

HYDROLOGY AND GEOCHEMISTRY STUDIES, DISTRICT OF KEEWATIN, NORTHWEST TERRITORIES, CANADA

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Abstract

A program of study was initiated in the Barrenlands of the central District of Keewatin, in midsummer 1988, to investigate hydrologic processes in an area underlain by continuous permafrost. Reconnaissance-level isotopic and geochemical sampling of surface and active-layer waters was conducted within an 850 km² watershed.

The ¹⁸O and ²H contents of surface waters and groundwaters reflect seasonal variations in the isotopic composition of precipitation, and subsequent alteration due to evaporation and mixing. Snow and ground-ice fall close to the Global Meteoric Water Line ($\delta^2\text{H} = 8\delta^{18}\text{O} + 10$). Most samples (including surface and subsurface waters) plot off the GMWL, defining a local evaporation line having a slope of 5.5. Scatter about this line results from mixing between components of the local hydrologic system.

Hydrogeochemical data provide additional information about the evolution and mixing of waters in the study area. Although all waters have low total ion concentrations (conductivity < 70 $\mu\text{S}\cdot\text{cm}^{-1}$), waters in the active layer become progressively enriched in most major ions through interaction with overburden materials. Surface waters reflect mixing between groundwaters and more dilute precipitation, consistent with isotopic evidence.

Résumé

Un programme de recherche a été commencé dans le centre du District de Keewatin en 1988 pour étudier les processus hydrologiques dans une région de pergélisol continu. Un échantillonnage isotopique et géochimique de reconnaissance des eaux de surface et des eaux du mollisol a été accompli dans un bassin hydrographique de 850 km².

La teneur en ¹⁸O et en ²H des eaux de surface et des eaux souterraines reflète les variations saisonnières dans la composition isotopique de la précipitation (eau de pluie), et un autre changement subséquent dû à l'évaporation et au mélange des eaux. La neige et la glace du sol sont près de la ligne des eaux météoriques globale (Global Meteoric Water Line = GMWL; $\delta^2\text{H} = 8\delta^{18}\text{O} + 10$). La composition de la plupart des échantillons étudiés (incluant les eaux de surface et les eaux souterraines) est hors de la ligne GMWL, et délimite une ligne d'évaporation locale ayant une pente de 5.5. La dispersion des points autour de cette ligne est le résultat du mélange entre les composantes du système hydrologique local.

Les données hydrogéochimiques nous donnent des informations sur l'évolution et le mélange des eaux dans la région étudiée. Quoique la concentration totale en ions soit faible pour toutes les eaux (conductivité < 70 $\mu\text{S}\cdot\text{cm}^{-1}$), les eaux dans le mollisol deviennent progressivement enrichies avec la plupart des ions majeurs par l'interaction avec le sol. Les eaux de surface reflètent le mélange des eaux souterraines avec les eaux de précipitation plus diluées, ce qui est en accord avec les données isotopiques.

Introduction

Preservation of natural water quality is a critical component of environmental protection in all regions of Canada. Degradation of water quality has long been recognized as an issue of national concern, although awareness of the risks and extent of groundwater contamination (see Cherry, 1987) has lagged well behind recognition of anthropogenic influence on atmospheric and surface waters. In spite of the vast area and sparse settlement, the surface and subsurface waters of Canada's

North are also vulnerable to contamination from various sources, particularly those related to resource exploitation such as mining and pipeline construction.

Protection of water quality in the North presents a special challenge for several reasons, including the harsh climatic conditions, the existence of permafrost, and the relative paucity of basic hydrologic information from the diverse range of arctic environments (notwithstanding the notable efforts of previous workers: e.g. Michel, 1982; Roulet & Woo, 1986; Dyke & Egginton, 1988).

Additional impetus for improved understanding of Northern hydrology arises from the sensitivity of Northern environments to anticipated global warming, which is likely to be most rapid and pronounced at high latitudes (Luckman, 1989). Accelerated ground-ice melting and consequent slumping and slope failure, in response to unusually elevated summer temperatures in the High Arctic in 1988, may portend the profound hydrologic changes that would accompany projected warming (Edlund, 1989).

In this paper we report results from the first (reconnaissance) phase of a longer-term project aimed at obtaining an understanding of the hydrology of a tundra watershed in the District of Keewatin. The study applies the tools of physical hydrogeology and hydrogeochemistry to investigate the movement, mixing, and chemical evolution of water (in the surface and subsurface) as it passes through the local hydrologic system. An important component of these studies is the establishment of a water balance (relying mainly on isotopic techniques) for the system under present hydrometeorological conditions. In addition to fundamental documentation of natural history, the knowledge gained from examination of this undisturbed watershed will be directly applicable to problems associated with anticipated mine site development in the region, such as that of the nearby Kiggavik uranium deposit (Caine & Brown, 1987).

Study Area

Field work was carried out between July 28 and August 11, 1988, in the (informally named) "Whatever" Lake watershed, central District of Keewatin, N.W.T. (62° 41'N; 97° 03'W; fig. 1). The study site lies in the zone of continuous permafrost, approximately 170 km north of the present tree-line.

The main watershed is a headwater basin having a surface area of 850 km² (fig. 1), characterized by gently rolling topography with a maximum relief of 108 m. The watershed drains through Whatever Lake, which covers about 3.2% of the basin area. The lake has a maximum depth of 32 m and an average depth of about 10 m (Edwards, 1980). Lakes and ponds throughout the region are typically much smaller and reach maximum depths of less than 10 m (Edwards *et al.*, 1987; Shilts *et al.*, 1976). All sampling was conducted within the catchment area of Whatever Lake, including detailed work within a 3.5 km² subbasin (fig. 1).

The study site is situated within the Churchill Structural Province of the Canadian Shield. Bedrock consists mainly of foliated and migmatized granitic to dioritic gneiss (Eade, 1984), which is discontinuously mantled by glacially derived overburden. The drift cover averages about 3 m thick and contains prominent components of sedimentary and felsic volcanic rocks of the Proterozoic Dubawnt Group, which crops out to the north and west of the study area (Kaszycki & Shilts, 1979). Till and derived materials of similar texture in the active layer are highly prone to liquefaction and exhibit development of mudboils on land (Shilts, 1974), and rib-and-trough and stone circle patterns in shallow lake areas (Shilts & Dean, 1975).

Meteorological records from 1951 to 1980 are available for Baker Lake (175 km NNE) and Ennadai Lake (280 km SSW). During this period, the region received an average of 235 to 295 mm of precipitation annually (59% as rain), and mean annual temperatures between -12 and -13 °C (Environment Canada, 1982). Mean monthly temperatures above freezing were recorded for the June through September period.

Analytical Methods

Isotopic analyses of water samples were performed at the Environmental Isotope Laboratory, University of Waterloo, following the methods of Epstein & Mayeda (1953) for ¹⁸O/¹⁶O and Coleman *et al.* (1982) for ²H/¹H. Results are expressed in conventional "δ" notation as deviations in permil (‰) from the SMOW standard. Cited values for δ¹⁸O and δ²H have analytical uncertainties of ± 0.2 ‰ and ± 4 ‰, respectively.

Major ion analyses of water samples were performed at the Water Quality Laboratory, University of Waterloo, by ion chromatography (anions) and atomic absorption spectrometry (cations). Alkalinity (as HCO₃⁻) was determined in the field by colorimetric (brom cresol green-methyl red indicator) titration of unfiltered 25 ml aliquots to approximately pH 4.5.

VEGETATION AND ACTIVE LAYER PROPERTIES

The tundra surface is dotted by sparse dwarf birch and willow shrubs, which may occur in dense thickets along stream courses. Sphagnum moss, sedge grasses, labrador tea, blueberry and lichen form an organic mat about 5 to 25 cm thick. The soil is intensively cryoturbated, and dead roots and wedges of organic material are commonly found at tens of centimetres depth.

Overburden in the study area is predominantly till, typical of that described at other central Keewatin sites (e.g. Shilts, 1971; Shilts, 1974; Kaszycki & Shilts, 1979). Buried and exposed boulder fields are a common feature of the area. The till matrix (< 2 mm) is generally sandy (32 to 57%), with moderate to abundant silt (35 to 54%) and minor clay (8 to 14%).

Saturated hydraulic conductivities (K) at selected piezometer sites were estimated by falling head tests. K varied from 10⁻⁴ to 10⁻⁶ cm.s⁻¹, at depths between 50 and 150 cm, in agreement with those predicted from grain size distributions (Hazen's power-law relation; Freeze & Cherry, 1979). Elevated K values may occur locally because of flow through thawed ice lenses, held open by pore-water pressures (Dyke & Egginton, 1988).

STABLE ISOTOPE DATA

A plot of δ¹⁸O vs δ²H for sampled waters (fig. 2) readily identifies the influence of evaporation and the effects of

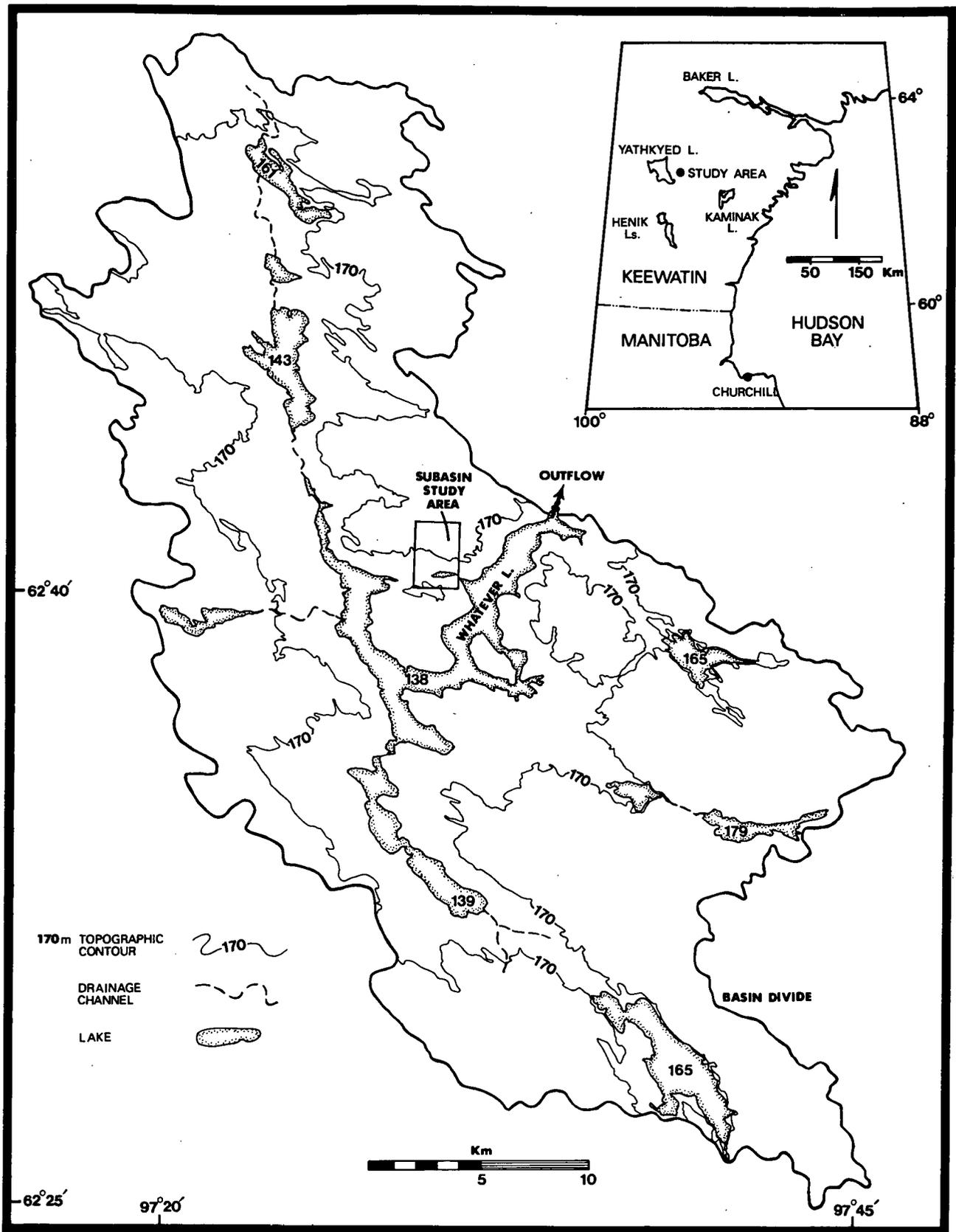


Figure 1. A simplified map view of the Whatever Lake watershed, highlighting the major lakes and the 170 m topographic contour. Selected lake elevations are also shown.

mixing from different sources within the hydrologic system. Unevaporated meteoric waters are generally recognized by their proximity to the Global Meteoric Water Line (GMWL; Craig, 1961) whereas waters altered directly by evaporation or mixed with evaporatively enriched water plot to the right of the GMWL. Based on this criterion, snow from three levels in a perennial snowbank, one groundwater sample, and several ground-ice samples (average value given in figs. 2 and 3) bear little or no evidence of evaporation effects. Most samples of surface waters and groundwaters from the study area cluster to the right of the GMWL along a well-defined trend representing a local evaporation line (LEL) having a slope of 5.5 (fig. 2). Different degrees of evaporative enrichment can be recognized by displacement along the LEL from the GMWL; points at the upper end of the line originated from shallow tundra ponds having limited surface inflow or outflow and show strong evaporation effects. Points at the lower end include groundwaters and stream waters, as well as larger lakes such as Whatever Lake, where the influence of evaporation is mitigated by substantial throughflow and(or) a larger volume-to-surface area ratio.

A single, short storm permitted collection of only one rain sample during the brief field visit. This sample is somewhat problematic since it plots significantly to the right of the GMWL, close to the suggested evaporation trend (fig. 2). In the absence of additional summer-rain samples it is difficult to assess the significance of this result; it may reflect the existence of a "local meteoric water line" offset to the right of the GMWL, as suggested on figure 3. Possibly analogous offsets for summer precipitation at other Canadian sites are believed to reflect aspects of the local climatic regimes or vapour histories (Fritz *et al.*, 1987). Results from sampling conducted in 1989 (Burse, in prep.) will test this presumption.

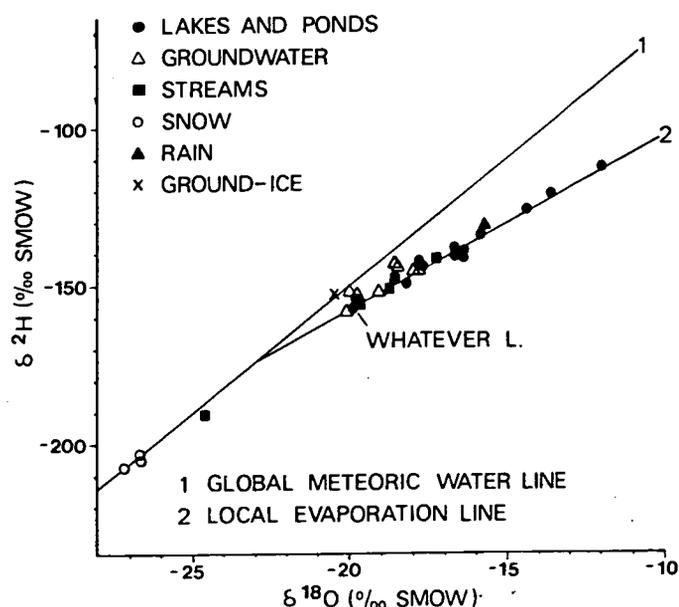


Figure 2. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for selected waters relative to the Global Meteoric Water Line (GMWL); the data points represent the full range of variation.

The isotopic data clearly document mixing between waters from different pools in the local hydrologic system. A stream water sample ($\delta^{18}\text{O} = -24.6\text{‰}$, $\delta^2\text{H} = -191\text{‰}$), for instance, was fed by a mixture of evaporatively enriched pond water ($\delta^{18}\text{O} = -18.3\text{‰}$, $\delta^2\text{H} = -149\text{‰}$) and unaltered snowmelt ($\delta^{18}\text{O} = -26.8\text{‰}$, $\delta^2\text{H} = -206\text{‰}$), evidently in a 35:65 ratio. The isotopic composition of stream water at another location ($\delta^{18}\text{O} = -17.3\text{‰}$, $\delta^2\text{H} = -142\text{‰}$) suggests a 62:38 mixture of pond water ($\delta^{18}\text{O} = -16.4\text{‰}$, $\delta^2\text{H} = -139\text{‰}$) and local groundwater ($\delta^{18}\text{O} = -17.8\text{‰}$, $\delta^2\text{H} = -144\text{‰}$).

Although the period of observation and sampling was brief, the isotopic data (and meteorological records) permit a qualitative hydrologic assessment of the study watershed. Input from precipitation is weighted toward summer and fall rain (57%), and most has been recorded for the July through September period, July being the wettest month (Environment Canada, 1982). Isotopically depleted winter precipitation enters the system as a pulse in the spring and early summer, likely running off rapidly into lakes and ponds prior to significant thawing of the active layer. Input from rainfall, on the other hand, is probably split between direct run-off and recharge to the active layer prior to freeze-up. Progressive deepening of the active layer during the thaw season gradually releases stored precipitation (as melting ground-ice), which mixes with groundwater, and may contribute to evaporatively enriched surface waters along local flow systems.

The intersection of the LEL with the GMWL yields an estimate for the bulk composition of the total water input to the watershed (δ_p : $\delta^{18}\text{O} = -22.9\text{‰}$, $\delta^2\text{H} = -174\text{‰}$; see fig. 3). δ_p is lighter than the isotopic signature of meteoric water suggested by the mapped summary of Fritz *et al.* (1987) for this area ($\delta^{18}\text{O} = -17$ to -19‰).

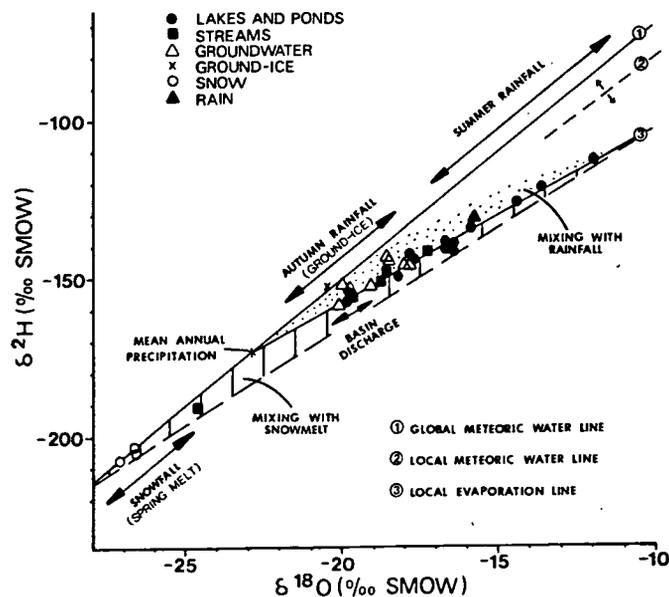


Figure 3. Summary of the hydrologic components for the Whatever Lake watershed and mixing relationships between unaltered (i.e. not evaporated) meteoric waters and evaporated surface and subsurface waters, as defined by $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values.

The isotopic data can also provide an estimate of the overall water balance in the study area, since snowmelt and rainfall inputs are uniquely labelled and can therefore be traced through the system, and the loss of vapour is identified through evaporative enrichment of residual water. Preliminary isotope-mass balance calculations suggest that evaporation accounts for about 15% of the output from the watershed, which compares with the value of about 25% estimated by Roulet & Woo (1986) in similar terrain using entirely different techniques.

WATER CHEMISTRY

Various geochemical surveys conducted by the Geological Survey of Canada have investigated the chemistry of surface waters in the District of Keewatin. Lakes and ponds commonly display low to neutral pH values (5.9 to 7.3) and low electrical conductivity (13 to 40 $\mu\text{S}\cdot\text{cm}^{-1}$) (Edwards *et al.*, 1987; Shilts *et al.*, 1976). Surface waters in the present study area displayed pH values between 6 and 7.7 and conductivities of 7 to 28 $\mu\text{S}\cdot\text{cm}^{-1}$. Subsurface waters had a narrower range of pH (5.8 to 7.0), presumably owing in part to elevated CO_2 partial pressures *in situ*, and a broader range of electrical conductivity (10 to 70 $\mu\text{S}\cdot\text{cm}^{-1}$), indicative of higher solute concentrations. Processes such as cation exchange and mineral dissolution are probably important. Much greater solute concentrations in active layer groundwaters were inferred from conductivity measurements on Banks Island, N.W.T. (up to $\approx 1000 \mu\text{S}\cdot\text{cm}^{-1}$), by Lewkowitz & French (1982).

Water quality parameters for subsurface and surface water samples from the Whatever Lake watershed are summarized in table I and selected chemical analyses are presented in table II. The high charge balance errors for the latter data are thought to be related to the alkalinity determinations performed in the field, which may have had interference from elevated dissolved organic carbon contents. Gran titration procedures carried to lower pH (3.0) may help to minimize this error in future investigations (Sullivan *et al.*, 1989).

Mineral saturation calculations suggest that Fe^{2+} is a particularly important ion in the subsurface waters (Burse, in prep.). The existence of groundwater discharge is

commonly indicated by the presence of iron oxyhydroxide precipitates, such as that observed in the bed of a stream adjacent to the piezometer from which sample GB-23 was obtained (total Fe = 13 ppm; see table II).

Surface and subsurface waters can be distinguished chemically on the basis of differing ionic ratios. The cation triangle (fig. 4) shows that most groundwaters and groundwater-fed streams are dominated by Ca^{2+} over Mg^{2+} and $\text{Na}^+ + \text{K}^+$. The Cl^- versus K^+/Na^+ plot (fig. 5) suggests a distinction between surface and subsurface waters at a K^+/Na^+ ratio of about 0.4. Relatively high Cl^- contents detected in several waters from the watershed may be associated with ionic redistribution during freezing (Anisimova, 1973).

Mixing relations among different waters in the local hydrologic system are less readily discerned from the water chemistry than from the isotopic data, owing to non-conservative behaviour of most ions (excepting Cl^-) and pH. Nevertheless, mixing between dilute precipitation and comparatively concentrated groundwaters appears to account

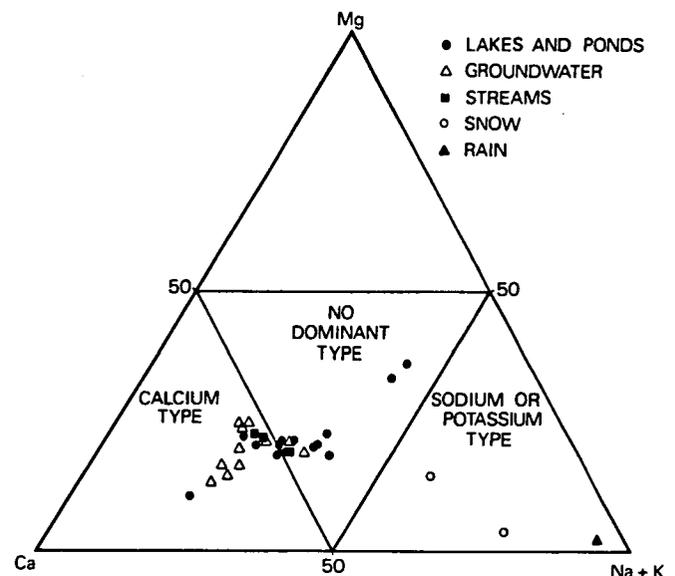


Figure 4. Cation triangle displaying the relative percentage distribution of Ca^{2+} , Mg^{2+} , and $\text{Na}^+ + \text{K}^+$ (from $\text{mg}\cdot\text{l}^{-1}$ data) for sampled waters.

Table I. Average water quality data for the various water types sampled. Electrical conductivities have been corrected to 25 °C. TDS refers to the calculated summed ion concentration excluding HCO_3^- .

SAMPLE TYPE (average of)	FIELD TEMPERATURE (°C)	pH	ELECTRICAL CONDUCTIVITY ($\mu\text{S}\cdot\text{cm}^{-1}$)	TDS ($\text{mg}\cdot\text{l}^{-1}$)
SNOW (2)	0.2	6.8	2 TO 5	1.0
RAIN (1)	—	—	—	11.8
LAKES (13)	13.0	7.2	7 TO 28	14.3
STREAMS (3)	10.2	6.6	9 TO 18	5.9
SEEPS AND SPRINGS (6)	10.0	6.3	10 TO 34	25.4
PIEZOMETER (2)	13.0	6.5	70	89.5

Electrical conductivity has been corrected to 25 °C. TDS refers to the calculated, summed ion concentration excluding HCO_3^- .

for the intermediate composition of surface waters in the watershed (tables I and II). Ongoing studies (Bursey, in prep.) using both chemical and isotopic data will help to further define interactions between subsurface and surface waters in the study area.

Summary

Surficial materials in the Whatever Lake watershed have characteristically low saturated hydraulic conductivities below the organic horizon. Hydraulic conductivity values predicted from grain-size analyses and piezometer response tests range between 10^{-4} and 10^{-6} cm.s $^{-1}$.

Snow, ground-ice, and a groundwater sample are characterized by close correlation with the GMWL. Rain water from a short summer storm plotted to the right of the GMWL and may be part of a local meteoric line, similar to those observed for other stations in Canada.

Isotopic evidence indicates that surface waters and some groundwaters are influenced by evaporative enrichment. Most samples fall close to a distinct local enrichment line to the right of the GMWL having a slope of 5.5. Evaporation likely accounts for 15% to 25% of the total output in the local hydrologic system.

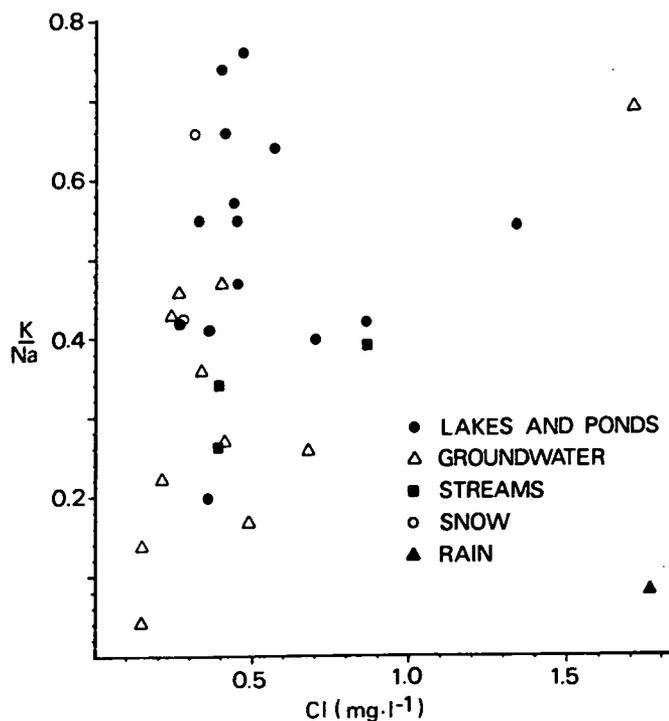


Figure 5. Cl $^{-}$ content versus K $^{+}$ /Na $^{+}$ (from mg.l $^{-1}$ data) for sampled waters.

Table II. Major ion analyses of selected water samples (mg.l $^{-1}$). Colorimetric titrations were performed on 25 ml unfiltered aliquots. The charge balance errors were determined using field alkalinities.

SAMPLE NO.	TYPE	Ca $^{2+}$	Mg $^{2+}$	Na $^{+}$	K $^{+}$	Fe(T)	Mn(T)	Si $^{4+}$
GB 1	Sn	.1	.0	.2	.1	-	-	
GB 28	R	.1	.1	2.5	.2	1.0	-	1.4
GB 30	L	.7	1.1	1.0	.4	-	-	.2
GB 4	L	1.3	.5	.6	.3	.1	.0	.2
GB 11	L	1.2	.6	.6	.4	-	-	.8
GB 3	St	1.3	.5	.6	.2	.2	.0	.2
GB 14	St	2.1	.9	.8	.3	.1	-	1.2
GB 12	G	2.7	.7	.8	.2	.2	-	.9
GB 23	G	3.5	1.6	1.3	.2	13.2	.8	3.1
GB 20	G	6.5	1.4	1.3	.9	.2	-	2.7

SAMPLE NO.	TYPE	HCO $_3$ FIELD	HCO $_3^{-}$ CALCULATED (0% error)	Cl $^{-}$	SO $_4^{2-}$	CHARGE BALANCE ERROR
GB 1	Sn	-	0.0	.3	.2	5.2
GB 28	R	-	5.9	1.8	.7	-
GB 30	L	26.0	9.2	.3	.4	43.2
GB 4	L	4.2	6.9	.9	.2	20.1
GB 11	L	5.2	5.8	.4	1.2	6.4
GB 3	St	4.0	6.4	.9	.5	16.1
GB 14	St	9.2	11.4	.5	.7	12.0
GB 12	G	8.5	12.9	.7	.6	17.3
GB 23	G	37.0	51.6	.5	.4	16.0
GB 20	G	19.0	28.6	1.7	.4	18.1

Symbols Sn = snow R = rain L = lake or pond St = stream G = groundwater

Colorimetric titrations for HCO $_3^{-}$ were performed on unfiltered 25 ml sample aliquots. The charge balance errors were determined using field alkalinities.

Consideration of ion ratios allows differentiation of these chemically dilute waters. With longer residence times, groundwaters become increasingly dominated by Ca⁺, probably through cation exchange and mineral dissolution. Surface water chemistry is mainly controlled by mixing between dilute precipitation and more concentrated groundwaters. Elevated Cl⁻ concentrations in several waters are presently unexplained but may be related to freezing processes.

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