



## Importance of groundwater in the water balance of an alpine headwater lake

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[1] The response of snow- and glacier-fed mountain streams and lakes to climate warming is of growing concern. A full understanding of these systems must include the role of groundwater, but this is poorly understood, especially for high-elevation lakes. This study addresses the role of groundwater in an alpine watershed, located at the continental divide of North America, with a focus on quantifying the groundwater exchange with Lake O'Hara in British Columbia, Canada. This is facilitated using a water balance approach and measurements of electrical conductivity in inflowing streams. The water balance indicates that groundwater inflow is substantial, as it was equivalent to at least 30–67% and 35–74% of the total outflow for the 2004 and 2005 field seasons, respectively. Hydrological and chemical data also suggest contributions from both deep and shallow groundwater flow paths. **Citation:** Hood, J. L., J. W. Roy, and M. Hayashi (2006), Importance of groundwater in the water balance of an alpine headwater lake, *Geophys. Res. Lett.*, 33, L13405, doi:10.1029/2006GL026611.

### 1. Introduction

[2] Mountainous regions tend to be dominated by snow-melt, or occasionally glacier melt, and often are the primary source of water to surrounding lowlands. In fact, more than one-sixth of the Earth's population relies on glaciers or seasonal snow packs for their water supply [Barnett *et al.*, 2005]. With an increase in global temperature, a predicted consequence of rising levels of greenhouse gases, it is anticipated that less precipitation would fall as snow and the melting of snow and ice would begin earlier. These effects will shift the peak in river runoff earlier in the year, away from the peak demand of summer and autumn, likely causing severe water shortages in areas without sufficient reservoir capacity [Barnett *et al.*, 2005]. Such changes also have significant potential effects on the distribution and abundance of flora and fauna in high-elevation areas [Hauer *et al.*, 1997].

[3] The predicted changes in river runoff are largely based on statistical regression analysis or numerical simulations using large-scale hydrologic models [Barnett *et al.*, 2005 and references therein]. Most of these models do not incorporate the physical processes affecting groundwater recharge and discharge, or they rely on calibration to address the groundwater component. Thus, if groundwater plays a more significant role than represented in these

models, it may provide a storage mechanism to mitigate potentially negative effects of climate warming on water availability predicted by the models.

[4] Understanding of the role of groundwater in mountain areas has grown over the past decade. The percentage contribution from groundwater to streams, based on field studies in mountainous areas, has been reported as high as 60 % by Liu *et al.* [2004], greater than 75 % by Clow *et al.* [2003], and up to 80–100 % for snowmelt in three high-elevation basins by Huth *et al.* [2004]. In a study of six basins, Sueker *et al.* [2000] calculated that subsurface water accounted for 37–54 % of May–October stream flow in five of the basins, and 89 % in the sixth (with extensive surficial debris and shallow slopes). Most of these values are based on chemical or isotopic data sets, often hydrograph separation, and contain a fair amount of uncertainty. The results of the studies listed above show that there is substantial variability in the groundwater contribution, both on a seasonal basis and related to precipitation or melt events, implying that rapid flow through shallow groundwater paths appears to be dominant. However, Rademacher *et al.* [2005] measured mean groundwater residence times of 15 to 28 years, demonstrating that the behaviour can be more complex. The previous studies also indicate that the geology (especially the type and extent of surface materials) is likely a key controlling factor [e.g., Clow *et al.*, 2003].

[5] One might expect that lakes would provide a better measure of the roles of both shallow and deeper groundwater than streams. However, there have been few published studies on the exchange of groundwater with high-elevation lakes in mountainous areas. Groundwater exchange was considered negligible for two small lakes overlying fractured basalt, in the Flattops Wilderness Area, Colorado [Michel *et al.*, 2002]. In his review of the hydrology of lakes, Winter [2003] stated that Loch Vale, Colorado, and Emerald Lake, California, both overlying granitic bedrock, were probably very strongly dominated by surface water. Other researchers working with ponds or lakes in Colorado [Campbell *et al.*, 2004] and Montana [Gurrieri and Furniss, 2004] have suggested groundwater played a significant role. However, groundwater fluxes were not directly quantified for any of these lakes or ponds.

[6] Reliable predictions of the response of mountain streams and lakes to climate warming is dependent on an improved understanding of storage and flow mechanisms within their watersheds. Thus, the objective of this study was to evaluate the role of groundwater in an alpine system in the Canadian Rockies. This was facilitated using a water balance approach for Lake O'Hara in Yoho National Park, British Columbia. A key element of this study was the quantification of the groundwater contribution to the lake water balance and its seasonal distribution. Such data sets

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are also useful in assessing the predictions of hydrological models, but are rare.

## 2. Site Description

[7] The Lake O'Hara study area is located in a 14 km<sup>2</sup> watershed, which encompasses rugged terrain, ranging in elevation from 2010 m to 3490 m.a.s.l. (Figure 1). The Lake O'Hara region is comprised of sedimentary bedrock, like most of the Canadian Rockies. The bedrock underlying most of the watershed is the Cambrian Gog Group, which is primarily composed of thickly bedded quartzite and quartzose sandstone separated by thin layers of siltstone, sandstone and grey shale, while carbonate rocks of the Mt. Whyte, Cathedral, Stephen and Eldon Formations are found at the summits of most of the peaks [Lickorish and Simony, 1995; Price *et al.*, 1980]. Carbonate material is also present in talus and glacial debris in localized areas. Approximately 20 percent of the watershed is sub-alpine coniferous forest and 80 percent is alpine. The alpine terrain is dominated by exposed bedrock (45%), talus slopes (30%) and glacial moraine materials (25%). This setting is representative of numerous alpine lakes in the region, which are the headwaters of mountain rivers.

[8] Mean annual precipitation is estimated to be 1100 to 1500 mm, depending on elevation [Meteorological Service of Canada (MSC), 2005]. The watershed is snow-covered for eight months of the year and contains a few small pocket glaciers. Lake O'Hara is 0.26 km<sup>2</sup> in area, has a maximum depth of 42m, and is ice-free from June until October. It is fed by four inflowing creeks from three sub-watersheds (Mary, Opabin and Oesa) and is drained by a single outlet (Figure 1).

## 3. Methods

### 3.1. Water Balance Calculation

[9] The exchange of groundwater with Lake O'Hara was investigated using the volumetric water balance equation:

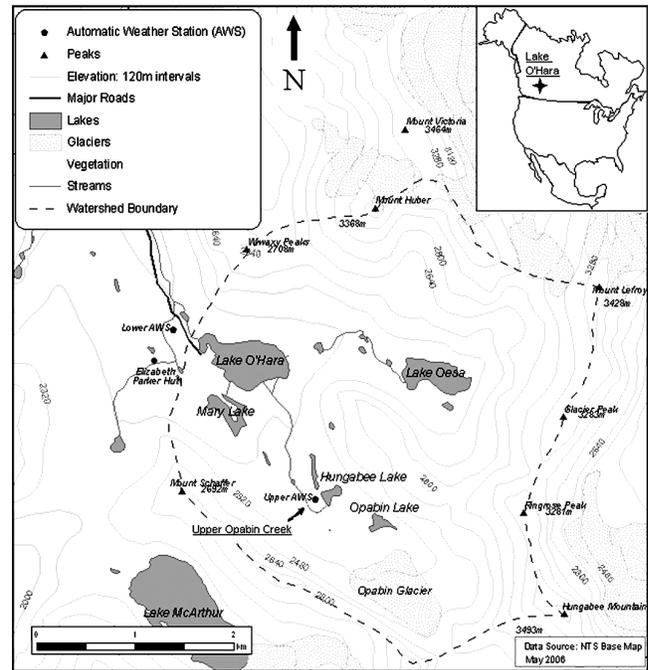
$$\Delta S = \sum Q_{in} + P - E - Q_{out} + Q_{GWin} - Q_{GWout} \quad (1)$$

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. Direct surface runoff is not included in equation (1) as it was not deemed significant for Lake O'Hara. There was little evidence of overland runoff once the snow at the edge of the lake had melted away by late May.

[10] Since groundwater inflow and outflow were not measured directly, the water balance equation was simplified to:

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

where  $Q_{res}$ , the groundwater residual, is the net amount of groundwater inflow or outflow to the lake. The groundwater residual for Lake O'Hara was calculated using equation (2) for the period of 1 July to 13 November, 2004 and from 3 June to 20 October 2005. The temporal resolution of the water-balance calculation was determined by the frequency



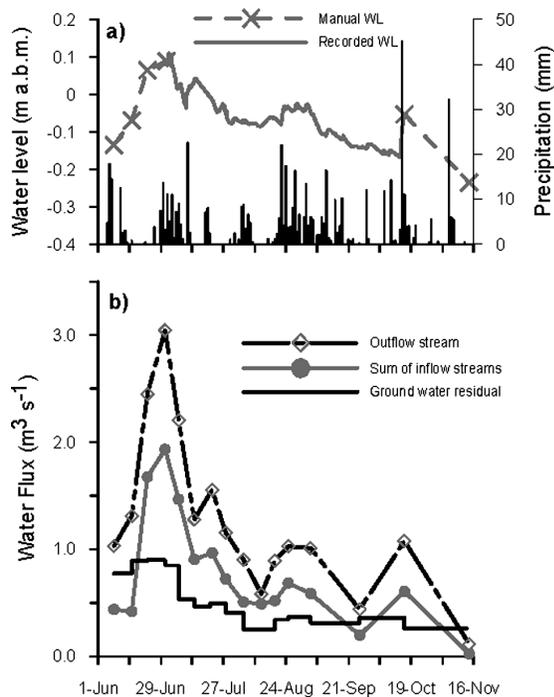
**Figure 1.** Lake O'Hara Research Basin location and topographic map. Contour interval is 120 m.

of stream discharge measurements for 2004, and was calculated on a daily interval for 2005.

### 3.2. Surface Water Measurements

[11] Water level in Lake O'Hara was measured manually on a weekly basis from 6 June to 30 June, 2004, after which it was monitored with a pressure transducer (In-situ, Mini-Troll), until 16 October 2004. During the 2005 field season, the pressure transducer was deployed on 2 June and removed on 25 October. The transducer measured water level every 10 minutes and recorded one-hour average values to minimize the effects of surface waves and seiche (estimated period of several minutes, according to Rueda and Schladow [2002]; equation (2)), though these are not expected to be substantial due to the small size of the lake (Figure 1). The water level changes were converted to lake storage changes assuming a constant lake area.

[12] Discharge in the four inflowing creeks and single outflow was calculated using the area-velocity method from manual measurements made using a hand-held propeller flow meter (Global Water FP101). The locations of stream gauging were not ideal, but were generally well-constrained, being near a constructed bridge-crossing, with the stream bottom cleared of obstructions by hand prior to each measurement. In order to assess the magnitude of stream gauging errors, discharge was measured at three different sections within a 100 m stream reach located in the Opabin sub-watershed (Upper Opabin Creek - Figure 1) seven times between July 18 and August 31. The coefficient of variability for these discharge measurements ranged between 4% and 9% over these seven dates, with an average of 6%. Discharge in inflow and outflow creeks was measured weekly through the summer and occasionally in the autumn. In addition, continuous stream stage measurements were obtained from 3 June to 24 October, 2005, using



**Figure 2.** Lake O'Hara water balance data, 2004 field season, including (a) lake water level and daily precipitation; and (b) weekly measurements of total surface water inflow to and outflow from the lake, and the calculation of groundwater residual (difference between groundwater inflow and outflow,  $Q_{res}$  in equation (2)).

pressure transducers (In-situ, Mini-Troll). Thus, a stage-discharge rating curve for each stream was developed for calculation of continuous stream discharge for 2005. The root-mean-squares (RMS) error associated with the rating curves averaged  $0.04 \text{ m}^3 \text{ s}^{-1}$  for the inflowing creeks and  $0.10 \text{ m}^3 \text{ s}^{-1}$  for the outflow creek, representing 14% and 10% of flow, respectively.

[13] Stream water temperature and electrical conductivity (EC) were measured in-stream using hand-held meters at the same location as discharge. Measured EC values were standardized to  $25^\circ\text{C}$  [Hayashi, 2004].

### 3.3. Meteorological Measurements

[14] Precipitation data for 8 June to 26 August 2004 were provided by Lake O'Hara Lodge, which uses a manual gauge. A meteorological station (O'Hara met station) was established 500 m northwest of Lake O'Hara (Figure 1) on 25 August 2004, and recorded hourly precipitation using a cumulative gauge equipped with a wind shield (Geonor, T-200).

[15] Evaporation was only a minor component of the water balance (see below), but attempts were made to estimate it as accurately as possible from given data sets. The calculation of evaporation with physically-based methods was not possible for the 2004 field season. Therefore, a crude approximation of monthly average evaporation was obtained using the Thornthwaite temperature index method [Dunne and Leopold, 1978, p.136]. Temperature data were obtained from Lake O'Hara Lodge when available, or else from the Environment Canada Wapta Lake meteorological

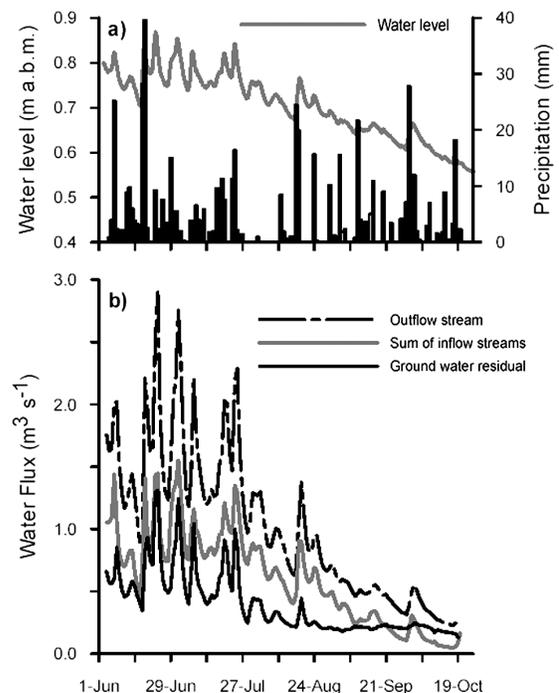
station [MSC, 2005]. Wapta Lake is located 5 km north of Lake O'Hara at an elevation of 1650 m.a.s.l.

[16] Evaporation for the 2005 field season was calculated using the Priestley Taylor [1972] method with  $\alpha = 1.26$ , where  $\alpha$  is a dimensionless constant related to the Bowen ratio. This method was selected because it had been shown to produce reasonably accurate values of evaporation in small lakes and wetlands [Rosenberry et al., 2004]. The method requires measurements of net radiation, air temperature and heat storage in the lake. Prior to 28 June, net radiation was obtained through correlation ( $R^2 = 0.815$ ) with incoming shortwave radiation data from a second meteorological station located on the Opabin plateau (Figure 1). Subsequently, a net radiometer (Campbell Scientific, NR-Lite) deployed over the water surface was used. Air temperature was measured at the O'Hara met station. The change in lake heat storage was calculated from monthly temperature depth profiles, taken at the deepest location using a Hydrolab Datasonde 4 (unpublished data provided by Susan Watson). Evaporation was calculated over these monthly periods and was divided by the number of days in the period to produce daily values. Energy loss through surface water and groundwater advection was ignored, thus the calculations likely overestimated evaporation.

## 4. Results and Discussion

### 4.1. Surface Water Hydrographs

[17] The surface water hydrographs – total inflowing surface water, outflowing surface water and lake level – are illustrated in Figure 2 for 2004 and Figure 3 for 2005.



**Figure 3.** Lake O'Hara water balance data, 2005 field season, including (a) lake water level and daily precipitation; and (b) continuously-measured total surface water inflow to and outflow from the lake, and the calculation of groundwater residual (difference between groundwater inflow and outflow,  $Q_{res}$  in equation (2)).

**Table 1.** Summary of the Water Balance for Lake O'Hara on a Monthly-Basis for 2005

Month	Lake Storage Increase, mm	Stream Inflow, mm	Precipitation, mm	Stream Outflow, mm	Evaporation, mm	GW Residual, mm
June	34	7790	185	13300	41	5430
July	-82	8720	94	14200	62	5330
August	-75	5510	87	8070	43	2450
September	-19	2250	124	4160	63	1830

All the hydrographs, for both years, follow a similar pattern, with high flows or water level in June and July in response to snowmelt, followed by a general decline over the summer and into the autumn. However, isolated maxima in the hydrograph that corresponded to storm events, as indicated by the precipitation data, occurred throughout the observation period. The minimal lag between rain events and hydrograph response suggests that much of the event water is rapidly transported to nearby surface water bodies. The Lake O'Hara hydrographs present a picture of a system that is dominated by snowmelt, but that also responds strongly and quickly to rain events.

#### 4.2. Groundwater Contribution

[18] In both years, the water balance yielded a positive groundwater residual at all times (Figures 2b and 3b), indicating that groundwater inflow dominates over groundwater outflow. The groundwater residual can be considered a minimum estimate of groundwater inflow, as there may be groundwater outflow, but it is not quantifiable from the available data.

[19] The calculation of groundwater residual indicates that groundwater inflow was at least  $0.25\text{--}0.90\text{ m}^3\text{ s}^{-1}$  for the 2004 field season and  $0.13\text{--}1.31\text{ m}^3\text{ s}^{-1}$  for the 2005 field season. The groundwater input was greatest during the snowmelt period but maintained a relatively stable flux through the late summer and into the autumn (Figures 2 and 3). At times during the autumn, the groundwater flux even surpassed that of surface water inflows. As a contribution to the water balance, these groundwater inflow values were equivalent to at least 30–66% and 35–74% of the surface water outflow for 2004 and 2005, respectively. Together, the calculated flux values and percent contribution illustrate that groundwater flow to Lake O'Hara is substantial and that it is an important part of the lake water balance.

[20] While *Campbell et al.* [2004] and *Gurrieri and Furniss* [2004] suggested that groundwater exchange with alpine lakes may be significant, the quantitative results of this study on Lake O'Hara provide confirmation. Thus, groundwater discharge to lakes may influence the response of downstream flows to climatic warming and the functioning of local aquatic ecosystems. It may also have implications for snow and glacier melt modeling, wherein traditionally only surface water flows have been considered in validation. However, this finding is in direct contrast to the negligible groundwater exchange for some alpine lakes suggested by *Michel et al.* [2002] and *Winter* [2003]. Therefore, further study is required to determine how common it is to have substantial groundwater exchange with alpine lakes and under what geological conditions it must be considered.

#### 4.3. Uncertainty in Water Balance Calculation

[21] Since the groundwater contribution is calculated as the residual of the water balance (equation (2)), it is important to evaluate the uncertainty in all other terms in the equation. The monthly summary of water balance for 2005 (Table 1) clearly indicates that evaporation, precipitation and change in lake storage were minor components. Therefore, only the uncertainty in the stream discharge measurements contributes significantly to the uncertainty in the calculated groundwater contribution. The standard method for error propagation [*Harris*, 1991] was used to quantify the uncertainty associated with this calculation. Considering the estimated error of 6% for each discharge measurement and the RMS errors associated with the rating curves (discussed above), the error applicable to the total surface water inflow and outflow for 2005 is 15.2% and 11.7%, respectively. Thus, the error associated with the calculation of groundwater residual (equation (2)) in 2005 ranges between 20% (low flows) and 33% (high flows). A similar magnitude of uncertainty is expected for 2004.

#### 4.4. Groundwater Flow Paths

[22] Researchers commonly use patterns and trends in stream hydrographs to infer information about the groundwater flow paths in mountain environments, especially when more sophisticated hydrograph analyses [see *Vitvar et al.*, 2002; *Lafreniere and Sharp*, 2003] are not feasible. In this case, we attempt to infer such information from the groundwater flux hydrograph for the 2005 field season (Figure 3b).

[23] There is evidence of two groundwater flow regimes in the groundwater hydrograph. From early June through July, the groundwater residual fluctuated following snowmelt and precipitation events, mimicking the surface inflow response, with a similar magnitude and amplitude (Figure 3b). The lag between the surface and groundwater peak for nine major events was always less than 24 hours. This regime is highly-responsive and is likely dominated by shallow groundwater flow paths. By the end of August through to the end of the monitoring period (19 October), the groundwater residual remained stable at about  $0.20\text{ m}^3\text{ s}^{-1}$ , despite receiving similar precipitation (Figure 3b). This regime is likely affected by deeper groundwater flow paths and could be considered base flow, but it is still a substantial flux. It likely extends to the start of the monitoring period and combines with the shallow flow regime to produce higher groundwater inflows during the snowmelt period, as was also evident in 2004 (Figure 2b).

[24] The reduced influence of the shallow groundwater regime over the summer likely results from drying soils and a decline in the water table. Thus, there would be less flow in highly conductive zones, such as surface talus, eroded soils at the top of bedrock, and near-surface fracture zones [*Weiler*

and McDonnell, 2004]. This conclusion is supported by observations of reduced soil saturation and seepage/spring flow over the summer. Similarly, a pair of piezometers installed at the lake edge indicated upward flow into the lake, which was greatest during the snowmelt period and declined over the summer. The exact groundwater pathways and their distribution around the lake cannot be identified at this time, though studies on this topic are planned for Lake O'Hara.

#### 4.5. Composition of Stream Water

[25] Weekly measurements of EC in the inflowing creeks ranged from 100–170  $\mu\text{S cm}^{-1}$  for 2004 and 90–190  $\mu\text{S cm}^{-1}$  for 2005. These EC values were much higher than those measured for rain, ice and snowmelt samples: 1.5–18.7  $\mu\text{S cm}^{-1}$ , which suggests that a significant portion of this water had been routed through subsurface flowpaths for a sufficiently long time to dissolve minerals.

[26] A seasonal trend of low EC during peak flows (late June and early July) and a subsequent gradual rise was observed in the inflow creeks during both 2004 and 2005. These observations suggest that there was a greater contribution from direct runoff and/or shallow groundwater flow pathways during the snowmelt period, with base flow from deeper groundwater paths becoming increasingly dominant in late summer and autumn.

#### 5. Conclusions

[27] The water balance for Lake O'Hara has shown that groundwater inflow is substantial, representing at least 30–67% and 35–74% of the total outflow for 2004 and 2005, respectively. The groundwater flux was often of a similar magnitude as the input from inflowing streams and became the dominant input in the autumn. Trends in the groundwater flux hydrograph suggest two groundwater flow regimes. One is highly-responsive to hydrologic events, and is likely dominated by shallow groundwater flow paths when soils are saturated and the water table is high (snowmelt period). The other is a more stable yet still substantial base flow, mostly comprised of deeper groundwater flow paths, which likely occurs through most of the year. In addition, the high EC of the inflowing streams suggests that much of this water had also passed through the subsurface. The combination of hydrological and chemical data in this study indicate that both deep and shallow groundwater play a major role in the Lake O'Hara watershed. We suggest that groundwater be considered more explicitly, making use of hydrological measurements, in the management or modeling of other watersheds in mountainous regions.

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#### References

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, 438(17), 303–309.

- Campbell, D. H., E. Muths, J. T. Turk, and P. S. Corn (2004), Sensitivity to acidification of subalpine ponds and lakes in north-western Colorado, *Hydrol. Processes*, 18, 2817–2834.
- Clow, D. W., L. Schrott, R. Webb, D. H. Campbell, A. Torizzo, and M. Dornblaser (2003), Ground water occurrence and contributions to streamflow in an alpine catchment, Colorado Front Range, *Ground Water*, 41(7), 937–950.
- Dunne, T., and L. B. Leopold (1978), *Water in Environmental Planning*, 818 pp., W. H. Freeman, New York.
- Gurrieri, J. T., and G. Furniss (2004), Estimation of groundwater exchange in alpine lakes using non-steady mass-balance methods, *J. Hydrol.*, 297, 187–208.
- Harris, D. C. (1991), *Quantitative Chemical Analysis*, 3rd Edition, W. H. Freeman, New York.
- Hauer, F. R., J. S. Baron, D. H. Campbell, K. D. Fausch, S. W. Hostetler, G. H. Leavesley, P. R. Leavitt, D. M. McKnight, and J. A. Stanford (1997), Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada, *Hydrol. Processes*, 11, 903–924.
- Hayashi, M. (2004), Temperature-electrical conductivity relation of water for environmental monitoring and geophysical data inversion, *Environ. Monit. Assess.*, 96, 119–128.
- Huth, A. K., A. Leydecker, J. O. Sickman, and R. C. Bales (2004), A two-component hydrograph separation for three high-elevation catchments in the Sierra Nevada, California, *Hydrol. Processes*, 18, 1721–1733.
- Lafreniere, M. J., and M. J. Sharp (2003), Wavelet analysis of inter-annual variability in the runoff regimes of glacial and nival stream catchments, Bow Lake, Alberta, *Hydrol. Processes*, 17, 1093–1118.
- Lickorish, W. H., and P. S. Simony (1995), Evidence for late rifting of the Cordilleran margin outlined by stratigraphic division of the Lower Cambrian Gog Group, Rocky Mountain Main Ranges, British Columbia and Alberta, *Can. J. Earth Sci.*, 32, 860–874.
- Liu, F., M. W. Williams, and N. Caine (2004), Source waters and flow paths in an alpine catchment, Colorado Front Range, United States, *Water Resour. Res.*, 40, W09401, doi:10.1029/2004WR003076.
- Meteorological Service of Canada (MSC) (2005), National climate data archive of Canada, Environment Canada, <http://climate.weatheroffice.ec.gc.ca/>, Dorval, Can.
- Michel, R. L., J. T. Turk, D. H. Campbell, and M. A. Mast (2002), Use of natural  $^{35}\text{S}$  to trace sulphate cycling in small lakes, Flattops Wilderness Area, Colorado, U.S.A., *Water Air Soil Pollut. Focus*, 2, 5–18.
- Price, R. A., D. G. Cook, J. D. Aitken, and E. W. Mountjoy (1980), Geology, Lake Louise, Alberta and British Columbia, *Map 1483A*, Scale 1:50 000, Geol. Surv. of Can., Ottawa, Ont.
- Priestley, C. H. B., and R. J. Taylor (1972), On the assessment of surface heat flux and evaporation using large-scale parameters, *Monthly Weather Rev.*, 100, 81–92.
- Rademacher, L. K., J. F. Clark, D. W. Clow, and G. B. Hudson (2005), Old groundwater influence on stream hydrochemistry and catchment response times in a small Sierra Nevada catchment: Sagehen Creek, California, *Water Resour. Res.*, 41, W02004, doi:10.1029/2003WR002805.
- Rosenberry, D. O., D. I. Stannard, T. C. Winter, and M. L. Martinez (2004), Comparison of 13 equations for determining evapotranspiration from a prairie wetland, Cottonwood Lake area, North Dakota, USA, *Wetlands*, 24(3), 483–497.
- Rueda, F. J., and S. G. Schladow (2002), Surface seiches in lakes of complex geometry, *Limnol. Oceanogr.*, 47, 906–910.
- Sueker, J. K., J. N. Ryan, C. Kendall, and R. D. Jarrett (2000), Determination of hydrologic pathways during snowmelt for alpine/subalpine basins, Rocky Mountain National Park, Colorado, *Water Resour. Res.*, 36(1), 63–75.
- Vitvar, T., D. A. Burns, G. B. Lawrence, J. J. McDonnell, and D. M. Wolock (2002), Estimation of baseflow residence times in watersheds from the runoff hydrograph recession: Method and application in the Neversink watershed, Catskill Mountains, New York, *Hydrol. Processes*, 16, 1871–1877.
- Weiler, M., and J. J. McDonnell (2004), Virtual experiments: A new approach for improving process conceptualization in hillslope hydrology, *J. Hydrol.*, 285, 3–18.
- Winter, T. C. (2003), The hydrology of lakes, in *The Lakes Handbook*, vol. 1, *Limnology and Limnetic Ecology*, edited by P. E. O'Sullivan and C. S. Reynolds, pp. 61–78, Blackwell Sci., Oxford, U. K.

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