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Measurement of Waves and Currents Off Brant St.,  
Lake Ontario

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# MEASUREMENT OF WAVES AND CURRENTS OFF BRANT ST, LAKE ONTARIO

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Burlington Ontario

## Preamble

The City of Burlington is undertaking a Class Environmental Assessment and detailed design of a waterfront pier and a transient marina at the foot of Brant St in Lake Ontario. There are no existing data on waves and currents in the location of the proposed facility. To provide some data on these important processes in the nearshore zone, the City entered into an agreement with the National Water Research Institute to deploy one of their instruments near the study site to measure waves and currents.

The measurement period was marked by numerous wind events from the west and several from the east. A significant storm out of the east occurred on 26-27 January 2004. This storm had wind speeds out of the east close to the highest recorded at Toronto Island. Wave heights greater than 2 m and wave periods greater than 9 s were recorded in 5 m of water. Currents nearly 0.8 m/s were also recorded during this storm.

It was very fortunate to be able to capture the wave and current data from such a severe storm during the short time period the instrument was deployed. This data set provides a remarkable record for design guidance.

# MESURE DE LA HOULE ET DES COURANTS DANS LE LAC ONTARIO AU BAS DE LA RUE BRANT

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Burlington (Ontario)

## Préambule

La Ville de Burlington entreprend actuellement une évaluation environnementale par catégorie et la conception détaillée d'une jetée et d'un port de plaisance dans le lac Ontario, au bas de la rue Brant. Il n'y a aucune donnée sur la houle et les courants à l'emplacement projeté. En vue d'obtenir des données sur ces processus importants dans la zone riveraine, la Ville a conclu une entente avec l'Institut national de recherche sur les eaux en vue de l'installation d'un appareil de mesure de la houle et des courants près du site d'étude.

La période de mesure a été ponctuée par de nombreux épisodes de vent soufflant de l'ouest et par plusieurs épisodes de vent soufflant de l'est. Les 26 et 27 janvier, une forte tempête a balayé le secteur par l'est. Les vents d'est ont atteint des vitesses proches des records enregistrés dans l'île de Toronto. Les vagues ont dépassé 2 mètres et des périodes de houle supérieures à 9 secondes dans 5 mètres d'eau ont été enregistrées. Des courants de près de 0,8 m/s ont également été enregistrés pendant la tempête.

C'est une grande chance d'avoir pu recueillir des données sur la houle et les courants pendant une tempête de cette ampleur, compte tenu du court laps de temps où l'appareil a été utilisé. Ces données seront fort utiles pour la conception des installations.

# MEASUREMENT OF WAVES AND CURRENTS OFF BRANT ST

## LAKE ONTARIO

M G Skafel, National Water Research Institute, Burlington Ontario

### Summary

The measurement period was marked by numerous wind events from the west and several from the east. A significant storm out of the east occurred on 26-27 January 2004. This storm had wind speeds out of the east close to the highest recorded at Toronto Island. It was very fortunate to be able to capture such a storm during the short time period the instrument was deployed. This data set provides a remarkable record for design guidance.

The currents monitored over the period of record were generally less than 0.2 m/s and shore parallel to the easterly direction. During wind events from the east the currents reversed and were to the westerly direction and again shore parallel. The large storm on 26-27 January 2004 produced large currents up to 0.78 m/s shore parallel in a westerly direction.

The waves at the site were typically less than 0.3 m. Six events were recorded when waves were greater than 0.3 m. During the easterly storm of 26-27 January 2004 the waves were large and from a direction consistent with both wave generation under these conditions on Lake Ontario and refraction due to the shallow water at the site. The wave height peaked at 2.3 m and the period reached 9.8 s. Directions when the period was 9 s or greater were from about 98 to 110°T. These waves appear to be quite close to the maximum likely to occur at the site.

### Introduction

The City of Burlington is undertaking a Class Environmental Assessment and detailed design of a waterfront pier at the foot of Brant St in Lake Ontario. The National Water Research Institute (NWRI) has an ongoing research project addressing the problem of attached algae growth along the Lake Ontario waterfront from Burlington to Mississauga. Both projects need information on the physical processes of waves and currents in the nearshore to provide guidance in other aspects of their respective projects. There are no existing data on waves and currents in the location of the proposed facility, nor anywhere along that reach of shoreline in the very shallow nearshore waters. To provide some data on these important processes, the City entered into an agreement with the National Water Research Institute (NWRI) to deploy one of NWRI's instruments near the study site to measure waves and currents which will serve to benefit both parties.

NWRI deployed a bottom mounted RD Instruments acoustic Doppler current profiler with waves package (ADCP Waves Array) in 5 m of water off Brant St in Lake Ontario at 43° 19.3440'N 79° 47.3630'W, approximately half a kilometre east of the base of Brant St (Figure 1a). The first deployment, from October to December, did not return any data due to instrument malfunction. After assessing the risks of deploying over winter and concluding that the instrument would likely survive if placed in at least 5 m of water, the ADCP was redeployed from 15 Dec 2003 to 6 April 2004. This report summarizes the wave and current data from that deployment.

## Period of Record

During the deployment, several storms out of the east produced sizable waves at the site. Upon first inspection of the site in the spring, on 24 March 2004, it was found that the instrument was completely buried by sand. It was estimated that the top of the instrument was 0.2 to 0.3 m below the surface of the sand bottom. Several attempts were required to retrieve it, and with the use of diver operated water jets to mobilize the sand, it was finally recovered on 6 April 2004. Preliminary analysis of the data indicated good data from the deployment on 15 December 2003 but that the quality of the signal deteriorated after the storm on 26-27 January 2004, and finally became completely unacceptable on 2 February 2004. It was initially believed that the subsidence and/or burial of the instrument took place mainly during the height of that storm and that the sand thickness over it finally became thick enough to prevent operation by 2 February. A photo of the instrument as it was being recovered is show in Figure 1b.

## Currents

The currents are characterized in Figures 1 to 3. Figure 1a shows the principal axes of the currents at four depths in the water column. For each depth, the long line indicates the direction containing the most variance of the current and the short line the least, and the length of the line indicates the magnitude of the currents. These results show that the overall currents are very similar from near the water surface to near the bottom. The flow is dominantly in the alongshore direction, with very modest onshore-offshore flow. For comparison, the principal axes for the winds from the Toronto Island Airport are also show. The winds were mainly east-west, but winds from other directions were also of some importance. The currents are driven by the winds, but very strongly influenced by the close proximity of the shoreline and shore parallel bathymetric contours.

Current roses for the same four depths are shown in Figure 2. In this presentation the time the currents are in a particular speed and direction class are represented by the size and orientation of the coloured areas. Relatively modest currents towards the NNE and NE dominate the results. These figures confirm those of Figure 1 that the flow is mostly shore parallel, but additionally show that for most of the time the flow was in an easterly direction.

Finally, time series of the Toronto Island winds and the currents (at the same depths as previously) are shown in Figure 3. Here the time series have been filtered with a 24 hour filter to highlight the events or storms, at the expense of showing the short period fluctuations. During the period there were numerous relatively strong westerly wind events. During these events the currents at all depths were modest and towards the east and predominantly shore parallel. There were several events with winds out of the east, but only four were of sufficient magnitude and duration to generate currents to the west, again predominantly shore parallel. The storm on 26-27 January 2004 was by far the most important of these. The currents peaked on 26 January 2004 at 2100 Z at 0.78 m/s at the top three depths and at 0.74 m/s at the lowest depth. The direction varied from 224

at the top to 230°T (reported as 'direction towards') at the bottom, all closely shore parallel.

The winds at Toronto Island during this storm peaked on 26 January 2004 at 1300 and 1500 EST at 61 km/hr, from 80°T (and at Burlington Pier on 26 January 2004 at 1000 EST at 59 km/hr, from 90°T). To put the strength of the wind in this storm in perspective, over a recent 20 year interval the strongest winds out of the NE to E directions at Toronto Island were in the 65 to 70 km/hr range, and only occurred for 0.01% of the 20 year record. This storm was one of the worst in terms of magnitude from that direction.

### Waves

The wave data are summarized in Figure 4 and Table 1. Both the figure and the table only show wave readings when the significant wave height ( $H_s$ ) was greater than 0.3 m. Six events resulted in waves greater than 0.3 m. By far the most important event was the storm of 26-27 January 2004. The wave height peaked at 2.3 m with a corresponding peak period ( $T_p$ ) of 9.1 s and peak direction from ( $D_p$ ) of 98°T on 26 January at 2100 Z. The longest peak period occurred six hours later and was 9.8 s with a corresponding wave height of 1.96 m and direction from of 109°T.

When winds blow approximately along the long axis of a lake the resulting waves take the direction of that long axis, or in the case of this site, from about 80°T. As the waves approach shallow water they are refracted (that is, change direction) because of the difference in direction of the bottom contours and the wave direction in deep water. At this site 9 s waves would be expected to change direction from 80°T to about 105°T, based on theoretical considerations. The measured directions were in the range from 98 to 110°T, closely matching the expected direction.

### Elevation of the ADCP

At the end of the deployment the ADCP was buried under about 0.2 to 0.3 m of sand so that the bottom of the instrument frame was about 0.7-0.8 m below the bed. It was not clear whether the instrument subsided or stayed at the same elevation and was buried by a large scale movement of bottom sediment, or some combination. To shed some light on this issue, the elevation time series as measured by the depth sensor on the ADCP, corrected for water level using the gauge maintained by the Canadian Hydrographic Service at the Burlington Ship Canal, was constructed as shown in Figure 5. If the instrument stayed at the same level and was buried by bottom sediment migrating over it, the elevation record should be relatively constant. If the instrument subsided, there should be a general negative slope of the time series. In fact the elevation record of Figure 5 shows a gradual lowering throughout the period with an abrupt lowering of about 0.4 m during the storm of 5 January 2004, but not during the storm of 26-26 January. This evidence suggests that the primary mode of burial was subsidence, not a change in bed elevation caused by the sediment migration.

### **Bottom Sediment**

During the retrieval operation of the ADCP, a sample of bottom sediment was obtained for size analysis. In summary the sediment contained the following size fractions: gravel 0.56%; sand 97.8%; silt and clay 1.64%. The median diameter was 166.46 microns. Loss by ignition was 0.8%, indicating low organic content.



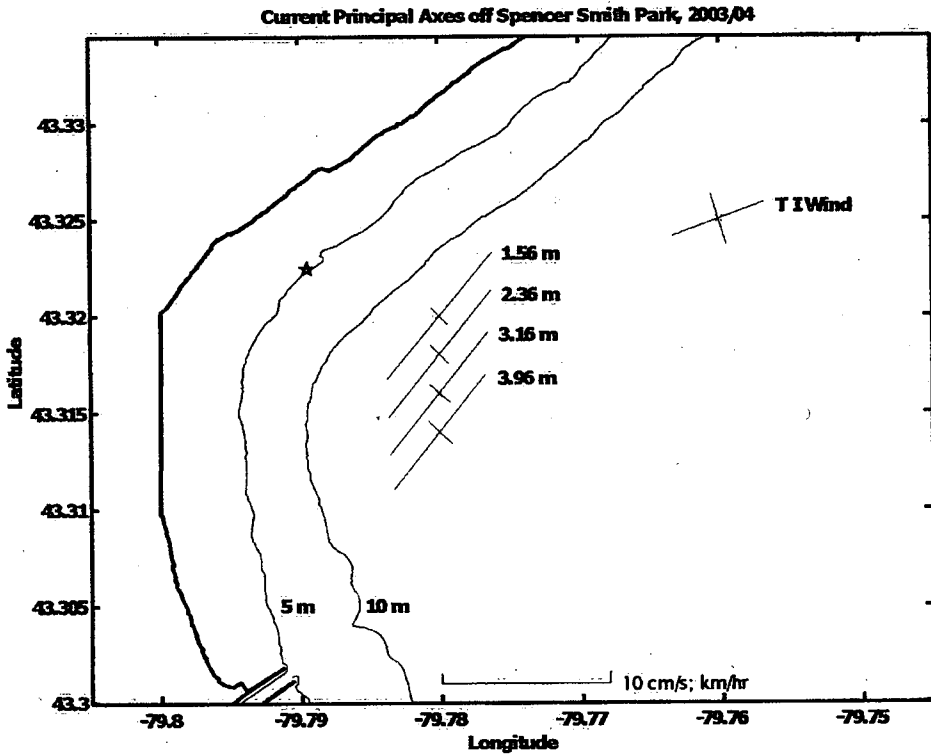


Figure 1a. The principal axes of the currents off Spencer Smith Park at four depths, in 5 m of water indicate that the flow was strongly shore-parallel and showed very little variation from near the surface to near the bottom.

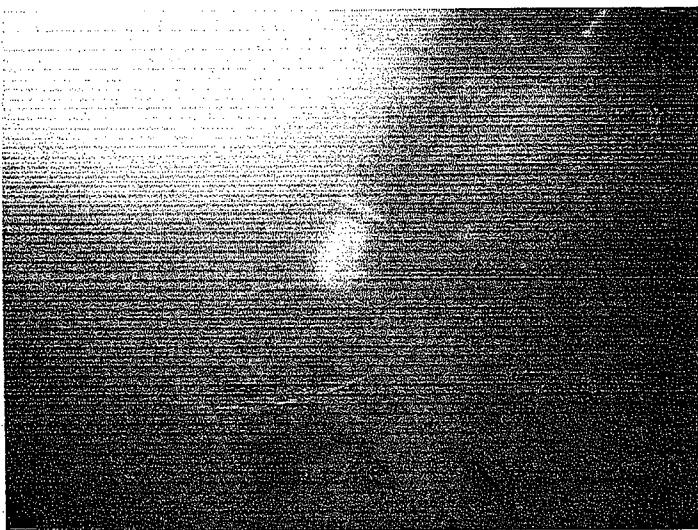


Figure 1b. The ADCP Wave Array meter with protective ring partially uncovered during retrieval. The meter and base frame extended about 0.45 m underneath the sand at the time of this photo.

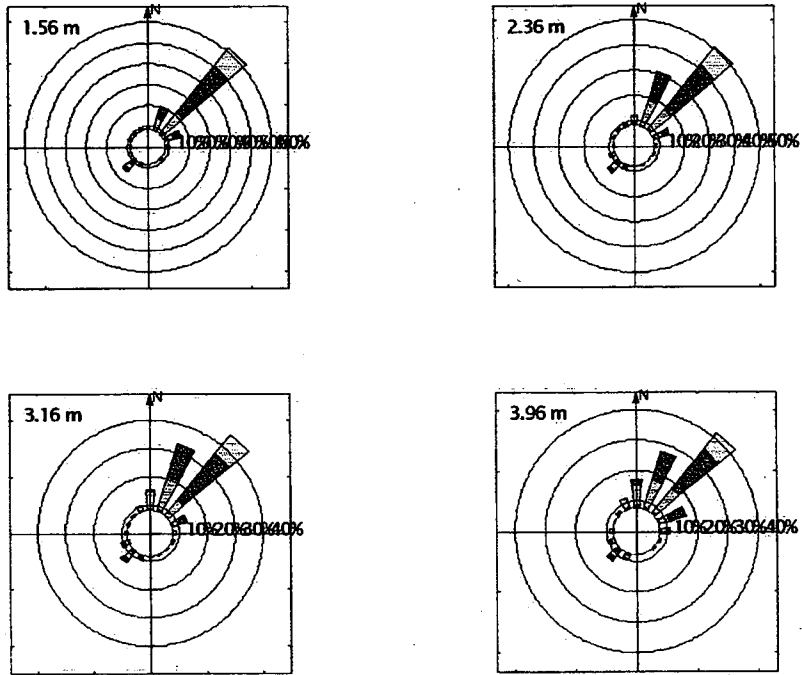


Figure 2. Current roses at four depths. Most of the time the flow is shore parallel in a northeasterly direction. The very strong southwesterly flows during storms were of such short duration that they are hardly discernable in this format. The inner circle represents flows less than 0.005 m/s; magenta: 0.005 to 0.02; cyan: 0.02 to 0.05; red 0.05 to 0.1; green: 0.1 to 0.2; blue: 0.2 to 0.5; magenta: 0.5 to 1.0;... Directions are "to".

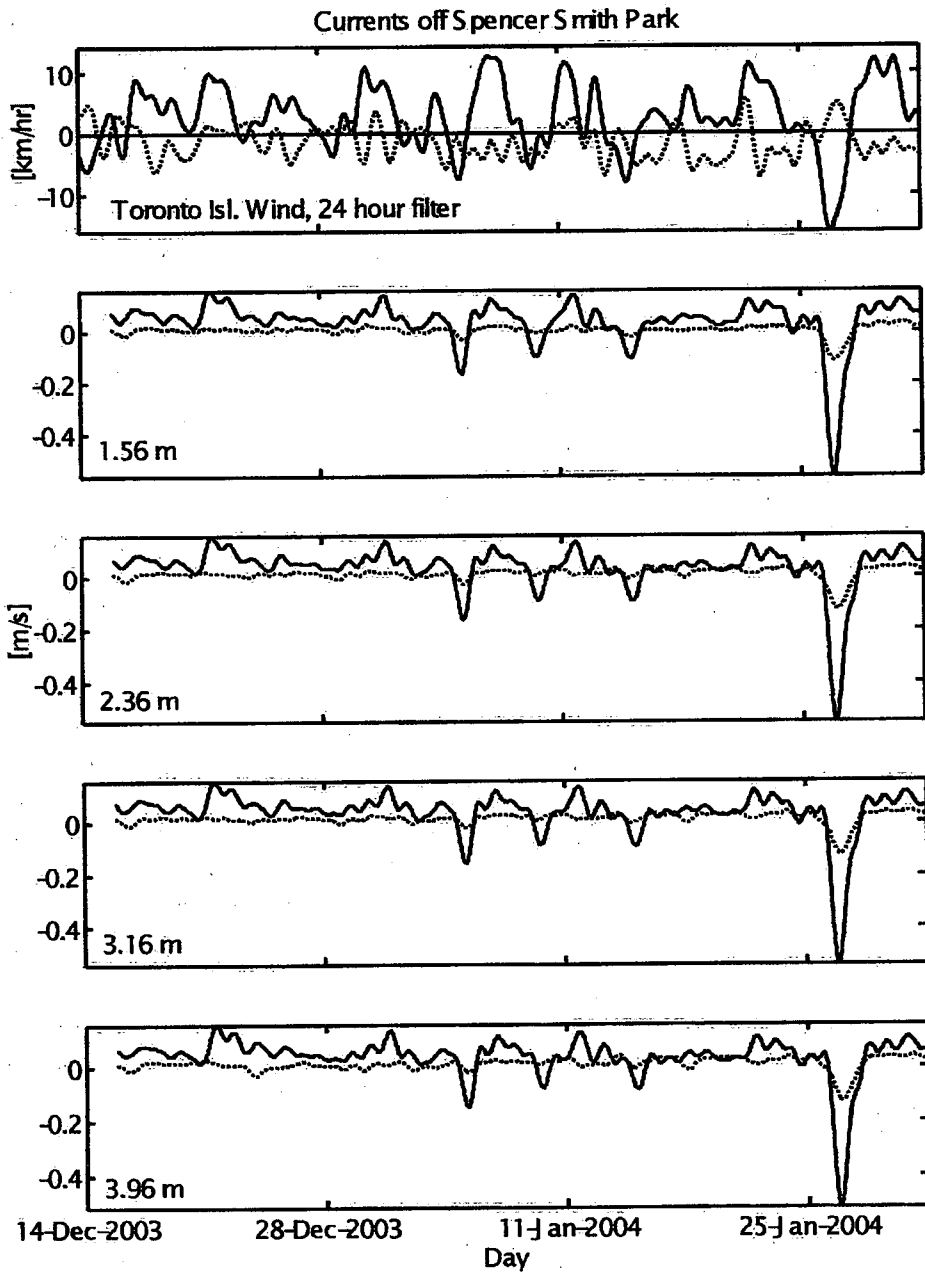


Figure 3. Time series of the Toronto Island winds and currents at four depths, all filtered at 24 hours. The solid line is alongshore (positive is towards the easterly direction,  $20^\circ\text{T}$  for the winds and  $37^\circ\text{T}$  for the currents), and the dashed line is the cross-shore flow (positive is onshore).

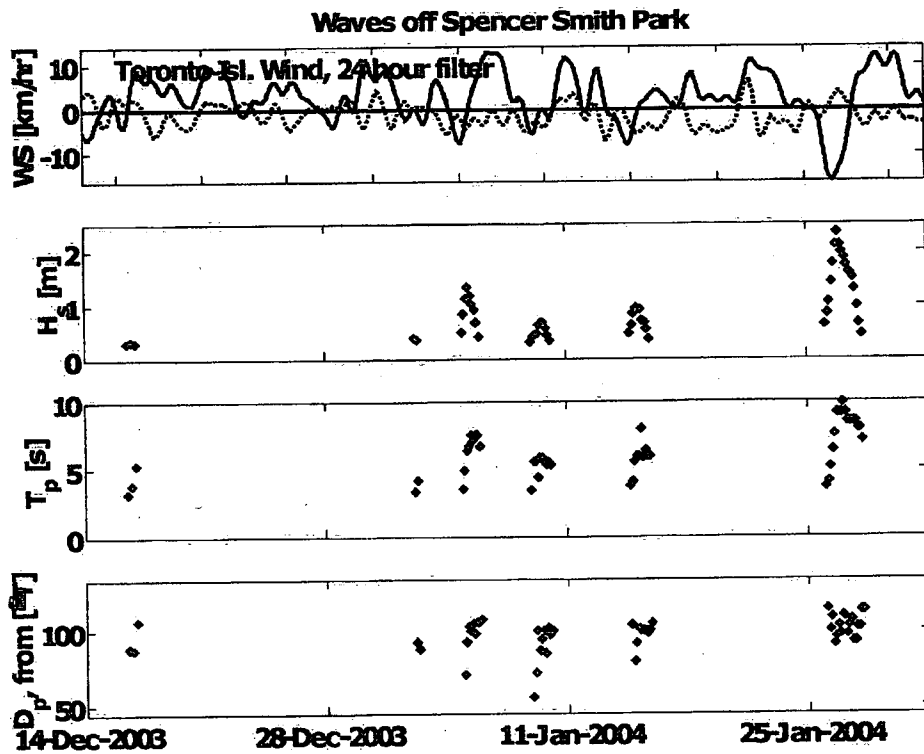


Figure 4. Time series of the wave parameters and the winds from Toronto Island. The solid line in the upper panel is the alongshore component of the wind (Negative is from the east) and the dashed line is the cross-shore component (negative is offshore). Only wave records with significant height greater than 0.3 m are shown.

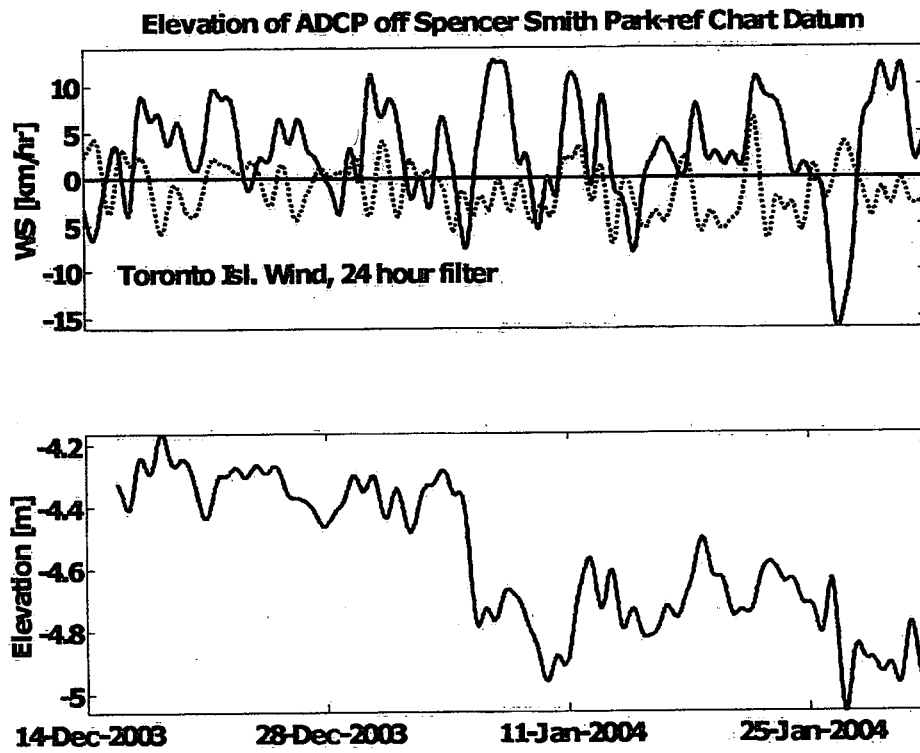


Figure 5. Elevation of the ADCP relative to chart datum. Both the wind record and the elevation record have been passed through a low pass filter with 24 hour cutoff.

Table . Summary of waves greater than 0.3 m in height.

Year	Month	Day	Hour	Hs [m]	Tp [s]	Dp [°T, from]
3	12	16	12	0.3	3.2	89
3	12	16	18	0.32	3.8	88
3	12	17	0	0.3	5.3	107
4	1	2	6	0.38	3.3	93
4	1	2	9	0.36	4.2	88
4	1	5	0	0.48	3.5	71
4	1	5	3	0.83	4.9	93
4	1	5	6	1.13	6.4	103
4	1	5	9	1.34	6.7	100
4	1	5	12	1.17	7.5	105
4	1	5	15	1.01	7.1	99
4	1	5	18	0.92	7.5	106
4	1	5	21	0.68	7.5	106
4	1	6	0	0.4	6.7	108
4	1	9	0	0.3	3.4	56
4	1	9	3	0.42	5.5	72
4	1	9	6	0.43	5.5	100
4	1	9	9	0.47	4.4	87
4	1	9	12	0.63	5.8	95
4	1	9	15	0.66	5.8	100
4	1	9	18	0.66	5.5	85
4	1	9	21	0.56	5.3	102
4	1	10	0	0.44	5.5	98
4	1	10	3	0.34	5.3	100
4	1	14	18	0.47	3.7	104
4	1	14	21	0.63	4.1	80
4	1	15	0	0.83	5.5	92
4	1	15	3	0.93	6	101
4	1	15	6	0.9	6	100
4	1	15	9	0.9	8	100
4	1	15	12	0.71	5.8	100
4	1	15	15	0.68	6.4	99
4	1	15	18	0.54	6	100
4	1	15	21	0.35	6	105
4	1	26	3	0.63	3.6	115
4	1	26	6	0.82	4.1	100
4	1	26	9	1.05	5.1	109
4	1	26	12	1.42	6.4	91
4	1	26	15	1.74	7.5	96
4	1	26	18	2.08	9.1	103
4	1	26	21	2.32	9.1	98
4	1	27	0	2.08	9.1	110
4	1	27	3	1.96	9.8	109
4	1	27	6	1.86	9.1	98
4	1	27	9	1.72	8.5	103
4	1	27	12	1.58	8.5	107

4	1	27	15	1.56	8.5	93
4	1	27	18	1.5	8.5	93
4	1	27	21	1.28	8.5	102
4	1	28	0	0.96	8	102
4	1	28	3	0.64	8	114
4	1	28	6	0.44	7.1	114
4	2	2	15	0.56	3.4	66
4	2	2	18	0.7	4.7	81
4	2	2	21	0.73	3.7	122

# Groundwater exchange with two small alpine lakes in the Canadian Rockies

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## 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

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## 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 (Kattelman 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

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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 sub-surface 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<sup>2</sup> 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<sup>2</sup> 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

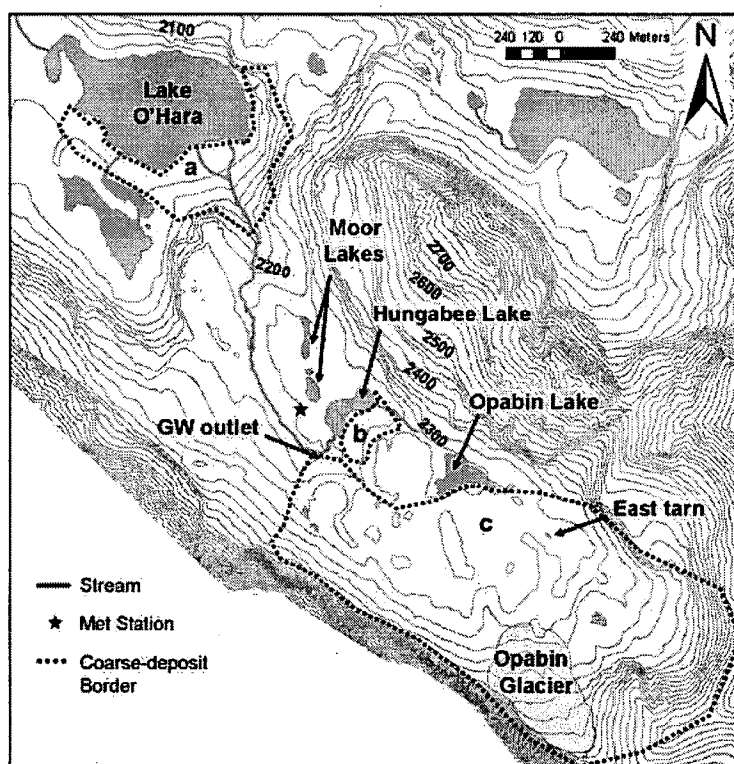


Figure 1. Map of the three alpine lakes of interest in the Lake O'Hara Research Basin, showing the extent of coarse deposits in contact with each ((a)—talus slopes around Lake O'Hara; (b)—talus slope below bedrock knoll by Hungabee Lake; (c)—moraine-talus field around Opabin Glacier). Contours of 25-m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

streams, but does have one inflow streamlet (discharge less than  $0.0025 \text{ m}^3 \text{ s}^{-1}$ ) 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  $0.26 \text{ km}^2$  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  $>1 \text{ m}$  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 glacial 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):

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

where  $\Delta S$  is the change in lake storage,  $\sum Q_{in}$  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:

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

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  $0.002 \text{ m}^3 \text{ s}^{-1}$  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  $\alpha = 1.26$ , where  $\alpha$  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  $2 \text{ mm day}^{-1}$  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  $25^\circ\text{C}$  (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

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<sup>-1</sup> 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<sup>-1</sup> 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<sup>-1</sup> 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<sup>-1</sup> and pH between 8 and 9), which has no inflow streams.

The calculated net groundwater flux (groundwater residual) surpassed 0.1 m<sup>3</sup> s<sup>-1</sup> 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<sup>3</sup> s<sup>-1</sup> 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

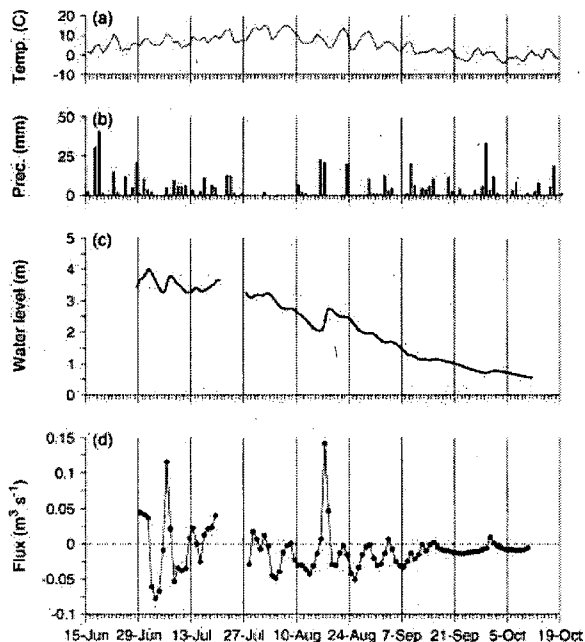


Figure 2. Time series associated with Opabin Lake for 2005: (a) daily average air temperature; (b) precipitation measured at the Opabin met station; (c) lake water level with respect to a local bench mark; and (d) net groundwater flux (zero flux level marked; error bars do not pass beyond symbol height)

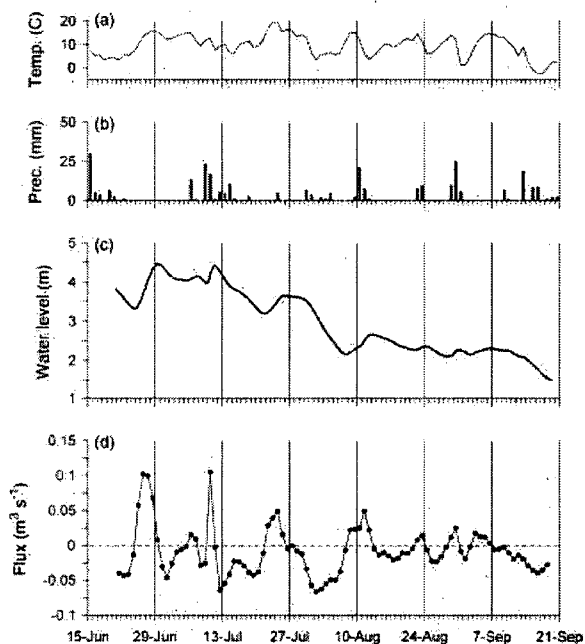


Figure 3. Time series associated with Opabin Lake for 2006: (a) daily average air temperature; (b) precipitation measured at the Opabin met station; (c) lake water level with respect to a local bench mark; and (d) net groundwater flux (zero flux level marked; error bars do not pass beyond symbol height)

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

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

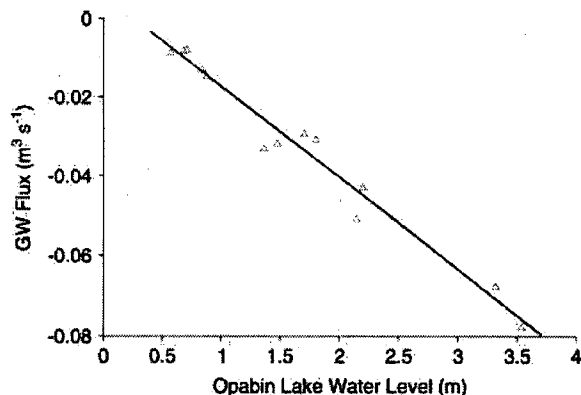


Figure 4. Scatter plot of the water level versus net groundwater flux for Opabin Lake in 2005 (symbols). The line indicates a possible linear relationship between groundwater outflow (negative net flux) and lake level, evident for times when inflow is likely at a minimum

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.

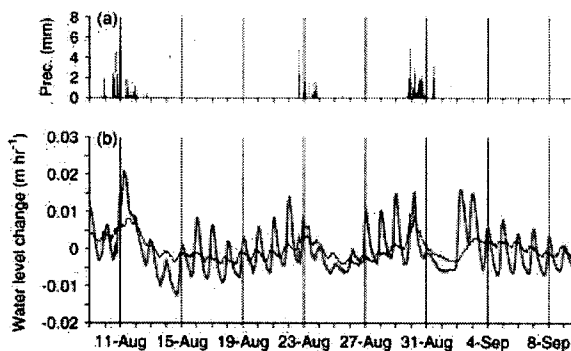


Figure 5. Hourly data from the 2006 field season for (a) precipitation (rain); and (b) change in water level of Opabin Lake (thin black line) and East Tarn (thick grey line)

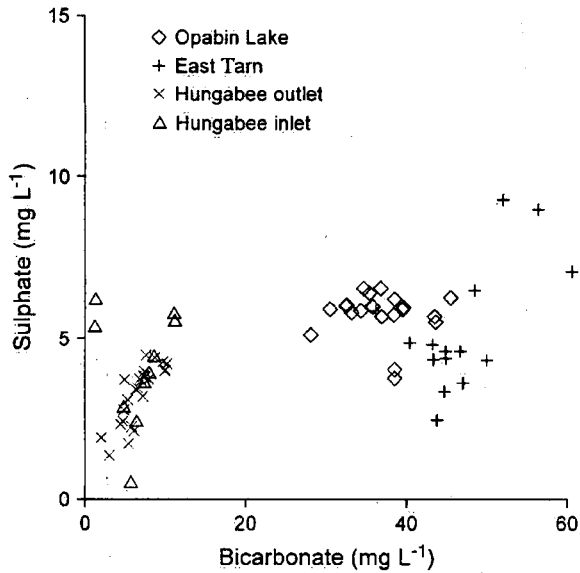


Figure 6. Graph showing the relationship between bicarbonate (based on alkalinity) and sulphate for water samples from Opabin Lake, the East Tarn, and the Hungabee Lake inlet and outlet streams, for 2005 and 2006. Opabin Lake data includes samples collected at surface and depth (8–9 m); the average deviation between same-day samples was  $<3.0 \text{ mg L}^{-1}$  bicarbonate and  $<0.3 \text{ mg L}^{-1}$  sulphate

#### 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  $3 \text{ mm day}^{-1}$  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  $0.001 \text{ m}^3 \text{ s}^{-1}$ . 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

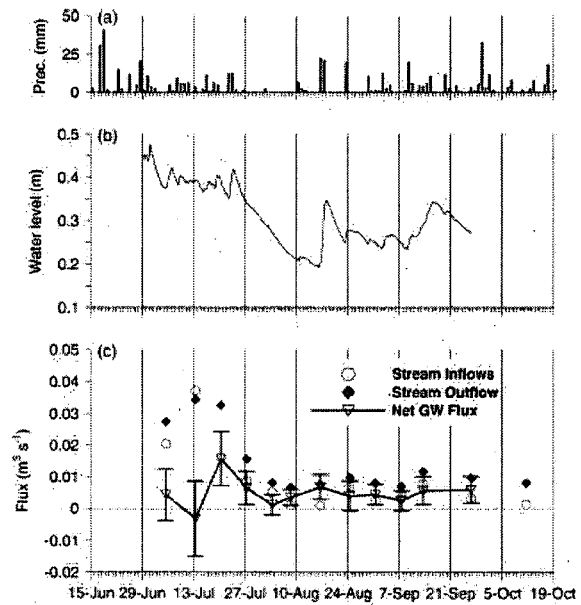


Figure 7. Time series associated with Hungabee Lake for 2005: (a) precipitation measured at the Opabin met station; (b) lake water level with respect to a local bench mark; and (c) stream inflow and outflow fluxes, and net groundwater flux for Hungabee Lake (zero flux level and error bars marked)

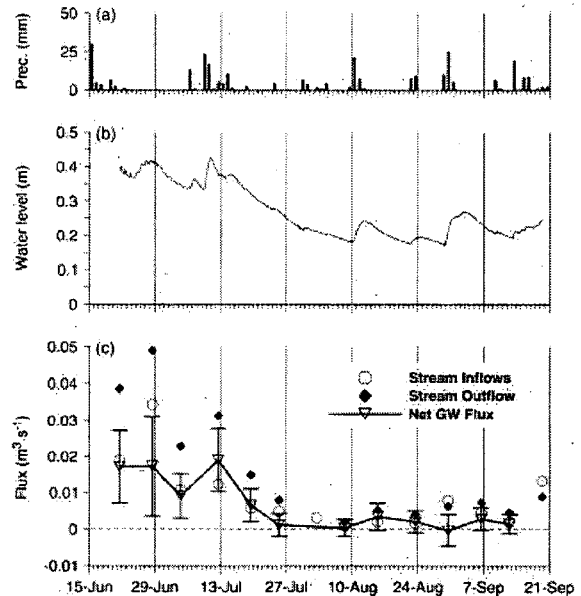


Figure 8. Time series associated with Hungabee Lake for 2006: (a) precipitation measured at the Opabin met station; (b) lake water level with respect to a local bench mark; and (c) stream inflow and outflow fluxes, and net groundwater flux for Hungabee Lake (zero flux level and error bars marked)

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.

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  $\mu\text{S cm}^{-1}$  over the season (Figure 9), while Opabin Lake exhibited higher values of 60 to 80  $\mu\text{S cm}^{-1}$ . 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

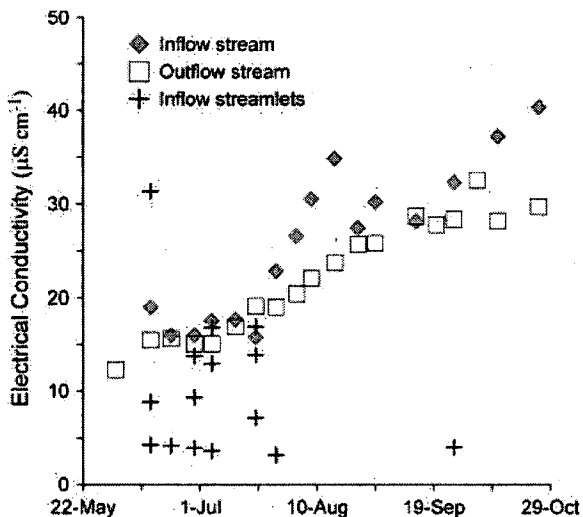


Figure 9. Temporal series of electrical conductivity for the two major streams (inflow and outflow) and the compilation of the small streamlets (all inflow) associated with Hungabee Lake for the 2006 field season

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

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  $0.15 \text{ m}^3 \text{ s}^{-1}$ ) with its large surrounding moraine field than for Hungabee Lake (maximum net influx around  $0.02 \text{ m}^3 \text{ s}^{-1}$ ) 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  $1.3 \text{ m}^3 \text{ s}^{-1}$  (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

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