08-287

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By:
James W. Roy and Masaki Hayashi

HYDROLOGICAL PROCESSES
Hydrol. Process. 22, 2838–2846 (2008)
Published online 21 April 2008 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6995

Groundwater exchange with two small alpine lakes in the Canadian Rockies

James W. Roy[1]* and Masaki Hayashi[2]

[1] *National Water Research Institute, Environment Canada, Burlington, ON, Canada L7R 4A6*
[2] *Department of Geoscience, University of Calgary, Calgary, AB, Canada T2N 1N4*

Abstract:

Recent studies have shown that groundwater can play an important role in the water balances of alpine lakes. However, a number of uncertainties remain, including (i) whether substantial groundwater exchange is common or rare, (ii) what types of interactions may occur, and (iii) what are the important factors affecting groundwater exchange. This understanding is important for predictions of hydrology, water chemistry and ecology patterns and interactions in the headwaters of mountain watersheds. These questions were addressed for the Lake O'Hara watershed in the Canadian Rockies, using lake water balances applied to two alpine lakes. The results were compared to those of a previously published water balance for the larger Lake O'Hara. Groundwater was a major component of the water balance in both lakes, but the type of groundwater interactions differed despite the lakes being similar in size and located only 500 m apart. The water balance for Opabin Lake was dominated by the groundwater components, with alternating periods of substantial groundwater inflow and outflow. Meanwhile, groundwater inflows were much greater than outflows for Hungabee Lake, with net groundwater fluxes of similar magnitude as the incoming streams. The study results suggest that both groundwater inflow and outflow occurred through a moraine field for Opabin Lake, while groundwater inflow occurred from a talus slope to Hungabee Lake. Thus, the presence of coarse overburden deposits in contact with alpine lakes is a potentially important factor affecting groundwater exchange, which in turn affects the hydrology and ecology of mountain watersheds. Copyright © 2008 John Wiley & Sons, Ltd and Her Majesty the Queen in right of Canada.

KEY WORDS mountain hydrology; talus; moraine; glacier; water balance; ground water

Received 14 June 2007; Accepted 17 December 2007

INTRODUCTION

Lakes play an important role in the hydrologic cycle of mountain watersheds, being a source of water to rivers and aquifers that supply local communities and those in neighbouring lowlands. They can act as a natural water reservoir, providing storage and delaying the release of water from the spring freshet. This is an important consideration, as an increase in global temperature will shift the peak in mountain river runoff earlier in the year, away from the peak demand of summer and autumn (Barnett *et al.*, 2005). In fact, Hauer *et al.* (1997) suggest that mountain lakes, as well as streams, may be among the most sensitive indicators of changing global climate. Lakes also affect the overall stream ecology within mountain watersheds. For example, mountain lake outlet streams can display less variability and more algal species diversity than other types of mountain streams (Hieber *et al.*, 2001).

Groundwater exchange with lakes can influence their biogeochemical status, shoreline vegetation zones and fish-spawning sites (Hayashi and Rosenberry, 2002). However, there have been few studies on the groundwater exchange with mountain lakes, especially in high-elevation headwater watersheds, though field studies have shown that the groundwater contribution to streams in mountainous areas is often substantial (Campbell *et al.*, 1995; Ward *et al.*, 1999; Michel *et al.*, 2000; Sueker *et al.*, 2000; Clow *et al.*, 2003; Huth *et al.*, 2004; Liu *et al.*, 2004).

A number of studies focused on other topics, such as watershed hydrology and the geochemistry and ecology of lakes, provided some evidence that groundwater—lake interactions might be important (Stoddard, 1987; Albrecht, 1999; Campbell *et al.*, 2004), while others suggested they were minor (Kattelmann and Elder, 1991; Michel *et al.*, 2002). In addition, groundwater piping through moraine dams has been linked to outbursts of some alpine lakes (see review by Clague and Evans, 2000). However, none of the above studies were designed to directly address the issue of groundwater exchange with headwater mountain lakes. Gurrieri and Furniss (2004) conducted the first such study on four alpine lakes in Montana, U.S.A, using a tracer mass-balance analysis. Three were considered flow-through lakes, and one was deemed a groundwater recharge lake. Hood *et al.* (2006) estimated groundwater exchange for Lake O'Hara in the Canadian Rockies from the lake water balance, and showed that groundwater contributed at least 25–50% to the total input of water to the lake.

An improved understanding of larger scale issues, such as climate-watershed interactions, downstream water

* Correspondence to: James W. Roy, National Water Research Institute, Environment Canada, Burlington, ON, Canada L7R 4A6.
E-mail: jim.roy@ec.gc.ca

supply management, and the management of mountain parks and forests, depends on the prediction of hydrology, water chemistry and ecology patterns and interactions for entire watersheds. Increasingly, researchers are attempting to identify patterns among monitored watersheds that can be applied more generally, based on information available in air photos, satellite pictures, and geologic maps (Soranno *et al.*, 1999; Kamenik *et al.*, 2001). For mountain settings, application of this concept to lake systems in remote basins would require the ability to predict, without on-site measurements, the importance and type of groundwater exchange for individual alpine lakes. To achieve this goal, an improved understanding of the subsurface hydrology associated with these lakes is needed. Relevant questions to be addressed include (i) substantial groundwater exchange common or rare, (ii) the types of interactions that may occur, and (iii) what factors (e.g. lake attributes, geology, position in the watershed) control the importance and type of groundwater exchange? This study addresses these questions for the Lake O'Hara watershed using a lake water balance approach for two alpine lakes, with comparisons to Lake O'Hara (Hood *et al.*, 2006). While similar studies on other watersheds will be needed to address these questions on a global scale, this work will add to the body of knowledge and assist in the development of an improved conceptual model for the hydrology of high-elevation mountain lakes.

STUDY AREA

The Lake O'Hara watershed is located in Yoho National Park, British Columbia, Canada (51·21 °N, 116·19 °W). The 14-km^2 watershed encompasses rugged terrain and ranges in elevation from 2010 m to 3490 m.a.s.l. (Figure 1). It is comprised of sedimentary bedrock, predominantly of thickly bedded quartzite and quartzose sandstone separated by thin layers of siltstone, sandstone and grey shale, of the Cambrian Gog Group with carbonate rocks at the summit of most of the peaks (Price *et al.*, 1980; Lickorish and Simony, 1995). Approximately 20% of the watershed is sub-alpine coniferous forest and 80% is alpine. The alpine terrain consists of exposed bedrock (40%), talus slopes (25%) and glacial moraine materials (15%). Mean annual precipitation is estimated to be 1100–1500 mm, depending on elevation (MSC, 2005). The watershed is snow covered for about 8 months of the year and contains Opabin Glacier and a few other small glaciers (Figure 1). There is visual evidence of buried ice within the proglacial moraine surrounding Opabin Glacier.

The two lakes under investigation, Hungabee Lake and Opabin Lake, reside in the alpine area of the watershed (Figure 1). Both lakes are about 0·026 km^2 in area, but Opabin Lake is deeper, with a maximum depth approaching 10 m compared to 2 m for Hungabee Lake. The Opabin Lake is at an elevation of 2266 m.a.s.l. and is nearest to Opabin Glacier. It has no outflow

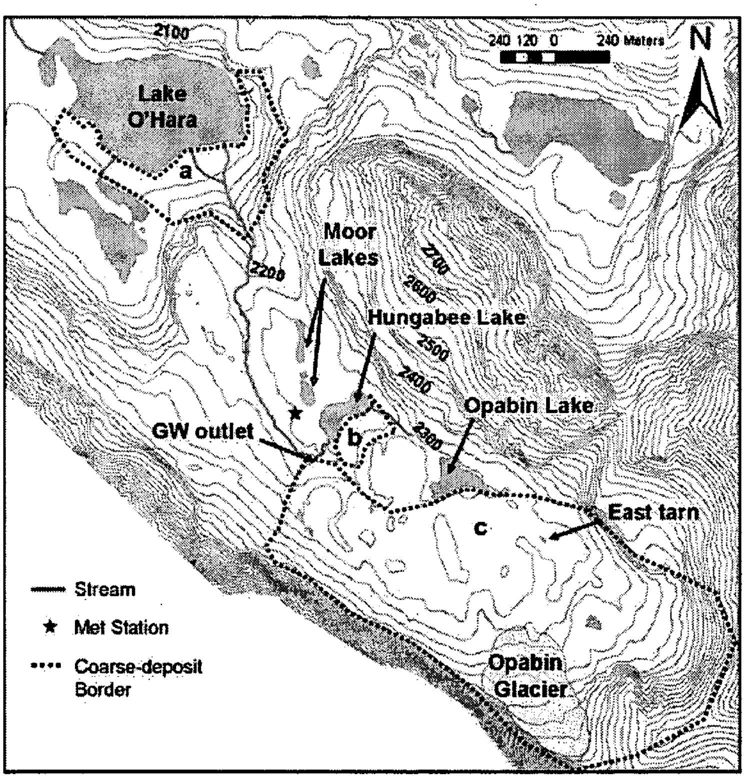

Figure 1. Map of the three alpine lakes of interest in the Lake O'Hara Research Basin, showing the extent of coarse deposits in contact with each ((a)—talus slopes around Lake O'Hara; (b)—talus slope below bedrock knoll by Hungabee Lake; (c)—moraine-talus field around Opabin Glacier). Contours of 25-m are shown

DOI: 10.1002/hyp

streams, but does have one inflow streamlet (discharge less than 0·0025 $m^3 s^{-1}$) sourced from the north-east ridge. Hungabee Lake is at an elevation of 2225 m.a.s.l., about 500-m down-valley of Opabin Lake. The lakes are separated by a reigel (bedrock knoll). Hungabee Lake has an inflow stream, which is also fed from the north-east ridge, and an outflow stream on the south-west side. It has a few intermittent inflow streamlets (north-west and north-east sides) as well. In contrast to these two lakes, Lake O'Hara is situated at the base of the watershed, at an elevation of 2012 m.a.s.l. It is a much larger lake, with an area of 0·26 km^2 and a maximum depth of 42 m. It is fed by four inflowing creeks and is drained by a single outlet.

All three lakes are generally ice-free from June or July until October. Findings of Reasoner and Hickman (1989) for Opabin Lake and Lake O'Hara and initial observations for Hungabee Lake indicate that each have >1 m of low-permeability lake bottom sediments. Together, these lakes are representative of many of the alpine lakes in headwater watersheds of the Rocky Mountains, being formed in topographic depressions created by glacier activity, with Opabin Lake partially dammed by glacial moraine material. Supplementary measurements were performed on a small pond between Opabin Glacier and Opabin Lake, referred to as East Tarn, Figure 1).

METHODS

Water balance calculation

Groundwater exchange with Hungabee Lake and Opabin Lake was investigated using a volumetric water balance equation (Hood *et al.*, 2006):

$$\Delta S = \sum Q_{\text{in}} + P - E - Q_{\text{out}} + Q_{\text{GWin}} - Q_{\text{GWout}} \quad (1)$$

where ΔS is the change in lake storage, $\sum Q_{\text{in}}$ is the sum of incoming stream water, P is precipitation, E is evaporation, Q_{out} is outgoing stream water, Q_{GWin} is incoming groundwater, and Q_{GWout} is outgoing groundwater. Overland runoff is not included in Equation (1) as there was little evidence of it once the snow at the edge of the lakes had melted away. Thus, it was not deemed significant over the time period considered.

Since groundwater inflow and outflow were not measured directly, the water balance equation was simplified as follows:

$$\Delta S = \sum Q_{\text{in}} + P - E - Q_{\text{out}} + Q_{\text{res}} \quad (2)$$

where the groundwater residual, Q_{res}, is the net amount of groundwater inflow (positive values) or outflow (negative values).

The change in lake storage was calculated from the measured change in the lake's water level, assuming a constant lake area. The error associated with this assumption was based on differences in lake area from spring and autumn and was estimated from air photo and GPS data to be <5% and <3% for Opabin and Hungabee, respectively. The water level in each lake was measured every 10 min with a pressure transducer (In-situ Inc., Mini-Troll). Values were averaged over 1-hour intervals to minimize the effects of surface waves and seiche, though these are not expected to be substantial due to the small size of the lakes. The water level of the East Tarn (Figure 1) was monitored in a similar manner.

Stream discharge for flows greater than 0·002 $m^3 s^{-1}$ was measured weekly by the area-velocity method using a hand-held propeller flow meter (Global Water FP101), with rocks moved from the sediment bed at the measured cross-section. The stream gauging error for the relatively small streams in this study is estimated about 10–25%, based on multiple-measurement gauging events along short sections of the streams. For lower flows (i.e. minor streamlets), the order of magnitude of discharge was visually estimated; the errors on these values likely reached 50%, but their contributions to the water balances were minor.

Air temperature and precipitation were measured with a thermistor and a tipping bucket rain gauge, respectively, at a meteorological station located 50 m west of Hungabee Lake (Figure 1). Evaporation from the lakes was estimated using the Priestley and Taylor (1972) method with $\alpha = 1{\cdot}26$, where α is a dimensionless constant. Rosenberry *et al.* (2004) determined that this method provided reasonably accurate values of evaporation in small lakes and wetlands. Hood *et al.* (2006) calculated evaporation rates for Lake O'Hara of about 1 to 2 mm day^{-1} for June—September, 2005, and noted that it was an insignificant component of the lake water balance. A similar result was expected for the lakes in this study. However, evaporation losses from each lake were calculated for the month of August, 2005, to be certain. The required measurements include net radiation, air temperature and heat storage in the lake. Net radiation data for Lake O'Hara (Hood *et al.*, 2006) was used for both alpine lakes. Air temperature was measured at the Opabin met station. The change in lake heat storage was calculated from temperature depth profiles for each lake. These calculations likely overestimate evaporation as losses of stored heat through surface water and groundwater advection are ignored.

Water sampling and analysis

Measurements and sampling were performed at multiple locations and depths for Hungabee Lake and Opabin Lake, as well as their inflow and outflow streams, and East Tarn (Figure 1). Stream water temperature, pH and electrical conductivity (EC) were measured in-stream using hand-held meters and with depth in the lakes using a Hydrolab Datasonde 4 or a YSI Model 6600 EDS Sonde. Measured EC values were standardized to 25 °C (Hayashi, 2004). Water samples were collected in new or acid-washed polyethylene bottles, pre-rinsed 3 times with sample water, with deep (8–9 m) lake samples first collected using a van Dorn sampler (Geo Scientific Ltd). Samples were stored in an ice-packed

DOI: 10.1002/hyp

cooler during transport and then at 4 °C in a refrigerator in the laboratory. Portions of the samples were filtered (0·45 μm) for major ions (acidified to pH <2 for cations), and analysed by ion-exchange chromatography. An unfiltered portion of these water samples underwent Gran titration (0·160 N sulfuric acid, Hach Company) for alkalinity, which was assumed equal to the bicarbonate concentration, given the near-neutral pH levels.

RESULTS AND DISCUSSION

Groundwater and Opabin Lake

The water level for Opabin Lake, measured with respect to a local benchmark, exhibited a general decline of 3 m or more from June to September in both years, but with changes (rises and falls) of 0·5 m (500 mm) in less than a week being common throughout the field seasons (Figures 2(c) and 3(c)). The calculated August evaporation rate was about 2 mm day^{-1} for Opabin Lake (14 mm over a week), which is similar to the values for Lake O'Hara (Hood *et al.*, 2006). Weekly precipitation rarely surpassed 30 mm, while the equivalent streamlet inflow ranged from about 50 (spring freshet) to <10 mm in a week. Evaporation, direct precipitation and inflow from the small streamlet each had a negligible effect on the daily water balance calculations for Opabin Lake. Thus, the substantial changes in lake storage (i.e. water level) were controlled, almost exclusively, by the groundwater components, which shows that groundwater plays a dominant role in the lake water balance.

Water property measurements provide support for this conclusion. For instance, the inflowing streamlet had EC values of 10 to 20 μS cm^{-1} and pH consistently around 7, while EC and pH values for rain and melted snow were even lower. In contrast, the EC and pH of Opabin Lake water were typically around 60 to 80 μS cm^{-1} and between 8 and 9, respectively, with the higher values associated with waters at greater depth. The lake became stratified over the summer, with a temperature difference of around 4 °C and a depth to thermocline of 3–4 m. This also corresponded to a greater range in chemistry values. The lake values likely reflect mineral dissolution during sub-surface flow, and are similar to those of East Tarn (EC between 60 to 120 μS cm^{-1} and pH between 8 and 9), which has no inflow streams.

The calculated net groundwater flux (groundwater residual) surpassed 0·1 m^3 s^{-1} on a number of occasions in both 2005 (Figure 2(d)) and 2006 (Figure 3(d)). It is important to note that the actual groundwater inflow may be greater than the values represented by the positive net groundwater flux (net inflow) and that this difference may change non-linearly over the season. Likewise, the maximum groundwater outflow may have been greater than the 0·077 m^3 s^{-1} calculated for July 3, 2005, and may have occurred on a different date. The uncertainty of the net groundwater flux calculations was determined from the errors associated with the measurements of the water balance components using the standard method of uncertainty propagation (Harris, 1991). The only error of consequence was the estimated 5% error in the lake area

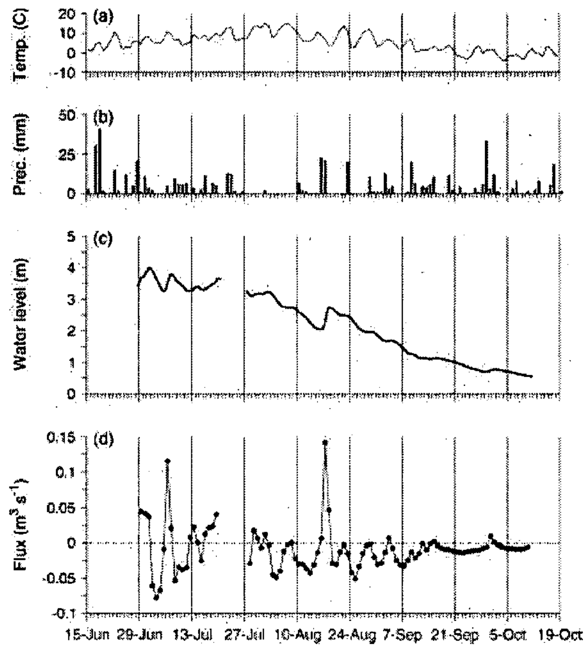

Figure 2. Time series associated with Opabin Lake for 2005: (a) daily average air temperature; (b) precipitation measured at the Opabin met station; (c) lake water level with respect to a local bench mark; and (d) net groundwater flux (zero flux level marked; error bars do not pass beyond symbol height)

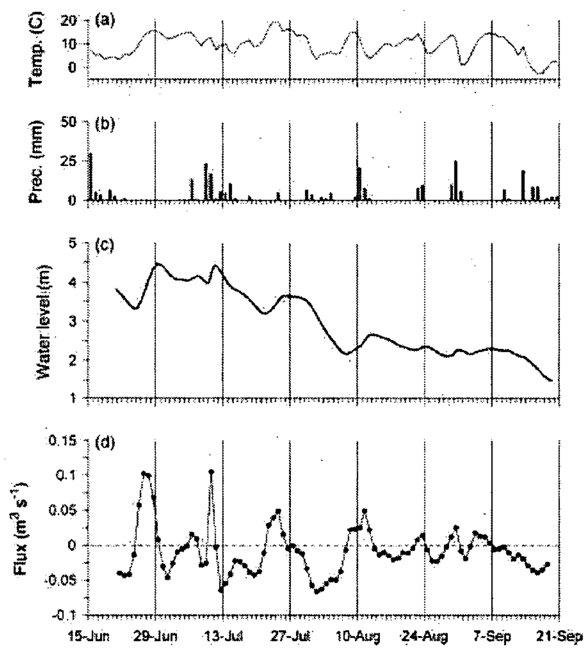

Figure 3. Time series associated with Opabin Lake for 2006: (a) daily average air temperature; (b) precipitation measured at the Opabin met station; (c) lake water level with respect to a local bench mark; and (d) net groundwater flux (zero flux level marked; error bars do not pass beyond symbol height)

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when applied to the conversion of the lake level to lake storage, which led to an uncertainty between 5 and 6% for the net groundwater flux (combining all the errors). However, error bars are not plotted in Figures 2 and 3 because they are of a similar size to that of the symbols.

The groundwater flux switched between net inflow (positive) and outflow (negative) repeatedly throughout both field seasons (Figures 2(d) and 3(d)), which shows that both groundwater inflow and outflow were important components of the water balance. The groundwater flux was negative in approximately 75% of the observation period in both years, indicating that the lake was serving as a net source of groundwater to the surrounding area most of the time, although it is likely that inflow and outflow were occurring simultaneously at different areas within the lake (i.e. it was acting as a flow-through lake). The groundwater flux was positive only during storm events and periods of high air temperature (i.e. high melt rate of snow and glacier), indicating that the inflow substantially exceeded the outflow during these events. To understand the nature of the lake level recession during non-event periods, we may use a technique similar to baseflow recession analysis of stream hydrographs. Figure 4 shows a plot of net groundwater flux versus Opabin Lake water level for 2005 data (2006 is similar but the data are less extensive) for 'baseflow' periods, which we defined as having air temperatures below 10 °C and little rainfall (<0·2 mm) recorded during the preceding 48 hours. A linear trend of increasing magnitude of net groundwater outflow with increasing lake level is evident, suggesting that the groundwater outflow during the baseflow period is controlled by the hydraulic gradient between the lake and a relatively constant water table boundary located some distance away from the lake.

The lack of data on groundwater levels and chemistry make it difficult to determine the spatial distribution of groundwater inflow and outflow within the lake and along the shoreline. However, substantial flow from underlying fractured bedrock through >1 m of low permeability lake bottom sediments seems improbable. The north-east side of the lake is lined by steeply rising bedrock, with a small area of talus that is unlikely to have the ability to supply such large groundwater fluxes. The west side is comprised of bedrock (rising to the reigel) with a thin soil cover. That leaves the large moraine field to the south (Figure 1) as the most likely candidate for capturing the required infiltration and rapidly transferring water to and from the lake. The high permeability associated with moraine materials (Parriaux and Nicoud, 1988) suggests it could fulfill this role.

There is also some field evidences linking groundwater exchange with the moraine. First, there are increases in the net groundwater flux during rain-free and high-temperature periods when there was very little snow left on the ground (e.g. 22–23 July and 3–5 Sept, 2006 Figure 3). The likely source of this groundwater is melt water from Opabin Glacier (about 700 m away, Figure 1), which was seen infiltrating into the ground at the glacier's edge at these times. Also, the water level of East Tarn behaved similarly to that of Opabin Lake. Figure 5 shows the rate of change of the water level of Opabin Lake and East Tarn for a 32-day interval through August and September, 2006. A daily pattern in the water level data is apparent through periods with minimal rain, though the moraine was essentially snow free. The matching patterns demonstrate that both water bodies connected to the moraine responded similarly to water inputs, including melting at Opabin Glacier. The water chemistry of Opabin Lake and East Tarn was very similar as well (Figure 6), with alkalinity levels reflecting the influence of carbonates, which are found in the moraine. These levels were much higher than those of the inflowing streamlet (same signature as Hungabee inlet stream; Figure 6) that is sourced from the north-east ridge. Therefore, the lake chemistry has a geochemical signature representative of the moraine as opposed to the north-east ridge. Finally, Roy and Hayashi (2007) provide evidence that water leaving Opabin Lake also flows through the moraine before discharging from a spring at its distal end.

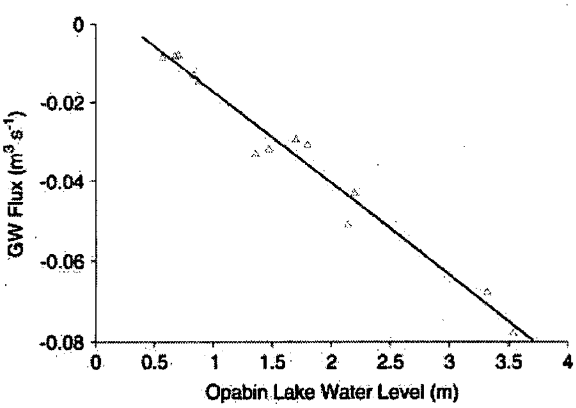

Figure 4. Scatter plot of the water level versus net groundwater flux for Opabin Lake in 2005 (symbols). The line indicates a possible linear relationship between groundwater outflow (negative net flux) and lake level, evident for times when inflow is likely at a minimum

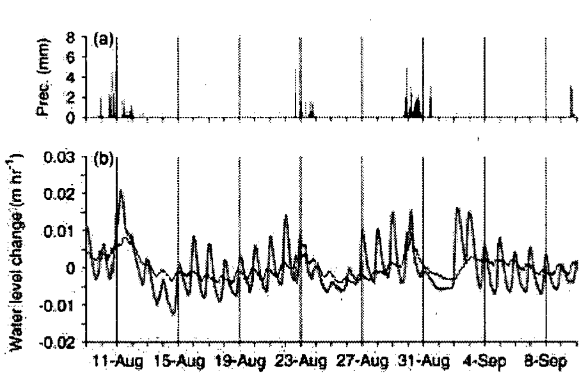

Figure 5. Hourly data from the 2006 field season for (a) precipitation (rain); and (b) change in water level of Opabin Lake (thin black line) and East Tarn (thick grey line)

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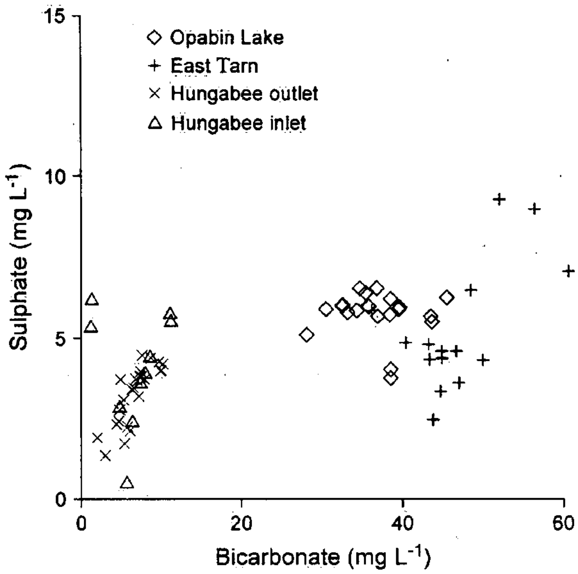

Figure 6. Graph showing the relationship between bicarbonate (based on alkalinity) and sulphate for water samples from Opabin Lake, the East Tarn, and the Hungabee Lake inlet and outlet streams, for 2005 and 2006. Opabin Lake data includes samples collected at surface and depth (8–9 m); the average deviation between same-day samples was <3·0 mg L^{-1} bicarbonate and <0·3 mg L^{-1} sulphate

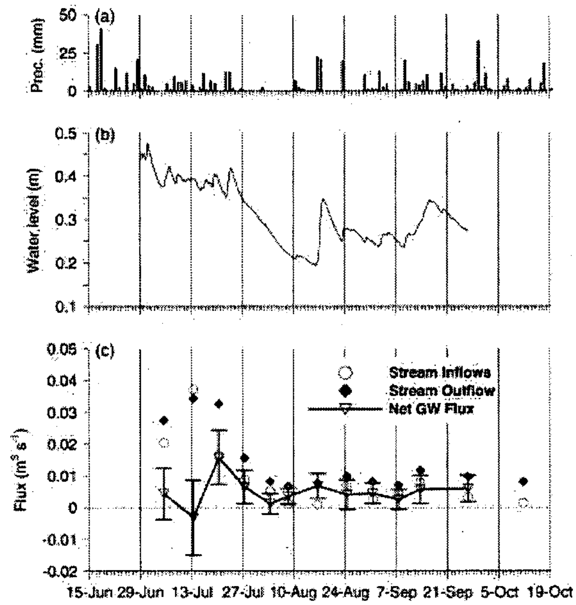

Figure 7. Time series associated with Hungabee Lake for 2005: (a) precipitation measured at the Opabin met station; (b) lake water level with respect to a local bench mark; and (c) stream inflow and outflow fluxes. and net groundwater flux for Hungabee Lake (zero flux level and error bars marked)

Groundwater and Hungabee Lake

The water balance for Hungabee Lake suggests that groundwater played a significant role in both field seasons, with net groundwater fluxes commonly of a similar magnitude as the total discharge of inflowing streams (Figures 7(c) and 8(c)). The calculated August evaporation rate was about 3 mm day^{-1} for Hungabee Lake, which is similar to that of Opabin Lake and Lake O'Hara (Hood *et al.*, 2006). Evaporation and precipitation played a minor, though non-negligible, role in this water balance, with each contributing an average of 0·001 m^3 s^{-1}. Stream flow contribution and lake storage changes were more and less important, respectively, than for Opabin Lake. Calculation of the net groundwater flux indicates that groundwater inflow was equivalent to at least 39 and 35% of the total inputs, on average, for 2005 and 2006, respectively, which is similar to the values reported for Lake O'Hara (Hood *et al.*, 2006).

This water balance was calculated on a weekly basis to match the measurement interval for stream discharge. This is expected to increase the uncertainty in flow calculations by 15%, based on a comparison of manual and continuous flow measurements at the Hungabee outlet stream. Otherwise, the uncertainty around the net groundwater flux calculation was determined in a similar manner as for Opabin Lake (Harris, 1991). However, the uncertainty for Hungabee Lake was much greater, as illustrated by the error bars in Figures 7 and 8. This was largely due to the increased importance of stream flows, which were affected by the discharge measurement errors (assumed 20% for streams, 50% for streamlets) and weekly based estimates (15%), compounded by the fact that both stream inflow and outflow appear in the water balance. The net groundwater flux calculated for 14 July 2005, is believed to have been affected by a substantial rain event. The discharge measurement of the inflow stream coincided with the peak storm flow, while that of the outflow stream did not, resulting in an underestimate of the net groundwater flux for that week.

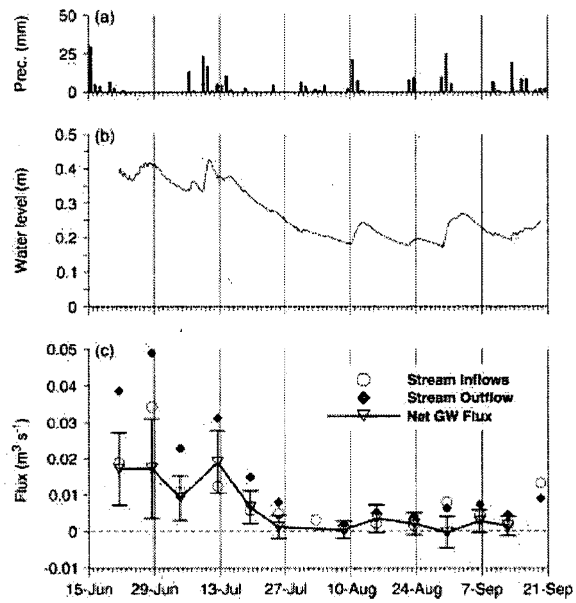

Figure 8. Time series associated with Hungabee Lake for 2006: (a) precipitation measured at the Opabin met station; (b) lake water level with respect to a local bench mark; and (c) stream inflow and outflow fluxes. and net groundwater flux for Hungabee Lake (zero flux level and error bars marked)

DOI: 10.1002/hyp

Generally, the net groundwater flux remained positive throughout both field seasons (Figures 7(c) and 8(c)), indicating that groundwater inflow was consistently higher than outflow. Groundwater inflow was highest in June and July, during snow melt, but decreased substantially in August, with near-zero values occurring after extended periods without rain (e.g. 3 August 2005—Figure 7; 8 August 2006—Figure 8). This pattern suggests that inflowing groundwater flow paths are predominantly short and likely shallow, with little storage capacity in the surrounding area for providing base flow. The groundwater outflow from Hungabee Lake may be negligible, but this cannot be determined from the water balance. However, the low relief down-valley of the lake (Figure 1) suggests the hydraulic gradient for groundwater outflow would likely be small.

Hungabee Lake is only 500 m from Opabin Lake and is 40 m lower in elevation (Figure 1). Thus, its hydrologic position and the fact that Opabin Lake is losing water to the ground, would suggest that Opabin Lake or the moraine field around Opabin Glacier, could be the primary source of groundwater flowing into Hungabee Lake. However, there is no evidence of this. A plot of water chemistry (sulphate vs. bicarbonate in Figure 6) clearly shows that waters associated with Hungabee Lake are different from those associated with Opabin Lake and the moraine. This difference holds for the other major ions: calcium and magnesium. The samples from the main Hungabee inflow and the Hungabee outflow stream plot together, indicating no major change in the water signature due to the groundwater inputs. These two streams also had similar pH, between 6·8 and 7·5, compared to 8 to 9 for Opabin Lake, and followed a similar trend in EC, rising from 15 to 40 $\mu S\ cm^{-1}$ over the season (Figure 9), while Opabin Lake exhibited higher values of 60 to 80 $\mu S\ cm^{-1}$. The addition of similarly high-EC groundwater to Hungabee Lake would be expected to cause the outflow stream EC to be higher than the inflow stream EC. The small volumetric contribution from the low-EC streamlets would not be enough to balance the input of a high-EC groundwater. However, the outflow stream EC was similar, sometimes even lower, than that of the inflow stream. Also, little spatial variability of EC was measured across the lake (not shown) indicating that the lake was well mixed. Thus, this water chemistry data suggest that the groundwater entering Hungabee Lake has similar properties (e.g. EC and chemical composition) to those of the streams. This is a note-worthy point, as it is commonly assumed that groundwater will possess significantly more dissolved minerals than surface waters (e.g. Michel *et al.*, 2002).

The lake level hydrographs also suggest that the two lakes are not connected. For example, on July 22–23, 2006, the level of Opabin Lake increased during a period of high temperature and minimal rain (Figure 3(c)), indicating a response to melting at Opabin Glacier. The water level of Hungabee Lake did not respond to this glacier melt event or the elevated water level in Opabin Lake that it caused (Figure 8(b)). Thus, groundwater

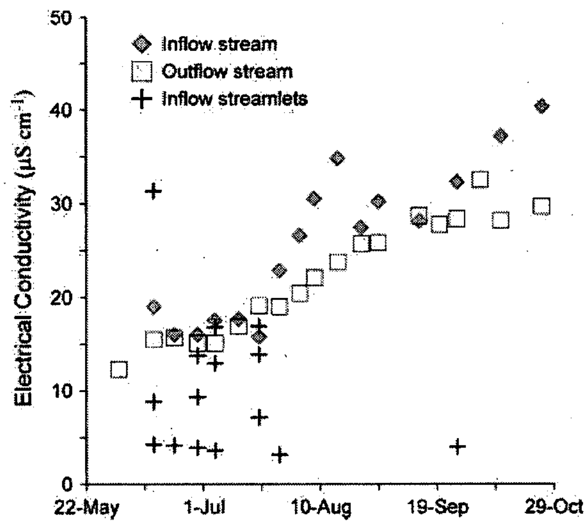

Figure 9. Temporal series of electrical conductivity for the two major streams (inflow and outflow) and the compilation of the small streamlets (all inflow) associated with Hungabee Lake for the 2006 field season

flow through the bedrock knoll that separates the two lakes appears to be restricted. Rather, the suspected similarity in groundwater chemistry to the inflow stream suggests that the groundwater flowing to Hungabee Lake is sourced locally through short flow paths. It is unlikely that much groundwater is flowing from the north, as the land is relatively flat there, though a small streamlet drains water from the Moor Lakes into Hungabee Lake. The west side of the lake holds the outlet stream, while the east side of the lake receives water from a number of small streamlets coming off the exposed bedrock ridge and minimal talus. Thus, the primary groundwater source is likely the vegetated talus slope to the south, which hangs down the edge of the bedrock knoll (Figure 1). Water has been observed dripping or seeping from the soil at the edge of the lake in this area during wetter periods, including during the spring freshet when snow near the lake shore had long melted. This suggests lateral sub-surface transport of melt water from further up on the vegetated talus slope. Interestingly, the prime candidate source area for groundwater is the only area that does not bear surface water, suggesting groundwater flow is sufficiently extensive and rapid for moving the infiltrated water down to the lake.

Coarse overburden materials and groundwater—lake exchange

The presence of highly permeable overburden materials (i.e. talus and moraine) adjacent to the lake appears to be an important factor controlling groundwater—lake exchange for both Opabin Lake and Hungabee Lake. Support for the importance of coarse overburden materials is provided by general observations in other high-elevation lake studies (Stoddard, 1987—talus; Albrecht, 1999—alluvial fans). Such materials have also been identified as important reservoirs of groundwater storage supplying mountain streams (Clow *et al.*, 2003). For Lake

DOI: 10.1002/hyp

O'Hara, field evidences of spring locations and groundwater discharge zones (Hood *et al.*, 2006; Roy *et al.*, in press) reveal groundwater discharging from overburden materials along the south and east sides of the lake (Figure 1), which are lined with talus slopes. Furthermore, the net groundwater flux in Lake O'Hara showed similarly timed fluctuations as the inflowing streams during periods affected only by glacier melt (Hood *et al.*, 2006, Figure 3). This response is likely the result of streambed infiltration from some or all of the streams as they cross talus areas at the south and east sides of the lake (Figure 1). It may be that the abundance of overburden material also influences groundwater exchange with these lakes. The levels of ground water exchange were apparently greater for Opabin Lake (max net influx of 0·15 $m^3 s^{-1}$) with its large surrounding moraine field than for Hungabee Lake (maximum net influx around 0·02 $m^3 s^{-1}$) with its small talus slope (Figure 1), though both lakes are the same size. The larger Lake O'Hara is also associated with a substantial volume of overburden (Figure 1); it had a maximum net influx of 1·3 $m^3 s^{-1}$ (Hood *et al.*, 2006), though the net influx per lake area was similar to that of Opabin Lake.

It also appears that high-elevation lakes without substantial groundwater exchange tend not to be associated with such overburden deposits. For example, Emerald Lake (Kattelmann and Elder, 1991) is largely surrounded by igneous bedrock (Figure 1 of Meixner *et al.*, 2004), while the lakes studied by Michel *et al.* (2002) occupy low-lying areas of a fractured basalt cap with minimal soil development. In both studies, groundwater exchange was deemed negligible. In addition, groundwater exchange, though significant, was generally orders of magnitude lower for the alpine and sub-alpine lakes studied by Gurrieri and Furniss (2004) than was observed for the lakes of the Lake O'Hara watershed. These lakes are situated in eroded fault zones in metasedimentary rocks, with some talus slopes but minimal glacial overburden.

Thus, the presence and, possibly, the abundance of overburden materials in contact with high-elevation mountain lakes appears to be an important factor controlling the degree and behaviour of groundwater-lake exchange in this watershed and others. No other consistent and significant factors, such as landscape position or lake area (identical for Opabin Lake and Hungabee Lake), were identified in this study. Although, the absence of streams may be a useful guide to identifying areas with ground water exchange, as neither the moraine nor the talus areas adjacent to Opabin Lake and Hungabee Lake, respectively, supported streams. However, the presence of streams should not be considered a limitation to having ground water exchange, as indicated above for the inflowing streams of Lake O'Hara feeding the groundwater system.

CONCLUSIONS

Water balances for two alpine lakes in the Lake O'Hara watershed showed that groundwater exchange with both lakes was important, and even dominant in the case of Opabin Lake. This is similar to the findings for Lake O'Hara (Hood *et al.*, 2006), which suggests that significant groundwater exchange with high-elevation mountain lakes may be more common than previously believed. However, the nature of this groundwater exchange was different between the two lakes, despite their similar size and close proximity. Opabin Lake repeatedly fluctuated between groundwater inflow being dominant and outflow being dominant, and is likely a flow-through lake. The groundwater regime of Hungabee Lake was dominated by inflows, with the net groundwater flux often of similar magnitude as the inflow from surface streams. And yet, groundwater exchange was associated with coarse overburden deposits for both lakes. The study findings suggest that groundwater inflow occurred from a talus slope for Hungabee Lake and a moraine field for Opabin Lake. It is likely that the substantial groundwater outflow from Opabin Lake occurred through the moraine field as well. Future work at this site will incorporate geophysical techniques in an attempt to better determine flow paths and storage potential in this moraine. Preliminary work shows promise, though measurements and interpretation are not straight-forward. Thus, the presence of overburden materials in contact with alpine lakes may be a useful indicator of groundwater—lake exchange in remote basins. In addition, the magnitude of ground water exchange may be directly related to the volume of unconsolidated overburden deposits (i.e. talus, moraine) in contact with the lake shore. A continuum of ground water exchange can be envisioned based on the permeability of the lake basin geologic materials ranging from little ground water exchange (impermeable bedrock basin) to large exchange (large volume of permeable overburden deposits). The amount of ground water exchange for the lakes in this study was orders of magnitude higher than the bedrock basin lakes described in Gurrieri and Furniss (2004).

Future work is needed to determine how well these patterns apply to other watersheds. Investigations into the effects of different bedrock geology and types of overburden features would be especially useful. However, the overall findings of this study strongly suggest that groundwater be accounted for in future studies of patterns in the hydrology, chemistry and ecology of mountain lakes, and their links to changes in climate or land use.

ACKNOWLEDGEMENTS

The field and laboratory assistance from Rebecca Haspel, Anne Heines, Jaime Hood, Greg Langston, Karen Miller, Jackie Randell and Jaclyn Schmidt is greatly appreciated. Jaime Hood also provided details on the watershed characteristics. Funding was provided by G8 Legacy Chair in Wildlife Ecology, Alberta Ingenuity Centre for Water Resources, Environment Canada Science Horizons Program, Canadian Foundation for Climate and Atmospheric Sciences, and the Natural Sciences and Engineering Research Council of Canada. Lake O'Hara Lodge and

DOI: 10.1002/hyp

Parks Canada provided logistical support. We thank two anonymous reviewers for their constructive comments.

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Canada

Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington (Ontario)
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon (Saskatchewan)
S7N 3H5 Canada

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H2Y 2E7 Canada

Place Vincent Massey
351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3 Canada

Place Vincent-Massey
351 boul. St-Joseph
Gatineau (Québec)
K1A 0H3 Canada