A winter water balance approach to quantifying lake-groundwater interactions in the Beaver River Basin, Alberta

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ABSTRACT
Quantifying lake-groundwater interactions using conventional techniques can be time consuming and costly. In the North American prairies several lakes are underlain with thick glacial clay-till deposits with irregular but frequently encountered interglacial aquifers. Seepage meters and monitoring wells, regardless of their abundance, can overlook key groundwater inflows or outflows. Conversely, sparse but strategic placements may produce an opposite bias. In cold climates, monitoring lake level fluctuations during ice covered periods offers a simpler approach. Under ice, surface water inflows, outflows, and evaporation can be considered negligible for closed basin lakes, and water balance changes can be attributed to groundwater and precipitation. By measuring the snow load on the lake ice surface, the groundwater contribution can be isolated. Eleven closed basin lakes in the Beaver River basin were selected for this study. Their lake levels were surveyed twice, once in December/January and once in February/March, during the coldest part of each winter from 2008 to 2012. Bulk snow surveys were also conducted to quantify snow load in millimetres of snow water equivalent. Results from the snow survey were subtracted from the lake level measurements to quantify groundwater inflow or outflow rates. Pressure transducers were deployed on each lake to monitor water levels from fall to spring and these hydrographs were evaluated with precipitation records from local weather stations to assist the interpretation of results. Groundwater inflows were observed on six of the lakes, with lake level increases ranging between 0.02 to 0.94 mm/d. Groundwater outflows were observed on one lake with declines ranging between -0.37 to -0.98 mm/d. Four lakes fluctuated between gaining and losing lake statuses. The most significant source of error was associated with snow drifting, which was minimized by conducting additional snow surveys with adequate spatial coverage. Groundwater inflow and outflow rates varied for each lake, reflecting recent local precipitation patterns indicating a shallow source of groundwater inflow.

1 INTRODUCTION

East-central Alberta has been suffering from dry conditions since the early 1980s and as a result several lake levels have consistently declined to a point where adjacent cottage owners are concerned that their lakes may eventually disappear. Many of the lakes showing such trends are clustered in the Beaver River watershed. In this part of Alberta, average annual lake evaporation losses outweigh gains from direct precipitation and lakes with declining trends typically have small and possibly shrinking effective runoff contributing areas. Additionally, these lakes are mostly situated near upland areas around the perimeter of the watershed where groundwater recharge likely occurs. As a result, they appear to be highly sensitive to climate change. While a lack of precipitation is the primary cause, there remains significant public concern that lake levels at some lakes are declining quicker than others due to groundwater seepage; possibly to recharge the water table as a result of the dry conditions, or possibly to recharge deeper aquifers as a result of groundwater use in the area.

During the winter, under ice, surface water inflows, outflows, and evaporation can be considered negligible for closed basin lakes, and water level changes can be attributed to groundwater and snow loading (Figure 1). It has been suggested by van der Kamp et al. (2008) that by measuring the snow load on the lake ice surface, the groundwater contribution can be isolated and quantified in a water balance. To gain further insight into the groundwater component of the declining lake level problem observed at several lakes within the Beaver River Basin, a water balance approach over the winter was used at eleven closed-basin lakes to: (1) identify which are gaining or losing lakes; and (2) quantify net groundwater discharge or recharge rates into or from each lake.

2 STUDY AREA

The Beaver River watershed is part of the Churchill River system that originates in east-central Alberta and drains into Hudson Bay. The hydrology of the watershed has been regionally characterized by Alberta Environment (2006) and the hydrogeology by the Alberta Geological Survey (Parks et al., 2005). The eleven Beaver River watershed lakes selected for the study include Beaver, Chickenhill, Garner, Harold, Upper and Lower Mann, Minnie, Missawawi, Muriel, North Buck and Skeleton Lakes, shown on Figure 2. Where possible, lake selection was based on a need to review lakes in different hydrological and hydrogeological settings as well as for investigating public concerns regarding groundwater seepage.

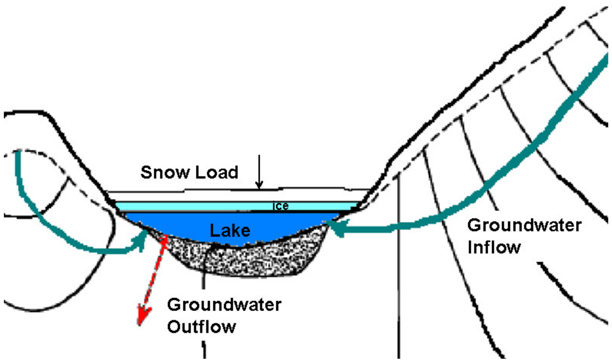

Figure 1. Winter Lake Water Balance (modified from Winter, 1976)

Figure 2. Selected Lakes within the Beaver River Basin: (A) Skeleton, (B) North Buck, (C) Missawawi, (D) Beaver, (E) Garner, (F) Upper and Lower Mann, (G) Minnie, (H) Chickenhill, (I) Muriel, and (J) Harold.

2.1 Hydrology

Several of subject lakes have been described in detail by Mitchell and Prepas (1990), Trew (1986), and Cooke (1998). Ongoing monitoring of water levels has been conducted by Alberta Environment and Sustainable Resources Development or the Water Survey of Canada since the mid to late 1960s with some lakes receiving periodic water quality monitoring conducted by the Alberta Lake Management Society. Each year, the lakes reach an annual low in the fall and annual highs in the spring after snow melt occurs. In this area, average annual lake evaporation is up to 200 mm more than average annual precipitation.

All lakes have declined steadily since at least 1998. As of spring 2012, all the lakes were several metres below their outlet elevation, so none of the lakes experienced surface outflow during the study period.

2.2 Hydrogeology

Most of the Beaver River watershed is underlain with thick (up to 200 m) Quaternary and Neogene unconsolidated sediments (Atkinson and Lyster, 2010) with up to seven preglacial, interglacial and Holocene aquifers regionally mapped (Andriashek and Fenton, 1989, Parks et al., 2005). The surficial geology of the area is dominantly blanketed by clay-till (Andriashek and Fenton, 1983) with frequent sand lenses encountered, many of which are water sources for shallow, low yielding, large diameter (600 to 900 mm) wells for households in the area.

Although most of the study lakes are nested in glacial clay-till, Chikenhill, Harold, Minnie, Muriel, and North Buck Lakes were selected for the study because they were thought to have higher potential to interact with groundwater based on (1) the presence of aeolian deposits, glacial meltwater channels, glaciotechtonic thrust zones, or (2) suspected interactions with regional groundwater flow, or past numerical modelling studies (Andriashek and Fenton, 1989, Parks et al., 2005, and Stein et al., 2000).

3 METHODOLOGY

The selected lakes were chosen for applying the winter water balance primarily because they could be classified as “closed basin lakes” during the winter. The only factors in the winter lake water balance for these lakes are precipitation (snow load) and net groundwater inflow or outflow. Assuming lake surface area is constant, the water balance becomes:

$$\Delta Z = q_{GW}\Delta t + \Delta SWE \qquad [1]$$

Where, ΔZ is the change in lake level (mm) over time period Δt (d), q_{GW} is the net inflow rate of groundwater (mm/d), and ΔSWE is the change in snow load on the lake surface (mm). This equation can be re-arranged to solve for net groundwater inflow:

$$q_{GW} = \left[(Z_2 - Z_1) - (SWE_2 - SWE_1)\right] / (t_2 - t_1) \qquad [2]$$

Where Z_2 and Z_1 are lake levels at time 1 (t_1) and time 2 (t_2), and SWE_1 and SWE_2 are snow loads at t_1 and t_2.

Lake levels were surveyed at ice-augered holes using direct levelling survey techniques. Based on documented closure error, surveyed water levels were determined with a 95 % confidence interval of ± 2.5 mm. Pressure transducers were deployed on each lake to monitor water levels from fall to spring and these hydrographs were evaluated with precipitation records from local weather stations to assist the interpretation of results.

The water levels were measured twice during the coldest part of each winter from 2008 to 2012: once in December/January, and once in February/March. The coldest part of the winter was considered to be optimal for the winter water balance approach to avoid melting events. The two month interval was considered necessary for allowing sufficient time for measurable groundwater seepage.

Snow surveys were conducted in accordance with Environment Canada snow surveying standards (2004). A Federal Metric Snow Sampler manufactured by Carpenter-Seattle was used for the snow surveys. Due to limited snow cover, the bulk method was used for each snow survey. Under this method, 10 snow cores were collected at 10 m intervals over a 100 m traverse. The cores were combined to determine the depth of Snow Water Equivalent (SWE) for each snow survey.

In the 2007-08, 2008-09 and 2009-10 winter seasons, snow surveys were conducted at a single location on each lake and this reading was assumed to be representative of the lake as a whole. In 2010-11, in order to estimate variability over a lake surface, SWE was measured at 20 points across Muriel Lake in a north-south and east-west cross-sectional pattern. Drifting effects were observed, so in the winter of 2011-12, gridded snow surveys, of 10 to 20 points each, were conducted on five lakes. The average coefficient of variation of the 5 early season multi-point surveys was 0.10 (ranging from 0.04 to 0.18), and 0.20 (ranging from 0.10 to 0.29) for the 6 late season surveys. The 95 % confidence intervals were therefore estimated at ± 20 % for the single-point early season snow surveys and ± 40 % for the single-point late season surveys. The confidence intervals for multi-point surveys were estimated directly from the observed variance of the individual snow surveys.

4 RESULTS

Winter water balance calculations for each lake from 2008 to 2012 are summarized in Table 1. Lakes were classified as: "gaining" if results indicate they are net groundwater discharge sites (q_{GW} > 0.05 mm/d); "losing" if results indicate they are net groundwater recharge sites (q_{GW} < -0.05 mm/d); or "flow-through" if the inflow is approximately the same as the outflow (q_{GW} within ± 0.05 mm/d).

Table 1 shows improved confidence in 2011-12 results, which stemmed from conducting detailed snow surveys. In most cases, the 95 % confidence interval was reduced by a factor of three for multi-point snow surveys compared to single-point surveys.

In general, groundwater inflow and outflow rates varied for each lake from year to year. Variation between the maximum and minimum observed groundwater fluxes ranged from 0.24 mm/d (Garner Lake) to 1.2 mm/d (Skeleton Lake). Shallow local groundwater systems tend to be more sensitive to recent climate patterns than intermediate and regional groundwater flow systems. This sensitivity appears to be an indication that the primary source of groundwater flowing into these lakes comes from shallow and local flow systems.

Table 1. Winter Water Balance Results, 2008-2012. Bold values show statistically significant gaining or losing trends. FT refers to flow-through.

Lake	q_{GW} (mm/d)	95% conf. interval (mm/d)	Lake Type
Muriel 07/08	0.17	0.51	Gaining
Muriel 08/09	**0.22**	**0.21**	**Gaining**
Muriel 09/10	**0.23**	**0.20**	**Gaining**
Muriel 10/11	**-0.08**	**0.08**	**Losing**
Muriel 11/12	**0.14**	**0.08**	**Gaining**
Minnie 08/09	**0.57**	**0.17**	**Gaining**
Minnie 09/10	**0.21**	**0.18**	**Gaining**
Minnie 10/11	**0.57**	**0.16**	**Gaining**
Minnie 11/12	0.02	0.06	FT
Garner 08/09	**0.46**	**0.12**	**Gaining**
Garner 09/10	**0.29**	**0.19**	**Gaining**
Garner 10/11	**0.54**	**0.17**	**Gaining**
Missawawi 08/09	0.15	0.21	Gaining
Missawawi 09/10	0.23	0.23	Gaining
Missawawi 10/11	0.51	**0.18**	**Gaining**
North Buck 08/09	**0.58**	**0.21**	**Gaining**
North Buck 09/10	0.13	0.25	Gaining
North Buck 10/11	**0.94**	**0.15**	**Gaining**
Skeleton 08/09	**0.45**	**0.21**	**Gaining**
Skeleton 09/10	0.08	0.26	Gaining
Skeleton 10/11	**1.11**	**0.13**	**Gaining**
Skeleton 11/12	**-0.09**	**0.06**	**Losing**
Upper Mann 08/09	**0.39**	**0.16**	**Gaining**
Upper Mann 09/10	0.03	0.20	FT/Uncertain
Upper Mann 10/11	**0.28**	**0.20**	**Gaining**
Lower Mann 08/09	**0.31**	**0.16**	**Gaining**
Lower Mann 09/10	**0.29**	**0.16**	**Gaining**
Lower Mann 10/11	**0.63**	**0.17**	**Gaining**
Beaver 08/09	**0.31**	**0.24**	**Gaining**
Beaver 09/10	**-0.50**	**0.25**	**Losing**
Beaver 10/11	**0.54**	**0.19**	**Gaining**
Chickenhill 08/09	-0.15	0.24	Losing
Chickenhill 09/10	0.16	0.17	Gaining
Chickenhill 10/11	0.15	0.23	Gaining
Chickenhill 11/12	**-0.20**	**0.07**	**Losing**
Harold 08/09	**-0.63**	**0.26**	**Losing**
Harold 09/10	**-0.81**	**0.14**	**Losing**
Harold 10/11	**-0.37**	**0.27**	**Losing**
Harold 11/12	**-0.98**	**0.07**	**Losing**

Consistent groundwater inflow was observed on Minnie, Garner, Missawawi, North Buck, Upper Mann, and Lower Mann Lakes. Lake level increases attributed to groundwater ranged from 0.02 to 0.94 mm/d at these lakes. These lakes are considered gaining lakes. Groundwater outflows were observed consistently on Harold Lake with declines ranging between -0.37 to -0.98 mm/d, classifying it as a losing lake. The above noted gaining and losing lakes typically had statistically significant trends and there is higher confidence in their lake type classification, with the exception of Missawawi Lake (2008-10), Upper Mann (2009-10) and Minnie Lake (2011-12). Upper Mann and Minnie Lake each had years where they were classified as flow-through lakes. However, there is improved confidence in the flow-through status of Minnie compared to Upper Mann resulting from the detailed snow survey. Muriel, Skeleton, Beaver, and Chickenhill lakes fluctuated between gaining and losing lake types. These lakes are thought to have groundwater flow regimes that are potentially more sensitive to climate changes than others.

5 CONCLUSIONS

Net groundwater fluxes to lakes are quantifiable using the winter water balance approach provided that there are no surface water inflows or outflows during the ice covered months. Improved statistical confidence is achieved by increasing the number of snow surveys and ensuring they are adequately spaced using a grid pattern to minimize positive or negative biases associated with snow drifting. In this study, the 95 % confidence interval in the results was reduced by a factor of three by increasing the number of snow surveys from 1 to 10 or 20 depending on the size and shape of the lake.

The winter water balance approach was capable of identifying gaining, losing and flow-through lakes. However, in the Beaver River Basin, at the selected 11 closed basin lakes, in spite of their significant declining lake level trends, net groundwater inflow was observed on most lakes, indicating that net groundwater outflow is not the cause of the declining lake level trends. One lake was consistently classified as a losing lake over a four year period and it is predicted that this lake will completely evaporate and infiltrate in the near future if dry conditions continue.

The groundwater inflow and outflow rates varied, indicating the primary source is shallow and most likely part of each lake's local flow system. For this reason, current observations may not be representative of past groundwater fluxes, especially if it is suspected that the water table has declined due to drought conditions. Similarly, it is possible that groundwater inflow to these lakes has declined due to groundwater withdrawals. Conducting periodic surveillance monitoring and striving towards building long term data sets is recommended for assessing whether or not changes to a lake's groundwater flow regime have occurred. Such data sets could also provide insight for evaluating whether or not changes have been induced due to anthropogenic activity or climate change.

Other potential uses for the winter water balance include using it for calibrating or verifying numerical groundwater flow models, improving water balance calculations, or general watershed planning purposes.

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