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A six-year isotopic record of lake evaporation at a mine site in the Canadian subarctic: results and validation

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Abstract:

An isotopic method is applied in conjunction with a water balance method and the Penman combination method to estimate evaporation from a small, high closure (low outflow) lake near Yellowknife, Northwest Territories, Canada (62°03′N 111°24′W). The study provides baseline hydrological information for assessment of tailings pond design and management at nearby mine sites, and, notably, enables intercomparison of several field-based evaporation methods and a standard climate approach in a subarctic setting. A non-steady isotope mass balance method is applied to estimate evaporation over time intervals ranging from five days to three weeks, based on isotopic surveys of lake water, groundwater, precipitation and atmospheric moisture during the open water periods of 1991 to 1996. Use of a relatively high precision non-steady technique, in contrast to the commonly employed approach assuming steady state, is feasible in the present setting owing to pronounced seasonal evaporative enrichment in lake water (20–30 times analytical uncertainty of $\delta^{18}O$). A comparative analysis reveals that the isotopic method is conservative relative to the Penman combination method, but less conservative than standard water balance, although estimates for the open water period are in agreement to within 20% in both cases. Interannual variability in evaporation is revealed to be 30–50% greater than predicted from standard pan-to-lake algorithms, and of the same order of magnitude as the annual snow water equivalent ($\approx$155–175 mm), which has important implications for the design and management of tailings ponds in the area. © 1998 John Wiley & Sons, Ltd.

KEY WORDS stable isotopes; evaporation; northern hydrology; subarctic; mining; tailings ponds

INTRODUCTION

Mining has become an important sustainable development issue in northern Canada, as a consequence of the industry's well-established and positive impact on the regional economy, and its leading role in the creation of industrial wastes that pose a significant potential threat to water resources and the environment. While the environmental consequences of mining, including the effect of acid mine drainage, have been studied extensively outside the north (Biggs, 1990; Fillion and Ferguson, 1990), basic processes controlling transport and the fate of soluble contaminants (which can include arsenic, lead, zinc, cadmium and mercury), their mobility within the hydrological cycle and their effect on freshwater and marine ecosystems are not well established for cold climate regions (Prowse, 1990). Accordingly, very basic strategies have been employed in northern Canada to mitigate direct environmental effects by optimizing the containment of liquid and solid mine wastes and ore processing by-products (Latham, 1988; Prowse 1990).

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Tailings ponds and evaporation

Artificially altered lakes or man-made reservoirs (tailings ponds) are frequently employed to contain and treat mine waste water prior to discharge into the natural aquatic environment (PAME, 1996). Owing to the finite life span of mining operations, tailings ponds are commonly abandoned and then allowed to resume a natural hydrological balance following cessation of mining activities. The main concern with this approach is that poorly contained ponds could act as a long-term source of acid mine drainage to the natural environment. Defining optimal strategies for containment of wastes has been problematic, especially in remote northern regions where information on water balance processes and variability is limited (Prowse, 1990). Related issues, such as the effectiveness of water covers to minimize acid generation in solid waste material and the stability of artificial dams, have been equally difficult to evaluate from the available hydrological data.

A tailings pond should ideally be constructed so that all surface or subsurface inflows are equalled or exceeded by evaporation losses, thus eliminating surface outflow of contaminated water. However, quantitative understanding of evaporation processes, as required to assess this containment potential and its variability across northern Canada, is limited (Latham, 1988). The only readily available evaporation data for most remote areas of northern Canada are for annual small lake evaporation, estimated from a sparse network of class-A pan stations (Prowse, 1990), which can be unreliable at unmonitored locations owing to steep regional climate gradients and large errors associated with the interpolation of estimates over hundreds or thousands of kilometres. Not surprisingly, use of erroneous evaporation data has led to unrealistic assessments of tailings pond containment potential in the past (Latham, 1988).

This study was initiated to develop a better understanding of evaporation and its role in the water balance at mine sites in northern Canada, as a basic step to improve evaluation of tailings pond containment potential. Field-based investigations have been carried out at six mine sites across the Northwest Territories, Canada, in environments ranging from arctic desert to subarctic forest (e.g. Gibson *et al.*, 1996a,b; Reid, 1997). Herein, results are presented from a subarctic forested site near the city of Yellowknife and within 10 km of two operating gold mines. The study provides the most complete interannual record of lake evaporation in the Canadian subarctic and enables a direct comparison of several field-based evaporation methods and a standard class-A pan approach applied at a nearby climate station. Notably, the study demonstrates that standard climate-based algorithms are effective for predicting mean evaporation from a nearby lake, but do not adequately characterize interannual variability. This emphasizes the need for *in situ* monitoring programmes for proper evaluation of containment feasibility, which is particularly important for describing evaporation and its role in the water balance at remote unmonitored locations.

Methodological development

In addition, this study has sought to develop and evaluate field procedures for characterizing evaporation, and to demonstrate their application and reliability. These activities are prerequisite to any standard use of the methods at operational mine sites in preparation for decommissioning and eventual abandonment.

Development and validation of the non-steady isotope mass balance approach was initially conducted at the Lupin mine site situated 375 km north of Yellowknife. The study at Lupin was the first to demonstrate that a non-steady isotopic method could be reliably applied to estimate evaporation within $\pm 15\%$ of standard hydrological methods, such as the Bowen ratio, Priestley–Taylor and aerodynamic profile over 50-day time-periods in an arctic tundra setting (Gibson *et al.*, 1996a). The comparative analysis presented herein supports the validity of the non-steady isotopic method and confirms that it can be applied to obtain comparable estimates of evaporation over the open water period for a forested subarctic lake.

Study site

Field studies were conducted near Pocket Lake, situated about 1 km from the north-west tailings pond at the Giant Yellowknife Mine, and 5 km north of the Environment Canada climate station at Yellowknife, Northwest Territories, Canada (Figure 1). The lake has an area of 4·8 ha and a mean depth of 2 m based on

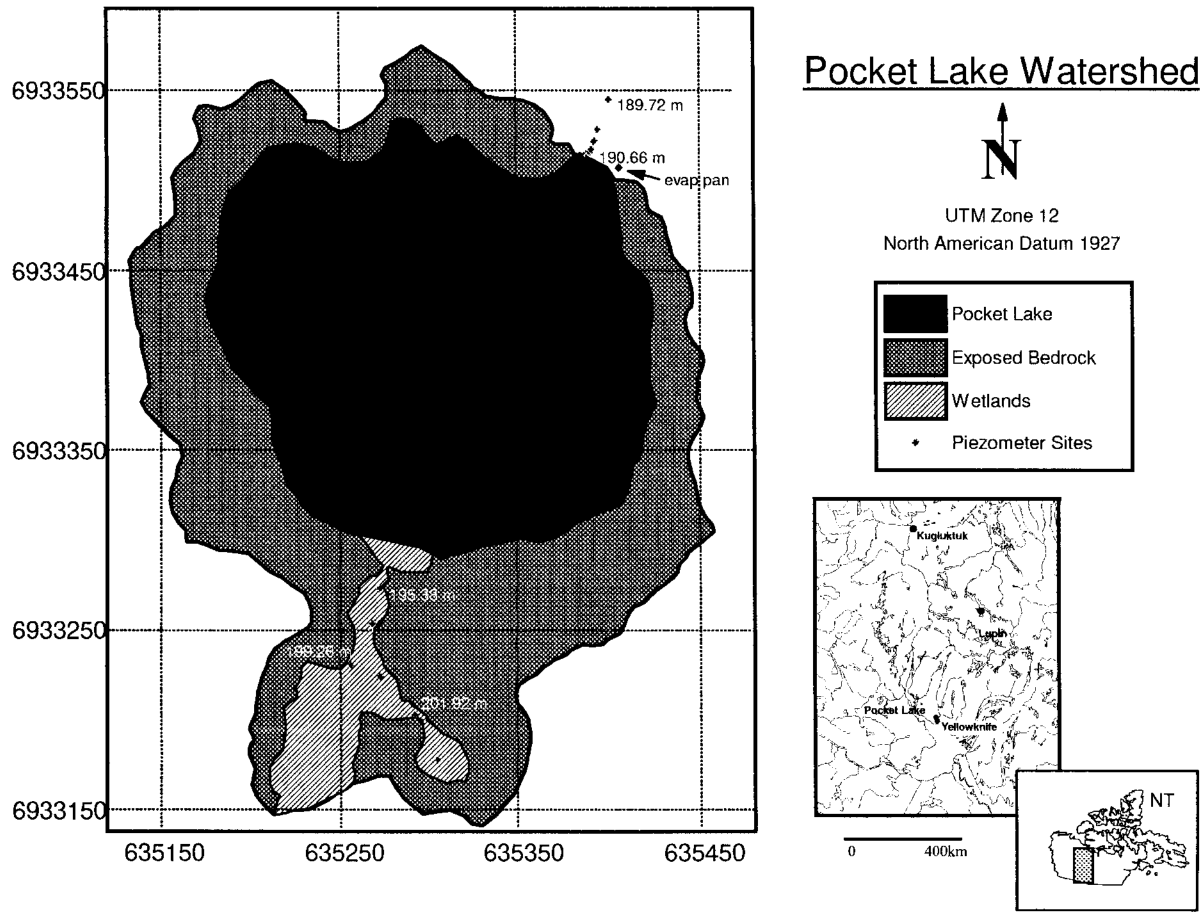

Figure 1. Map of the Pocket Lake catchment showing the distribution of dominant land cover types and instrumentation locations. Inset shows the study lake in relation to Yellowknife, Lupin and the Northwest Territories, NT, Canada

bathymetric surveys conducted in 1992 (Taal, 1994) and 1996 (this study). The 5·2 ha drainage basin surrounding the lake is dominated by exposed granite bedrock with isolated areas of wetland dominated by organic peat. Surface outflow from the lake has not occurred since 1975 (Canada, Environment Canada, 1996). Vegetation is predominantly open woodland black spruce and birch. Wetland areas are dominated by grass and sedge.

A series of hydrological studies were conducted in the lake catchment during the International Hydrological Decade programme (1965–1974), and include estimates of free surface evaporation using the temperature-based method of Thornthwaite (1948), as reported by Kakela (1969) and Wight (1973), and a study of snowmelt runoff, as reported by Landals (1970). Wight (1973) estimated lake evaporation for a typical year of 391 mm, which is broadly consistent with the mean small lake evaporation estimated from evaporation pan and supplementary climate data (den Hartog and Ferguson, 1978).

Reconnaissance level isotopic investigations began in the Pocket Lake catchment in 1991. Water samples were collected in that year from Pocket Lake and road-accessible lakes within about 50 km of Yellowknife. Pocket Lake was selected for detailed study from a suite of local lakes because of its proximity to the tailings reservoir and its appropriateness as a natural analogue for a high closure (low outflow) tailings pond in the post-operational period. Detailed studies began in 1992, aspects of which have been reported previously by Taal (1994). Taal (1994) estimated annual evaporation from Pocket Lake at 440–480 mm/a using a

Table I. Climate conditions during the study *versus* normal, Yellowknife Airport (June–September incl.). Above-normal values are in bold

	Normal 1961–1990	Mean (this study)	1991	1992	1993	1994	1995	1996
Temperature (°C)	12·6	**12·9**	**13·1**	11·0	12·0	**14·6**	**12·7**	**14·1**
Precipitation (mm)	129	120	**176**	102	127	73	88	**155**
Relative humidity	65	63	64	65	60	57	62	**67**

steady-state isotope mass balance approach described by Gibson *et al*. (1993), although use of the steady-state approach is not generally reliable for estimating evaporation from small lakes with pronounced seasonal variability in isotope composition (e.g. Gibson and Prowse, 1997).

Aspects of water balance and micrometeorological studies of evaporation during 1992–1996 have been reported previously by Reid (1994, 1997). Groundwater recharge and discharge estimates using isotopic and non-isotopic methods have been reported by Spence and Stephens (1997).

Climate

The climate at Yellowknife is characterized by short cool summers and long cold winters. Monthly temperatures range from 16 °C in July to −29 °C in January, with an annual precipitation of 268 mm, about 50% as snow. Compared with the 1961–1990 climate normals, mean temperature, humidity and precipitation observed during this study were typical. Of interest is the fact that 1994 was the warmest and driest summer in 48 years of record at Yellowknife. The 1992–1995 period was characterized by below-average summer precipitation. (Table I).

Field monitoring and instrumentation

Representative water samples for isotopic analysis were collected at regular intervals during the study from Pocket Lake, from class-A evaporation pans and a precipitation gauge located near the lake shore and from shallow groundwater within the catchment. Following 1991 and 1992, water samples were collected for the duration of the open water period, to permit estimates of evaporation over equivalent periods. Isotopic sampling procedures and protocols have been described elsewhere (Gibson, 1996; Gibson *et al*., 1996a).

During 1992–1996, temporal records of the isotopic composition of atmospheric moisture were compiled over intervals consistent with the lake sampling programme based on isotopic monitoring of class-A evaporation pans with controlled water balances. A description of the technique and comparisons with alternative approaches, such as direct vapour sampling and precipitation–equilibrium techniques, has been summarized by Gibson (1996). Groundwater was sampled using mini-piezometer nests (Lee and Cherry, 1978) with individual piezometers installed at depths ranging from 0 to 2·5 m. Nests were situated along the lake margin, in contributing wetland areas, and along potential lateral discharge zones where overburden depths permitted (Figure 1). Rain and snowpack samples were collected using a standard AES-type B rain gauge, with oil added to prevent evaporation, and a standard snow-tube, respectively. Surface runoff was not observed or sampled during the ice-free period over the course of the study. Snowmelt runoff was observed and sampled on one occasion.

Water samples for isotopic analysis were returned to the Environmental Isotope Laboratory, University of Waterloo, for determination of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios. Isotopic ratios are reported in standard 'δ' notation as deviations per mille (‰) from the Vienna–SMOW (standard mean ocean water), such that $\delta_{SAMPLE} = 1000\,[(R_{SAMPLE}/R_{SMOW}) - 1]$, where R is $^{18}O/^{16}O$ or $^{2}H/^{1}H$. $\delta^{18}O$ and $\delta^{2}H$ values cited herein are normalized to −55·5‰ and −428‰, respectively, for SLAP (standard light arctic precipitation) (see Coplen, 1996). ε values represent instantaneous isotopic separations in per mille between co-existing liquid and vapour, such that $\varepsilon_{LIQUID\text{-}VAPOUR} = 1000\,[(R_{LIQUID}/R_{VAPOUR}) - 1] \approx (\delta_{LIQUID} - \delta_{VAPOUR})$. Analytical uncertainties are $\pm 0{\cdot}1$‰ for $\delta^{18}O$ and ± 2‰ for $\delta^{2}H$.

Micrometeorological instrumentation was mounted on a 2-m tower situated within the lake and 10 m from the evaporation pan station (Figure 1). Automated sensors and dataloggers were configured to measure at 60-s intervals and record hourly averages of precipitation, relative humidity, air and water temperature profiles, wind speed and direction, lake level and net radiation. A standard rain gauge and staff gauge were also maintained as a manual control for the automated precipitation and lake level records. As described in Reid (1997), sensors were configured to provide estimates of evaporation using the Penman combination method and as the residual of the water balance.

METHODS

Isotope mass balance

Evaporation rate, *E*, was estimated using a non-steady, constant volume form of the isotope mass balance (Gibson, 1996; Gibson *et al.*, 1996a) from the record of the isotopic enrichment of lake water, δ_L, over time *t*, given by

$$\delta_L = \delta_S - (\delta_S - \delta_0)\exp[-(1 + mx)(It/V)] \tag{1}$$

where *I* is the rate of inflow, *V* is the lake volume (assumed to be well mixed), $m = (h - \varepsilon)/(1 - h + \varepsilon_K)$, *h* is the relative humidity (expressed as a decimal fraction), $\varepsilon = \varepsilon^* + \varepsilon_K$ is the total isotopic separation between liquid and vapour, comprised of the equilibrium ε^* and kinetic ε_K separations, δ_0 is the initial isotopic composition of the lake, $\delta_S = (\delta_I + mx\delta^*)/(1 + mx)$ is the steady-state isotopic composition that the lake approaches, $\delta^* = (h\delta_A + \varepsilon)/(h - \varepsilon)$ is the limiting isotopic composition under local atmospheric conditions, δ_A and δ_I are the isotopic compositions of atmospheric moisture and inflow, respectively, and $x = E/I$ is the fraction of lake water lost by evaporation. The approach, which incorporates the Langmiur-type resistance model of Craig and Gordon (1965) for describing isotopic fractionation at the air–water interface, is a realistic approximation for lakes where isotopic enrichment occurs following pronounced hydrological events such as snowmelt in nival regimes (Gibson *et al.*, 1996a) and following regulation of rivers to form new artificial reservoirs (Zimmerman, 1979). Values of $\varepsilon^*(T)$, where *T*, the mean air temperature, and ε_K are adopted from Gonfiantini (1986), where ε_K is selected to be representative of fully turbulent conditions in the boundary layer. General forms of the isotope mass balance equations are summarized in Gonfiantini (1986).

Two separate approaches were considered, as follows.

(i) Base case. A simplified model, which assumes no surface or groundwater inflow or outflow, in which only additions to the lake by precipitation are considered ($\delta_I = \delta_P$). Accordingly, base case calculations are made by solving Equation (1) assuming $E = I$ for individual time-steps of up to three weeks. This simplified approach differs slightly from that of Gibson *et al.* (1996a) but was possible because of low rates of inflow and negligible outflow. The model also assumes that volumetric changes have a negligible influence on isotopic enrichment in the lake. Trial and error values of $\bar{E}$ are used for each time interval to obtain the best-fit between δ_L modelled and δ_L observed. Required input parameters include: δ_0, $\delta_L(t)$, $\bar{\delta}_P$, $\bar{\delta}_A$, $\bar{h}$, $\bar{T}$; and *V*, where $\bar{i}$ refers to the interval mean value of parameter *i*. Output parameter is $\bar{E}$.

(ii) General case. Limits on groundwater inflow and outflow were evaluated using a general model similar to Equation (1) applied assuming $E = xI$, were *x* was fitted to evaporation estimated by the other methods, and $\delta_I = (P \cdot \delta_P + I_G \cdot \delta_G)/(I_G + P)$, where I_G is the groundwater inflow and δ_G is its isotopic composition. This permitted determination of the inflow, *I*, and a residual estimate of the outflow, *Q*, from the lake, assuming $I = Q + E$. Required input parameters include: δ_0, $\delta_L(t)\bar{\delta}_G$, $\bar{\delta}_P$, $\bar{\delta}_A$, $\bar{h}$, $\bar{T}$, *V* and $\bar{E}$. Output parameters are $\bar{x}$, $\bar{I}$ and $\bar{Q}$.

Although isotopic analysis included both $\delta^{18}O$ and δ^2H only estimates for $\delta^{18}O$ are presented owing to the less predictable behaviour of δ^2H on time-scales of less than about 50 days (see Gibson *et al.*, 1996a). As shown later, analysis of δ^2H is nevertheless prerequisite to distinct labelling of evaporation enrichment effects.

Water balances

A simple water balance method was applied to estimate evaporation, E, according to

$$E = P - \mathrm{d}V/\mathrm{d}t \tag{2}$$

where P is the precipitation rate falling on the lake surface and $\mathrm{d}V/\mathrm{d}t$ is the rate of change in the lake water level. Although this simplified approach neglects the influence of basin hypsometry, and surface and groundwater exchange, the method was applied as a comparative benchmark because of its common application in monitoring tailings ponds in northern Canada.

Penman combination method

Evaporation was also calculated from hourly meteorological observations by the Penman combination method (Chow *et al.*, 1988), which relies on determination of latent heat transfer using a combined energy partitioning and aerodynamic transfer approach. Similar to the Priestley–Taylor method, which has been widely applied in experimental studies in northern Canada (e.g. Rouse, 1990), this method was selected since it was found to yield more conservative results by about 10% (Reid, 1994). Details of the approach used in this study have been described elsewhere (Reid, 1997).

Climatological estimates of lake evaporation

Field-based estimates of lake evaporation were also compared with pan-derived lake evaporation estimates from the Yellowknife Airport weather station. Raw monthly pan evaporation is converted to lake evaporation (as reported in the Canadian Atmospheric Environment Service climate archives) using an algorithm found to be fairly reliable for shallow lakes (see Trivett, 1983). The standard algorithm used in Canada, according to Trivett (1983) is

$$E_L = 0{\cdot}7[E_P + 0{\cdot}00642p\alpha_p(0{\cdot}37 + 0{\cdot}0025U_p)T_d] \tag{3}$$

where E_L and E_p are lake evaporation (mm) and pan evaporation (mm), respectively; the station pressure $p(\mathrm{kPa}) = 101{\cdot}325(1 - 0{\cdot}00002257Z)^{5{\cdot}25}$, where Z is the station elevation station (m); α_p is the fraction of advected energy (class A) used for evaporation, given by

$$\alpha_p = 0{\cdot}35 + 0{\cdot}01044T_W + 0{\cdot}000559U_p \text{ if } 0 < U_p < 161$$

$$\alpha_p = 0{\cdot}35 + 0{\cdot}01044T_W + 0{\cdot}08 + 0{\cdot}000249(U_p - 161) \text{ if } 161 < U_p < 322$$

$$\alpha_p = 0{\cdot}35 + 0{\cdot}01044T_W + 0{\cdot}12 + 0{\cdot}000124(U_p - 322) \text{ if } 322 < U_p < 483$$

$$\alpha_p = 0{\cdot}35 + 0{\cdot}01044T_W + 0{\cdot}14 + 0{\cdot}000062(U_p - 483) \text{ if } U_p \geqslant 483$$

where U_p is the daily wind run across the pan and T_d is the mean temperature difference function, given by

$$T_d = (T_W - T_a)^{0{\cdot}88} \text{ if } T_W > T_a$$

$$T_d = (T_a - T_W)^{0{\cdot}88} \text{ if } T_W > T_W$$

$$T_a = 0 \qquad \text{if } T_W = T_a$$

and T_W and T_a are the mean pan water temperature (°C) and mean air temperature (°C), respectively.

Annual lake evaporation totals were compiled from monthly records of E_L obtained from the standard climate archives for the Yellowknife Airport weather station located 5 km from the study lake.

RESULTS AND DISCUSSION

Isotopic labelling of hydrological components and evaporation

On plots of $\delta^{18}0$ versus δ^{18}H (Figure 2), waters sampled from various sources in the Pocket Lake catchment and surrounding areas are shown to be distinctly labelled by their isotopic compositions. The meteoric water line (MWL), representing the mean trend of global precipitation (Craig, 1961), is included as a reference line commonly used for distinguishing between isotopic variations in precipitation input (shifts along the MWL) and evaporative isotopic enrichment (shifts below the MWL, along lines of reduced slope; see Gibson *et al.*, 1993). As shown, input sources, including snow, rain and groundwater, normally plot close to the MWL reflecting only negligible exposure to evaporation. However, some rain samples do plot significantly below the MWL reflecting alteration of their isotopic composition by evaporation, presumably during rain-out through unsaturated air (see Gat, 1980). Groundwater samples plot close to the value of mean annual precipitation collected at the Yellowknife climate station (GNIP, 1996), and intermediate between snow and rain collected during the course of the study. Groundwater samples collected within 1–2 m of Pocket Lake (denoted lake margin groundwater) plot below the MWL and close to the isotopic composition of lake water, suggesting that they are derived largely from the recharge of lake water to groundwater in the near-lake margins (e.g. Krabbenhoft *et al.*, 1990). This effect diminishes rapidly with distance from the lake, however, such that enriched water is not found beyond 2 m from the lake shore.

Water samples from Pocket Lake, and other lakes and rivers in the Yellowknife area, plot below the MWL along a local evaporation line (LEL) and are evidently isotopically enriched by evaporation (Figure 2b). Based on the degree of offset from the MWL, it is evident that the fraction of water lost by evaporation (E/I) is larger for Pocket Lake than for typical lakes and river basins in the Yellowknife area (see Gibson *et al.*, 1993). This is consistent with historical records and aerial surveys, which suggest that Pocket Lake is an anomalously high closure lake.

Temporal isotopic variations

Lake water (δ_L) typically undergoes pronounced isotopic enrichment (20–30 times analytical uncertainty of δ^{18}O) in response to cumulative evaporation loss over the course of individual seasons (Figure 3). Input of isotopically depleted snow (and snowmelt runoff), ranging from –23 to −34‰ in δ^{18}O (see Figure 2) serves to reset lake water to less enriched δ values each spring and prevents attainment of isotopic steady state. δ_L typically shifts to more depleted values near the end of the open water period owing to lower rates of evaporation and stable or increasing rates of inflow.

The isotopic composition of rainfall is shown to be highly variable on the time-scale of several days to several weeks, reflecting synoptic-scale variations in the local climate. The isotopic composition of groundwater is typically depleted relative to rainfall, reflecting snow and rain sources, and its compositional variability is predictably diminished with respect to rainfall as a result of storage effects. The isotopic composition of atmospheric moisture (δ_A) is also shown to be highly variable, and, at times, is temporally well correlated with variations in the isotopic composition of rainfall (Figure 3).

Evaporation estimates and intercomparisons

Evaporation from Pocket Lake is estimated for each sampling time interval, as shown in Figure 3, using the isotope mass balance method, the water balance method and the Penman combination method. Isotopic estimates (denoted δ^{18}O balance) are determined using the base case model assuming only precipitation input. Cumulative comparisons between evaporation totals estimated from the various methods during 1991–1996 are illustrated in Figure 4.

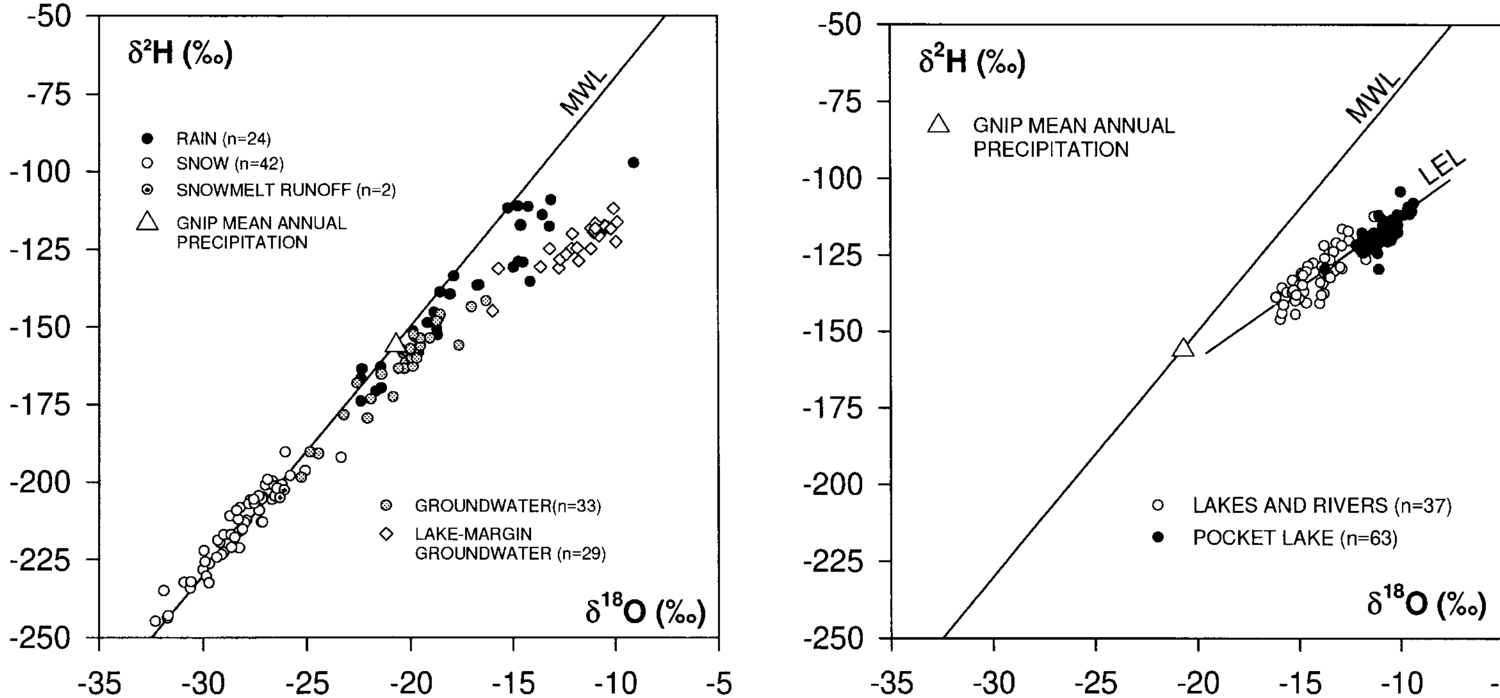

Figure 2. Plots of $\delta^{18}O$ versus $\delta^{2}H$: (a) showing distinct isotopic signatures of rain, snow, snowmelt runoff, groundwater, lake margin groundwater and the mean isotopic composition of annual precipitation at Yellowknife, 1989–1992 (GNIP, 1996); and (b) showing isotopic enrichment by evaporation in Pocket Lake and lakes and rivers in the Yellowknife area. Note that the MWL is the meteoric water line of Craig (1961); LEL is the local evaporation line determined by regression of data for lakes and rivers. See text for discussion

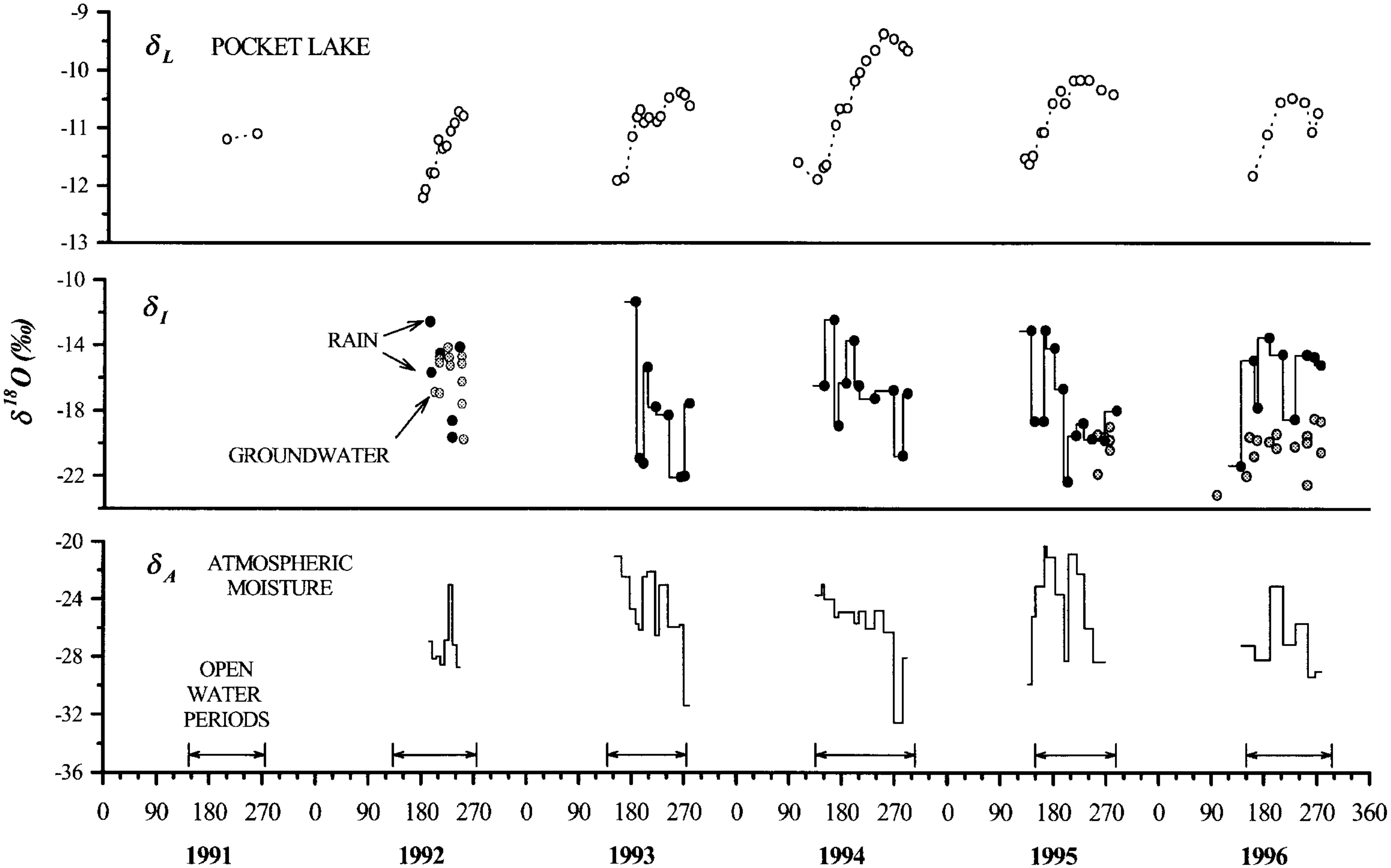

Figure 3. Temporal isotopic variations in Pocket Lake (δ_L), input sources (δ_I), including rain and groundwater, and atmospheric moisture (δ_A). Note that the seasonal isotopic enrichment cycles of Pocket Lake reflect changes in the water balance regime, as isotopic enrichment by evaporation is balanced by inflow. Input of isotopically depleted snowmelt at the beginning of the thaw season resets the isotopic composition of the lake to lower values each spring. Maximum isotopic enrichment is observed for 1994, the warmest and driest year in 48 years of record at Yellowknife. See text for discussion

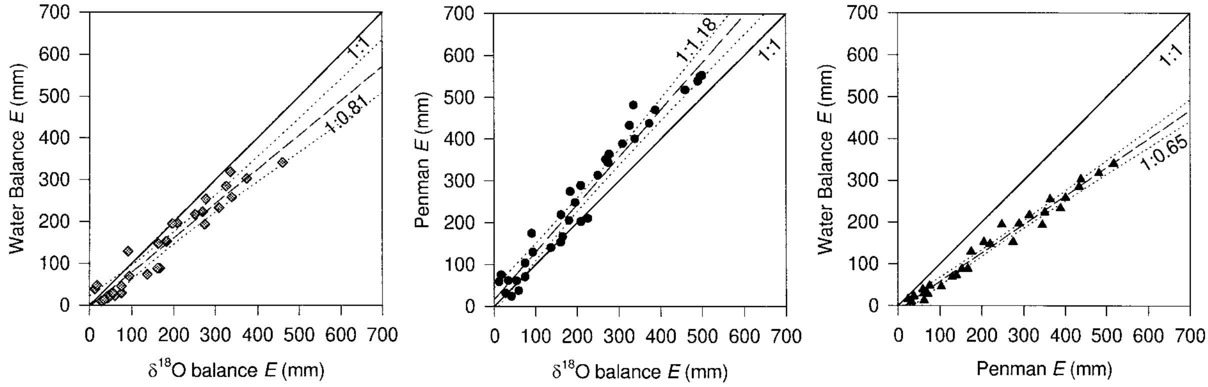

Figure 4. 1 : 1 plots of cumulative evaporation (mm) for the various methods computed over intervals used for the isotope mass balance calculations. Note dashed lines are the regression lines (with mean trends indicated) and dotted lines are the 99% confidence intervals, which reveal that the differences are significantly different from the 1 : 1 trend. See text for discussion

Overall, the water balance method is found to be the most conservative. On average, water balance estimates are 81 and 65% of the isotopic and Penman combination methods, respectively. The Penman method is shown to be the least conservative method, and overpredicts evaporation relative to the isotopic method by an average of 18%. Notably, isotopic estimates are shown to be intermediate between the water balance and Penman estimates.

Systematic differences between methods, which are supported at the 99% confidence level by the regressions shown in Figure 4, are undoubtedly rooted in the physical basis of the various approaches. Micrometeorological methods such as the Penman method, where evaporation fluxes are evaluated at point, can be predisposed to overestimating lake evaporation when instrumentation is located near the lake shore and prone to advection of sensible heat from the surrounding landscape (Rouse, 1990). In the present study, siting of the instrumentation near the lake shore was made mainly for practical reasons, since floating platforms are generally not a feasible option for monitoring remote, abandoned mine sites in northern Canada where equipment must be transported by small aircraft, erected in several hours and infrequently maintained. Considering previous studies in northern Canada, where imperfect fetch was analysed (Gibson *et al.*, 1996b), it is likely that overestimation was less than about 15–20%.

Residual estimates of evaporation from the water balance benefit from better spatial weighting than micrometeorological methods, since they reflect evaporation integrated over the lake surface. However, such estimates can be generally unreliable in cold regions owing to substantial uncertainty associated with the measurement of surface inflow and outflow (e.g. Gibson *et al.*, 1996b). In the present study, where inflow and outflow are restricted to subsurface pathways, uncertainty is probably less than $\pm 20\%$.

Isotope mass balance estimates are also spatially weighted over the lake surface and are therefore not susceptible to imperfect fetch conditions. Relative to standard methods, such as Bowen ratio energy balance, a similar isotopic approach has been shown to predict evaporation to within about $\pm 15\%$ for a small arctic lake (Gibson *et al.*, 1996a). Herein, the simplified approach assuming negligible groundwater exchange is likely to be accurate to within about $\pm 20\%$ based on comparisons with the other methods (Figure 4).

Importantly, the use of several methods has improved the confidence in the results, and has enabled the evaporation rate to be bracketed within practically useful limits.

Limits of groundwater exchange

As a test on the limits of groundwater exchange in the lake, a general form of the isotope mass balance [see Equation (2)] was applied to estimate the fraction of lake water lost by evaporation using the Penman E, which is evaluated independent of groundwater. The fraction of water lost by evaporation (x) was previously assumed to be equal to 1 in the base case model. Accordingly, if E is fitted to the Penman results, an average

Table II. Summary of Yellowknife Airport and Pocket Lake evaporation estimates. Mean daily evaporation rates are estimated based on the open water period given in Table III

Year	Yellowknife Airport		Pocket Lake evaporation				
	Pan evaporation uncorrected (mm)	Pan-calculated lake evaporation (mm)	1. $\delta^{18}O$ balance (mm)	2. Penman (mm)	3. Water balance (mm)	4. Average (1)–(3) (mm)	Mean daily rate (mm/d)
1991	638	492[a]	–	–	–	–	3·2[b]
1992	558	480[a]	–	–	–	–	3·7[b]
1993	650	377	335	–	–	335	2·3
1994	661	378	500	553	427	493	3·1
1995	579	439	388	480	334	401	2·5
1996	606	418	324	483	–	404	2·7
Mean	615	403	387	494	381	408	2·7

[a]Not included in calculation of the mean. [b]Early July to mid-September observations only.

estimate of x of 0·95 is obtained, suggesting that liquid outflow may be of the order of 5% of the total inflow. Considering that the Penman method is prone to overestimation of evaporation, it is probably accurate to assume that this is an upper limit for groundwater exchange in the lake. Lake margin groundwater, which is isotopically similar to Pocket Lake water (Figure 2) confirms that lake water infiltration or movement may be occurring at very slow rates.

Open water evaporation totals

Available evaporation estimates for complete open water periods are presented in Table II. Class-A pan estimates and lake evaporation estimated from a standard pan-to-lake algorithm at the nearby Yellowknife weather station (pan-calculated lake evaporation) are also given for comparison. Overall, pan-to-lake climate algorithms are found to yield similar results to field-based methods when averaged over several years, which lends support to the use of such algorithms for calculating mean annual small lake evaporation for nearby areas. However, because of a lack of climate stations with evaporation pans in northern Canada (Latham, 1988), it is unlikely that such methods can be employed to improve the understanding of evaporation at remote, unmonitored locations. Pan-calculated estimates of lake evaporation are moderately higher for the period 1991–1996 than reported by den Hartog and Ferguson (1978), which perhaps reflects below-normal precipitation and relative humidity during this time.

The pan-to-lake algorithms are evidently less successful in predicting evaporation for individual years (Table II). For a worst-case scenario, a difference of 30%, or 115 mm, is evident between average field-based estimates and the pan-derived estimates for 1994. In the same year, a difference of 46%, or 175 mm, is evident between Penman estimates and the pan-derived estimates. As a result, pan-to-lake algorithms are likely to be less reliable for predicting interannual variations in water levels and lake volume fluctuations in shallow reservoirs. Errors in evaporation of 115–175 mm for individual years, which is of the same order of magnitude as the annual snow water equivalent, may be a particular concern for estimating peak water levels during snowmelt the following spring, which is an important consideration for determining if episodic discharge will occur from tailings ponds.

Implications for tailings pond containment

Using average values for the field-based evaporation estimates, and precipitation recorded at the Yellowknife climate station, E/P ratios were computed for the 1993–1996 period at Yellowknife (Table III). As shown in Table III, evaporation exceeds precipitation by 28–157% over this period. Based on these results, it appears that there is a high potential for total containment of tailings pond waste water following cessation

Table III. Estimated open water period, lake evaporation and evaporation to precipitation ratios (E/P) for the indicated years. Precipitation is based on Yellowknife Airport climate records for each water year totalled from October to September. Estimates of the maximum catchment area : lake area ratio required to maintain a negative water balance (evaporation exceeds outflow) are also given based on a realistic water balance scenario outlined in the text

Year	Open-water period (days)	Lake evaporation (mm)	Precipitation (mm)	E/P	Estimated maximum catchment : lake area ratio for zero discharge
1993	143	335	261	1·28	0·57
1994	160	493	192	2·57	3·2
1995	158	401	251	1·60	1·2
1996	152	404	239	1·69	1·4

of mining activities in Yellowknife. In principle, a well-designed tailings pond with a small catchment area (i.e. negligible terrestrial runoff) could be maintained without liquid discharge. A natural example of such a reservoir is Pocket Lake, which has had no surface outflow since 1975 (Canada, Environment Canada, 1996), and has a catchment area roughly equivalent to the lake surface area. In contrast, the $E/P < 1$ computed for the Lupin mine site, situated 375 km north of Yellowknife, suggests that total containment of wastes is not possible in this nearby tundra region.

A more realistic water balance scenario for tailings design in the Yellowknife area is also considered which incorporates the effect of terrestrial runoff. This scenario assumes:

(i) 50% of all annual precipitation falls as snow;

(ii) all snow water equivalent on the terrestrial portions of the basin enters during the melt (gross oversimplification, but conservative given the problem); and,

(iii) no precipitation on the terrestrial portion of the basin enters the lake during the summer [which is unlikely given the amount of exposed bedrock around the lake, but compensates somewhat for the overestimate of input in (ii)].

Based on this scenario, which is found to be a good approximation of the Pocket Lake water balance, the maximum catchment area:lake area ratio was estimated for each year based on the condition of a negative water balance (i.e. $E \geqslant 1{\cdot}5P$; or annual evaporation exceeds precipitation + watershed runoff). As shown in Table III, tailings impoundments could be conservatively designed such that the watershed area constitutes less than 55% of the tailings pond surface area, to ensure that this condition is met on an annual basis. An average value of this ratio computed for the period 1993–1996 of 155% suggests considerable leeway for maintaining total containment in tailings ponds with somewhat larger catchment areas, providing adequate reservoir storage capacity is incorporated in the design.

While tailings pond containment potential is apparently high in the Yellowknife area and low in the Lupin area, further research will be required to predict the containment potential in remote intermediate areas that contain gold, base metals and diamond deposits under rapid development by mining and exploration companies.

CONCLUDING REMARKS

Recent Arctic environmental assessments have suggested that the overall effect of mining and other local contaminants is far outweighed by deposition of airborne contaminants from industrial activities outside the Arctic (e.g. Canada, 1996). Nevertheless, the expanded scope and intensity of current mining development and exploration is a reminder that local sources may pose a long-term and increasing hazard, particularly in districts of rapid growth such as the continental Arctic of the Northwest Territories (e.g. Canada, 1996).

Lessons from the past are clear; 109 of 1200 Superfund sites on the US national priority list in 1990 were mining related, with average clean-up costs approaching US$30 million per site (Biggs, 1990).

Improving estimates of evaporation is a first step towards improving guidelines for the design and management of tailings ponds in northern Canada. This study has established that field observations are beneficial to proper characterization of evaporation and its interannual variability, processes that are likely to control long-term and annual fluctuations in the water levels of tailings ponds. The next step will certainly be to incorporate realistic evaporation estimates in predictive models to obtain optimal strategies for tailings pond containment. A better understanding of acid mine drainage and its effect on the northern environment is also required and is now under development (Canada, Indian and Northern Affairs Canada, 1994).

Although the isotopic method, at its current stage of development, is not strictly a competitive method relative to micrometeorological methods for estimating evaporation from a single lake, it does offer considerable potential for future studies examining water balance differences in nearby reservoirs. This study has further improved the understanding of controls on isotopic variability and has demonstrated that the isotopic method provides results comparable to water balance and micrometeorological methods. Future studies at Yellowknife will include parallel isotopic monitoring of Pocket Lake and a nearby tailings pond, to aid in the assessment of potential groundwater seepage in the latter reservoir.

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