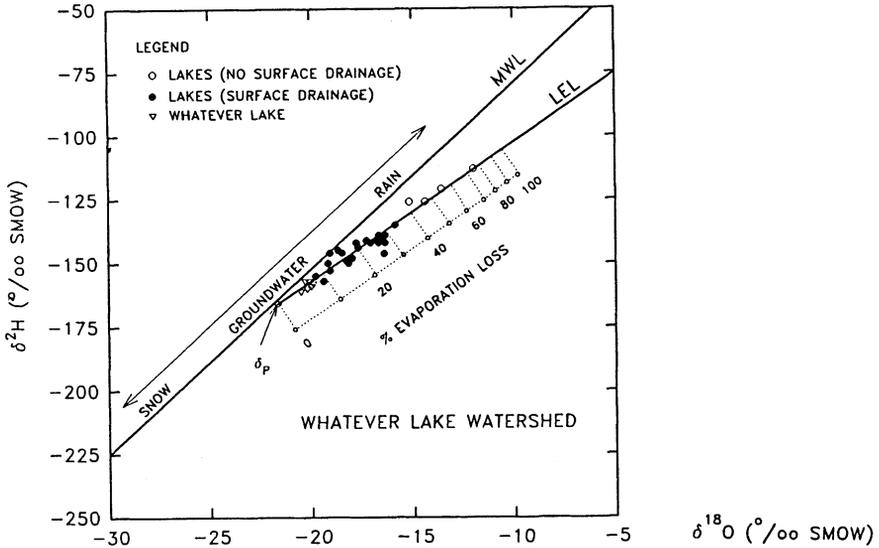


Fig. 3. Plot of $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ for Whatever Lake watershed. Data points represent the observed average isotopic compositions of water sampled from surface waters. LEL and MWL were determined by linear regression of data from Bursey (1990).

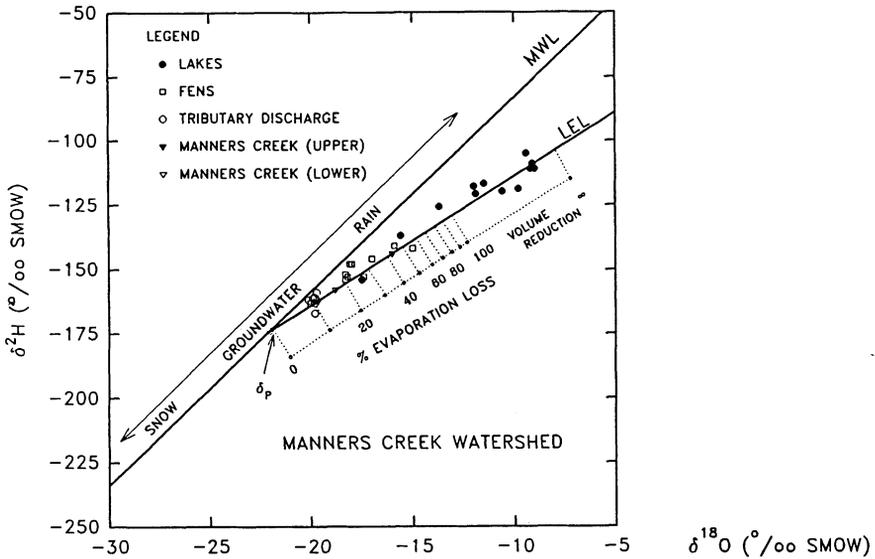


Fig. 4. Plot of $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ for Manners Creek watershed. Data points represent the observed average isotopic compositions of water sampled from various sources, except for points beyond 100% on the LEL, which reflect transitory values obtained at times of evaporative drawdown of lake levels. LEL and MWL were determined by linear regression of data from Gibson (1991).

Manners Creek drains about 300 km² of forest and wetland terrain, although the exact area of the watershed is difficult to ascertain due to poor integration of the drainage network. Samples collected for isotopic analysis included snow, rain, groundwater, and creek icings, plus water obtained from streams, lakes, and fens. Samples were also collected from evaporation pans to compare estimates of evaporation rate based on isotopic data with measured and modelled pan evaporation.

Isotopic data from natural waters in the Manners Creek watershed yielded a local MWL described by $\delta^2\text{H} = 7.78\delta^{18}\text{O} - 7.0$ and a LEL described by $\delta^2\text{H} = 5.0\delta^{18}\text{O} - 64$ (Fig. 4). Estimated δ_P values for the Manners Creek area are -22.0% and -174% , for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively.

Results and Discussion

The inclined scale bars in Figs. 3 and 4 indicate the estimated percentage of water loss *via* evaporation for varying degrees of evaporative enrichment in the Whatever Lake and Manners Creek watersheds. Given that no open-water evaporation is occurring during the ice-on period, the calculations assume mean relative humidities and temperatures for the average lake ice-free period at each site. Experimentally determined equilibrium fractionation factors of Bottinga and Craig (1969) and Majoube (1971) were used for oxygen and hydrogen, respectively. Also, kinetic fractionation factors reported by Gonfiantini (1986) were used for oxygen, with kinetic effects for hydrogen obtained by fitting to the observed local evaporation line (Zuber 1983). The isotopic composition of atmospheric vapour (δ_A) was assumed to be in equilibrium with estimated mean annual precipitation (δ_P) at each site. Although atmospheric vapour sampling was not conducted, the latter assumption is a first approximation that assigns conservative $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for δ_A . This approach is broadly consistent with observations in mid-continental environments having numerous lakes (*e.g.* see Craig and Horibe 1967; Gat 1991; Gat and Bowser 1991) and is supported by the results of evaporation pan experiments undertaken in the field (Gibson 1991). Table 1, for example, demonstrates a reasonable level of agreement between evaporation estimates based on isotope-mass balance calculations (assuming δ_P - δ_A equilibrium), direct measurement of volume change, and mass transfer analysis for a 23-day trial at the Manners Creek site. The use of δ_A based on equilibrium with annual precipitation naturally biases δ_A towards more depleted compositions than would occur if ambient vapour were in theoretical equilibrium with thaw-season precipitation. This is supported qualitatively by isotopic depletion of ambient vapour at times of maximum evaporation from Sparkling Lake, Wisconsin, observed by Krabbenhoft *et al.* (1990). In the absence of direct sampling (which is planned for future studies), assumed δ_A - δ_P equilibrium appears to provide a good proxy for δ_A during the seasonal period of evaporation at both sites. The influence of variation in δ_A is discussed further below.

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Table 1 – Estimates of pan evaporation for the period 11 August to 2 September 1990 (from Gibson 1991).

Method	Mean Daily Evaporation (mm)	23-day total Evaporation (mm)
Isotope-mass Balance^A		
$\delta^{18}\text{O}$	3.1	71
$\delta^2\text{H}$	3.5	80
Pan Measurement		
Class A Pan ^B	3.8	88
Class A Pan ^C	2.8	65
Floating Pan ^D	2.8	64
Mass Transfer		
Class A Pan	3.5	80
Study Lake	2.7	62

^A Performed on pan 1 using Eq. (5) and δ^* observed in pan 3
 $(\delta_L^{18,2} \equiv -10.5, -114; \delta_P^{18,2} \equiv -13.5, -130; h \equiv 0.53; I \equiv 146.2 \text{ mm})$

^B 122 cm diameter, unsheltered

^C 122 cm diameter, sheltered

^D 26 cm diameter, sheltered, drying, floated in class A pan ($\delta^{18,2} = -5.0, -88$)

The wide span of the data from Whatever Lake watershed plotted in Fig. 3 clearly depicts the varying importance of vapour outflow from lakes, showing a general decline in the proportion of evaporative loss from upland lakes with restricted surface drainage to larger lakes with well-defined surface drainage. Note that the isotopic composition of Whatever Lake integrates the evaporative enrichment signal of the entire watershed, most of which is inherited from the “pre-evaporated” water received from tributary sub-basins, and only a small amount is attributable to direct vapour loss from the surface of the lake. Based on this analysis, less than 10 % of precipitation received in the watershed as a whole discharges as vapour, although individual ponds may lose over 70 %.

The data from Manners Creek watershed plotted in Fig. 4 also reflect appreciable variation in vapour loss between individual lakes and fens, and include samples illustrating the effect of non-steady-state hydrologic balance on enrichment of surface waters. Points plotting beyond 100 % evaporation loss originated from closed upland lakes that were drawn down significantly by evaporation during the course of monitoring, and hence diverged strongly from the situation modelled by Eq. (5). Several of these points approach maximum theoretical isotopic enrichment of a desiccating water body under local conditions. Also of note are samples from several fens, which undoubtedly underestimate total vapour losses due to transpiration by emergent plants (a non-fractionating source of vapour discharge), yet range up to about 50 % evaporation loss. Transpiration may account for most of

Table 2 – Water balance summary of selected reservoirs in the Whatever Lake and Manners Creek watersheds. Calculations assume annual precipitation and thaw season relative humidity of 235 mm/yr and 54 % for Whatever Lake and 355 mm/yr and 64 % for Manners Creek.

(A) WHATEVER LAKE WATERSHED

LOCATION	δ_L 1. $\delta^{18}\text{O}$ (1 σ) 2. $\delta^2\text{H}$ (1 σ)	E/I ^(A)	E	O
			(mm/yr)	
LAKES (SUBDUED SURFACE DRAINAGE) (N=4)	1. -14.0 (1.4) 2. -122 (6)	0.51 0.55	119 130	116 105
LAKES (CONTINUOUS OR INTERMITTENT SURFACE DRAINAGE) (N=20)	1. -16.5 (1.1) 2. -142 (5)	0.29 0.23	67 55	168 180
WHATEVER LAKE (N=7)	1. -20.0 (0.2) 2. -158 (2)	0.07 0.07	17 15	218 220

(B) MANNERS CREEK WATERSHED

LOCATION	δ_L 1. $\delta^{18}\text{O}$ (1 σ) 2. $\delta^2\text{H}$ (1 σ)	E/I ^(B)	E	O	
			(mm/yr)		
LAKES (NO SURFACE DRAINAGE) (N=12)	1. -12.5 (2.8) 2. -128 (13)	1.24 1.12	441 399	-86 ^C -44 ^C	
FENS (SUBDUED SURFACE DRAINAGE) (N=19)	1. -18.1 (1.3) 2. -155 (6)	0.22 0.21	79 76	276 279	
SMALL TRIBUTARIES TO LOWER MANNERS CREEK (N=35)	1. -21.0 (0.1) 2. -164 (2)	0.04 0.10	16 34	339 316	
MANNERS CREEK	UPPER (20 km from mouth) (N=3)	1. -16.0 (0.5) 2. -144 (4)	0.43 0.43	154 154	201 201
	LOWER (0.2 km from mouth) (N=5)	1. -18.8 (0.7) 2. -158 (5)	0.17 0.20	60 70	295 285

^(A) Calculated from Eq. [5] using $\epsilon^{18,2} = (0.0171, 0.115)$; $\epsilon^{*18} = 0.0106$ from Bottinga and Craig (1969), $\epsilon^{*2} = 0.096$ from Majoube (1971), $\epsilon_K^{18} = 0.0066$ from Gonfiantini (1986), and $\epsilon_K^2 = 0.0189$ as fitted to the LEL.

^(B) Calculated from Eq. [5] using $\epsilon^{18,2} = (0.0154, 0.102)$; $\epsilon^{*18} = 0.0103$ from Bottinga and Craig (1969), $\epsilon^{*2} = 0.091$ from Majoube (1971), $\epsilon_K^{18} = 0.0051$ from Gonfiantini (1986), and $\epsilon_K^2 = 0.0116$ as fitted to the LEL.

^C **Note:** negative outflow values arise in the case of lakes where $dV/dt \ll 0$. See text for discussion.

the discharge from densely vegetated fens during the latter part of the growing season, as observed in rice paddies by Herczeg *et al.* (1991). The evaporative enrichment signature of lower Manners Creek (the surface discharge from the watershed) derives from mixing of less-enriched water from a major tributary stream with more-enriched water from upper Manners Creek, reflecting differing degrees of evaporation loss in the contributing sub-basins.

Selected representative estimates of evaporation/inflow ratios from the two watersheds are summarized for comparison in Table 2, including coarse numerical estimates of equivalent discharges assuming annual precipitation of 235 mm for Whatever Lake and 355 mm for Manners Creek. Estimates based on both oxygen and hydrogen isotope data are given for each example to illustrate typical differences arising from scatter of points about the LEL. No attempt has been made to account for transpiration or sublimation in either watershed.

Model Uncertainties

A sensitivity analysis was conducted in order to constrain potential errors arising from uncertainties in measurement or estimation of hydrologic and atmospheric parameters used in the model. Percentage errors in calculated evaporation/inflow ratios are shown graphically in Fig. 5 and summarized in Table 3 for the following: i) evaporative drawdown of reservoirs by 5 %; ii) variation in isotopic separation between δ_A and δ_P of ± 10 %; iii) variation in humidity of ± 5 %.

Reservoir Storage – Surface waters, particularly small lakes with subdued surface drainage, are commonly subject to gradual volume reduction over the course of the open water period as a result of evaporative drawdown. If not recognized, this would lead to overestimation of the mean E/I ratio, because of the enhanced isotopic enrichment of the reservoir. Fig. 5 illustrates the predicted error in E/I ratios for different values of $\delta^{18}\text{O}$ in both catchments, given a net decrease in storage volume of 5 %. Errors are largest for reservoirs having limited isotopic enrichment and, hence, small E/I ratios. This extreme sensitivity at low enrichment is somewhat artificial, however, as field monitoring indicates that such reservoirs in both watersheds undergo minimal changes in volume. Sensitivity for low levels of enrichment is also limited by isotopic analytical uncertainties. For smaller lakes with restricted surface drainage, 5 % evaporative drawdown would produce a 10 to 20 % overestimate in the calculated E/I ratio. Volume reduction in excess of 5 %, observed for lakes in the Manners Creek watershed, is likely responsible for E/I ratios in excess of 1 (*see* Table 2). As noted, the hydrologic regime of these reservoirs is poorly described by the steady-state model.

Isotopic Composition of Atmospheric Moisture – The assumption of isotopic equilibrium between δ_A and δ_P (*i.e.* $\delta_A = \delta_P - \epsilon^*$) introduces potential error in E/I ratios through the dependence of δ^* on δ_A (Eq. (6)). Fig. 5 illustrates the sensitivity of

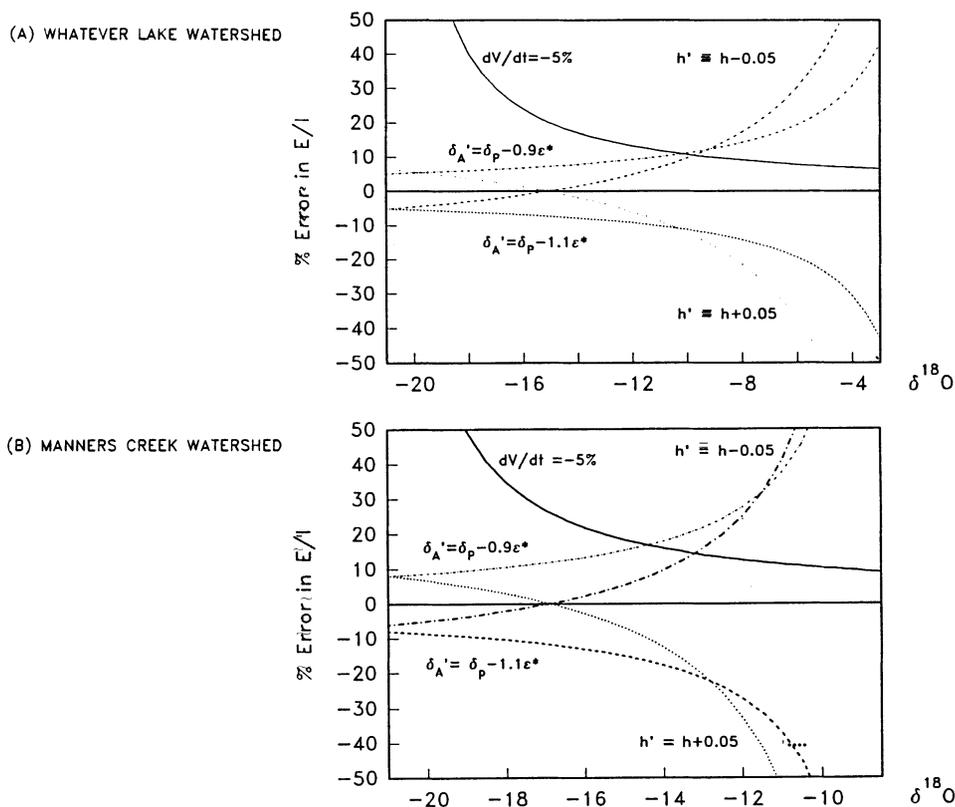


Fig. 5. Plot of $\delta^{18}\text{O}$ versus per cent error in calculated E/I ratios for the Whatever Lake and Manners Creek watersheds. Error curves illustrate that uncertainties vary with the degree of isotopic enrichment. Analogous plots can be constructed for $\delta^2\text{H}$. See text for discussion.

inferred E/I ratio to changes of $\pm 10\%$ in the values of the equilibrium separations used to calculate δ_A used for the two field sites. Evaporation estimates for the Whatever Lake watershed vary by about $\pm 13\%$, while estimates for most reservoirs in the Manners Creek watershed fall in the range $\pm 20\%$. The potential errors increase dramatically for extreme levels of isotopic enrichment (beyond that generally observed).

Humidity – The humidity dependence of calculated E/I ratios is evident in Eq. (5), both through the term $h/1-h$ and through δ^* (Eq. (6)). Fig. 5 shows the predicted errors in E/I estimates versus $\delta^{18}\text{O}$ given uncertainties of $\pm 5\%$ in humidity. As for δ_A , potential errors resulting from variation in humidity increase strongly at higher isotopic enrichment. However, for the range of reservoir $\delta^{18}\text{O}$ values observed in both watersheds the potential error is limited to $\pm 10\%$, except for the most highly enriched lakes in the Manners Creek watershed.

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Table 3 - Potential errors in calculated E/I ratios for the following scenarios: evaporative drawdown of 5% ($dV/dt = -5\%$); $\pm 10\%$ variation in δ_A (where $\delta_A' = \delta_P - [1.0 \pm 0.1] \epsilon^*$); and $\pm 5\%$ variation in relative humidity (where $h' = h \pm 0.05$). See text for discussion.

(A) WHATEVER LAKE WATERSHED

LOCATION	δ_L 1. $\delta^{18}\text{O}$ (1 σ) 2. $\delta^2\text{H}$ (1 σ)	dV/dt=-5%	δ_A'		h'	
			$\delta_P-0.9\epsilon^*$	$\delta_P-1.1\epsilon^*$	h+0.05	h-0.05
LAKES (SUBDUED SURFACE DRAINAGE) (N=4)	1. -14.0 (1.4)	18	7.9	-7.9	-1.8	1.5
	2. -122 (6)	13	13	-13	-7.7	6.2
LAKES (CONTINUOUS OR INTERMITTENT SURFACE DRAINAGE) (N=20)	1. -16.5 (1.1)	30	6.6	-6.6	2.0	-1.6
	2. -142 (5)	28	10	-10	-1.2	1.0
WHATEVER LAKE (N=7)	1. -20.0 (0.2)	>50	5.4	-5.4	5.7	-4.6
	2. -158 (2)	>50	8.8	-8.8	2.3	-1.8

(B) MANNERS CREEK WATERSHED

LOCATION	δ_L 1. $\delta^{18}\text{O}$ (1 σ) 2. $\delta^2\text{H}$ (1 σ)	dV/dt=-5%	δ_A'		h'		
			$\delta_P-0.9\epsilon^*$	$\delta_P-1.1\epsilon^*$	h+0.05	h-0.05	
LAKES (NO SURFACE DRAINAGE) (N=12)	1. -12.5 (2.8)	14	24	-24	-26	20	
	2. -128 (13)	12	41	-41	-39	30	
FENS (SUBDUED SURFACE DRAINAGE) (N=19)	1. -18.1 (1.3)	42	10	-10	3.1	-2.3	
	2. -155 (6)	35	18	-18	-4.1	3.1	
SMALL TRIBUTARIES TO LOWER MANNERS CREEK (N=35)	1. -21.0 (0.1)	>50	8.1	-8.1	8.1	-6.1	
	2. -164 (2)	>50	16	-16	0.43	-0.3	
MANNERS CREEK	UPPER (20 km from mouth) (N=3)	1. -16.0 (0.5)	23	13	-13	-3	2.2
		2. -144 (4)	19	24	-24	-12	9.4
	LOWER (0.2 km from mouth) (N=5)	1. -18.8 (0.7)	>50	9.8	-9.8	4.5	-3.4
		2. -158 (5)	44	17	-17	-2.4	1.8

It is apparent that model uncertainties increase substantially for both low and high values of E/I , where reservoir isotopic compositions approach either the inflow composition or the limiting enrichment, respectively. On the other hand, relatively modest potential errors are projected for intermediate levels of evaporative enrichment. Potential error curves like those plotted in Fig. 5 can be used as a guide in the selection of water bodies for isotope-mass balance studies, in order to optimize monitoring strategies.

Concluding Comments

This study demonstrates the application of a stable isotope-mass balance method for quantifying surface water evaporation from two watersheds in northern Canada. A sensitivity analysis suggests that variations in humidity and δ_A are not likely to be substantial sources of uncertainty in water-balance calculations for reservoirs having low to moderate isotopic enrichment. Application of the model for reservoirs undergoing evaporative drawdown would lead to overestimation of the evaporation/inflow ratio, especially for waters exhibiting limited evaporative enrichment.

Continued refinement of the isotope-mass balance method requires improved characterization of the isotopic composition of atmospheric vapour, and detailed calibration with micrometeorological measurements. Such studies are planned at several additional sites in northern Canada.

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References

- Allison, G.B., Brown, R.M., and Fritz, P. (1979) Estimation of the isotopic composition of lake evaporate, *Journal of Hydrology*, Vol. 42, pp. 109-127.
- Bottinga, Y., and Craig, H. (1969) Oxygen isotope fractionation between CO₂ and water and the isotopic composition of marine atmosphere, *Earth and Planetary Science Letters*, Vol. 5, pp. 285-295.
- Burgess, M.M. (1988) Permafrost and terrain preliminary results, Norman Wells pipeline, Canada. Permafrost: Fifth International Conference, Proceedings, Trondheim, Norway, 1, pp. 916-921.
- Burse, G.G. (1990) Geochemical and isotopic investigations in a watershed of the eastern Arctic, Northwest Territories. Unpublished M.Sc. Thesis. University of Waterloo, Canada, 214 pp.
- Burse, G.G., Edwards, T.W.D., and Frape, S.K. (1991) Water balance and geochemistry studies in a tundra watershed: District of Keewatin, Northwest Territories. In: Northern Hydrology: Selected Perspectives. T.D. Prowse and C.S.L. Ommanney, (Editors), NHRI

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- Symposium No. 6, National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan, pp. 17-32.
- Craig, D. (1991) Geochemical evolution of water in a continental high boreal wetland. In: *Northern Hydrology: Selected Perspectives*, T.D. Prowse and C.S.L. Ommanney (Editors), NHRI Symposium No. 6, National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan, pp. 47-56.
- Craig, H. (1961) Isotopic variations in meteoric waters, *Science*, Vol. 133, pp. 1702-1703.
- Craig, H., and Gordon, L.I. (1965) Deuterium and oxygen-18 variations in the ocean and marine atmosphere. In: *Stable Isotopes in Oceanographic Studies and Paleotemperatures*, E. Tongiorgi, (Editor), Lab. Geologia Nucleare, Pisa., pp. 9-130.
- Craig, H., and Horibe, Y. (1967) Isotopic characteristics of marine and continental water vapour, *Transactions of the American Geophysical Union*, Vol. 48, pp. 135.
- Dansgaard, W. (1964) Stable isotopes in precipitation, *Tellus*, Vol. 16, pp. 436-468.
- Dinçer, T. (1968) The use of oxygen-18 and deuterium concentrations in the water balance of lakes, *Water Resources Research*, Vol. 4, pp. 1289-1305.
- Ecoregions Working Group (1989) *Ecoclimatic Regions of Canada, First Approximation*, Canadian Committee on Ecological Land Classification Series No. 23, Canadian Wildlife Service, Environment Canada, Ottawa, Ontario.
- Environment Canada (1982) *Canadian Climate Normals: Temperature and Precipitation, 1951-80, the North – Yukon Territory and Northwest Territories*. Canadian Climate Program, Atmospheric Environment Service, 3, pp. 20, 34.
- Environment Canada (1984) *Canadian Climate Normals: Atmospheric Pressure, Temperature and Humidity, 1951-80, the North – Yukon Territory and Northwest Territories*. Canadian Climate Program, Atmospheric Environment Service, 8, pp. 61, 77.
- Fritz, P., and Fontes, J.Ch. (1980) (Editors) *Handbook of Environmental Isotope Geochemistry I*, Elsevier, New York, 557 pp.
- Fritz, P., Drimmie, R.J., Frappe, S.K., and O'Shea, K. (1987) The isotopic composition of precipitation and groundwater in Canada. International Symposium on the Use of Isotope Techniques in Water Resources Development, 30 March-3 April 1987, IAEA, Vienna, IAEA-SM-299/17, pp. 539-550.
- Gat, J.R. (1991) Stable isotopes and the water balance of fresh and saline lakes. In: *Lakes II*, A. Lerman (Editor), Springer-Verlag.
- Gat, J.R., and Bowser, C.J. (1991) The heavy isotope enrichment of water in coupled evaporative systems. In: *Stable Isotope Geochemistry: A Tribute to Samuel Epstein*, H.P. Taylor Jr., J.R. O'Neil and I. R. Kaplan (Editors), The Geochemical Society Special Publication No. 3, pp. 159-168.
- Gat, J.R., and Levy, Y. (1978) Isotope hydrology of inland sabkhas in the Bardawil area, Sinai, *Limnology and Oceanography*, Vol. 23(5), pp. 841-850.
- Gibson, J.J. (1991) Isotope hydrology and water balance investigations in the Manners Creek watershed, District of Mackenzie, N.W.T. Unpublished M.Sc. Thesis, University of Waterloo, Waterloo, Ontario, 218 pp.
- Gibson, J.J., Edwards, T.W.D., and Prowse, T.D. (1993) Runoff generation in a high boreal wetland in Northern Canada, *Nordic Hydrology*, Vol. 24 (2/3), pp. xx.
- Gonfiantini, R. (1986) Environmental isotopes in lake studies. In: *Handbook of Environmental Isotope Geochemistry 2*, P. Fritz and J.Ch. Fontes (Editors), Elsevier, New York, pp. 113-168.

- Herczeg, A.L., Simpson, H.J., Whitehead, R., Leaney, F.W., and Meyer, W.S. (1991) Deuterium and oxygen-18 as indicators of evaporation losses from rice crops in semi-arid climate zones. International Symposium on the Use of Isotope Techniques in Water Resources Development, 11-15 March 1991, IAEA, Vienna, IAEA-SM-319-3P, pp. 106-108.
- Krabbenhoft, D.P., Bowser, C.J., Anderson, M.P., and Valley, J.W. (1990) Estimating groundwater exchange with lakes 1. The stable isotope mass balance method, *Water Resources Research*, 26 Vol. (10), pp. 2445-2453.
- Majoube, M. (1971) Fractionnement en oxygène-18 et en deutérium entre l'eau et sa vapeur, *J. Chim. Phys.*, Vol. 197, pp. 1423-1436.
- Prowse, T.D. (1990) Northern Hydrology: An Overview. In: Northern Hydrology, Canadian Perspectives, T.D. Prowse and C.S.L. Ommanney, (Editors), NHRI Science Report 1, National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan, pp. 1-36.
- Reedyk, S. (1991) Contribution of icing ablation to streamflow in discontinuous permafrost. Unpublished M.Sc. Thesis, McMaster University, Canada, 99 pp.
- Rennie, J.A., Reid, D.E., and Henderson, J.D. (1981) Permafrost extent in the southern fringe of the discontinuous permafrost zone, Fort Simpson, N.W.T. Permafrost: Third International Conference, Proceedings, Edmonton, 1, pp. 439-444.
- Smith, D.G. (1992) Glacial Lake Mackenzie, Mackenzie Valley, Northwest Territories, Canada, *Canadian Journal of Earth Sciences*, Vol. 29, pp. 1756-1766.
- Welhan, J.A., and Fritz, P. (1977) Evaporation pan isotopic behaviour as an index of isotopic evaporation conditions, *Geochimica et Cosmochimica Acta*, Vol. 41, pp. 682-686.
- Zuber, A. (1983) On the environmental isotope method for determining the water balance of some lakes, *Journal of Hydrology*, Vol. 61, pp. 409-427.

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