

Estimating groundwater inflow and leakage outflow for an intermontane lake with a structurally complex geology: Georgetown Lake in Montana, USA

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Abstract Stable isotopes of the water molecule ($\delta^{18}\text{O}$ and δD) for groundwater, lake water, streams, and precipitation were coupled with physical flux measurements to investigate groundwater–lake interactions and to establish a water balance for a structurally complex lake. Georgetown Lake, a shallow high-latitude high-elevation lake, is located in southwestern Montana, USA. The lake is situated between two mountain ranges with highlands primarily to the east and south of the lake and a lower valley to the west. An annual water balance and ($\delta^{18}\text{O}$ and δD) isotope balance were used to quantify annual groundwater inflows of $2.5 \times 10^7 \text{ m}^3/\text{year}$ and lake leakage outflows of $1.6 \times 10^7 \text{ m}^3/\text{year}$. Roughly, 57% of total inflow to the lake is from groundwater, and 37% of total outflow at Georgetown Lake is groundwater. Stable isotopes of groundwater and springs around the lake and surrounding region show that the east side of the lake contains meteoric water recharged annually from higher mountain sources, and groundwater discharge to the lake occurs through this region. However, springs located in the lower western valley and some of the surrounding domestic wells west of the lake show

isotopic enrichment indicative of strong to moderate evaporation similar to Georgetown Lake water. This indicates that some outflowing lake water recharges groundwater through the underlying west-dipping bedrock in the region.

Keywords Stable isotopes · Groundwater/surface-water relations · Groundwater recharge/water budget · Lake · USA

Introduction

Understanding the hydrologic budget of lakes is essential for making both water quantity and water-quality management decisions (Millham and Howes 1994; Van Oel et al. 2013; Ameli and Craig 2014; Kummur et al. 2014; Lavoie et al. 2014). Water balances are increasingly important for understanding water resources under the stress of drought and/or climate change (Kebede et al. 2006; Swenson and Wahr 2009; Lei et al. 2013). Often, groundwater inflow and leakage outflow comprise a substantial percentage of a lake's water balance and, in some cases, can strongly influence lake-water quality (Hagerthy and Kerfoot 1998; Shaw et al. 2013; Jarosiewicz and Witek 2014; Karan et al. 2014; Lewandowski et al. 2015; Rosenberry et al. 2015). However, quantifying groundwater inflows and outflows can be very difficult for lakes in regions that are topographically and geologically complex due to aquifer heterogeneity, preferred fracture flow, multiple groundwater flow paths (Krabbenhof et al. 1990; Xiao et al. 2013).

The importance of groundwater in lake-water balances is often ignored or greatly simplified, and groundwater has recently been referred to as “the disregarded component in lake water and nutrient budgets” (Lewandowski et al. 2015; Rosenberry et al. 2015). If groundwater is even considered in lake studies it is often discussed in general terms as a

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process with no attempt to quantify fluxes (Ojiambo et al. 2001; Schuster et al. 2003; Kebede et al. 2006; Radke and Howard 2007; Shaw et al. 2013). By measuring surface water inputs and outputs combined with climate data to estimate direct precipitation and evaporation, it is possible to solve for the net groundwater inflow or outflow (i.e. the difference between groundwater inflow and leakage outflow). A common approach is to assume leakage outflow from lakes is negligible or absent and only estimate groundwater inflow (Corbett et al. 1997; Hagerthy and Kerfoot 1998; Kluge et al. 2007; Cartwright et al. 2009; Rodellas et al. 2012; Schmidt et al. 2010; Dessie et al. 2015; Isokangas et al. 2015). However, in the case of a flow-through lake that simultaneously gains and loses groundwater, the net groundwater flux does not reveal if the separate inflow and outflow components are large or small (Hood et al. 2006; Lei et al. 2013; Lee et al. 2014).

Numerical modeling can be used to estimate the flux of groundwater into and out of a lake, provided sufficient hydrogeologic data are available (Millham and Howes 1994; Bocanegra et al. 2013; Elsaywaf et al. 2014; Rudnick et al. 2014). Modeling in the most common approach for estimating groundwater inflow and leakage outflow in large lakes (i.e. lakes with total surface area >500 ha; Bocanegra et al. 2013; Elsaywaf et al. 2014). Geochemical mass balances provide another useful approach. Previous studies have used major ion chemistry (Krabbenhoft and Webster 1995; Nachiappan et al. 2015) and stable isotopes of water ($\delta^{18}\text{O}$ and δD ; Turner et al. 1984; Krabbenhoft et al. 1990; Gurrieri and Furniss 2004; Turner and Townley 2006; Stets et al. 2010; Sacks et al. 2014; Nachiappan et al. 2015). However, most previous studies that have employed geochemical or isotopic mass balances to quantify groundwater inputs and outputs have investigated lakes (<120 ha; Krabbenhoft et al. 1990; Millham and Howes 1994; Krabbenhoft and Webster 1995; Hunt et al. 2003; Gurrieri and Furniss 2004; Stets et al. 2010; Rudnick et al. 2014; Sacks et al. 2014; Nachiappan et al. 2015).

In this report, stable isotopes of water are used to elucidate the water budget of Georgetown Lake, a large (1,219 ha), flow-through mountain lake underlain by complexly folded and faulted metasedimentary rocks. Oxygen and hydrogen isotopes are ideal conservative tracers because they are part of the water molecule itself, not dissolved components subject to reactive transport processes (Sacks 2002). In the present study, direct evaporation of water from the lake surface produces a stable isotopic signal that deviates from local meteoric water, thereby increasing the sensitivity and precision of the stable isotope mass balance approach. The objectives in this report are to (1) create a water balance on a large mountain lake (1,219 ha) using a stable isotope mass balance approach to see if groundwater inflows and outflows can be accurately

estimated, and (2) use stable isotopes of regional groundwater and springs to establish a conceptual understanding of groundwater inflow and groundwater outflow to and from the lake.

Study area

Georgetown Lake, Montana, is a relatively high elevation reservoir, at 1,960 meters above sea level (m.a.s.l.). Its surface area is 1219 ha, and it is located 27.4 km northwest of Anaconda near the Flint Creek and Warm Springs Creek Divide in the Clark Fork River drainage (Fig. 1). Georgetown Lake is a relatively shallow lake, with a mean depth of 4.9 m and only 10.7 m at its deepest location (Knight 1981). The maximum water volume of Georgetown Lake is $3.83 \times 10^7 \text{ m}^3$. Before the reservoir was created in the mid 1880s, the setting was a large meadow called Georgetown Flats where cattle grazed and the land was irrigated to grow hay (Wright 1983). In the 1880s, Georgetown Flats was partially flooded by the construction of the Flint Creek Dam, and by the 1890s the hydroelectric dam was completed. By the early 1900s, the dam spillway was raised and Georgetown Flats became the current Georgetown Lake.

The Georgetown thrust fault underlies Georgetown Lake and creates a structurally complex geologic setting (Fig. 2). The Georgetown thrust fault is a low angle, westward dipping fault that emplaces mid-Proterozoic rocks of the Belt Supergroup over Paleozoic and Mesozoic sediments. The fault divides the bed of Georgetown Lake into two distinct domains (Figs. 1 and 2; Lonn et al. 2003). The eastern portion of the lakebed is composed mainly of upper Paleozoic carbonates of the Madison Group and Amsden Formation and the western lakebed is primarily composed of Proterozoic metasedimentary carbonates of the Piegan Group locally referred to as the Middle Belt Carbonates. The metasedimentary rocks underlying the western lakebed are mainly dolomitic siltites and quartzites (Lonn et al. 2003). Metamorphism has altered both geologic regions through the intrusion of late Cretaceous to early Tertiary granitic and dioritic plutons. Geologic formations in both domains have undergone extensive folding and faulting. Most of the rocks within the study area dip 40–60° to the northwest and strike to the northeast (Lonn et al. 2003). A smaller syncline within the regional structure forms the plateau that includes Georgetown Lake.

Georgetown Lake is surrounded by mountains that reach peaks greater than 3,000 m.a.s.l. The lake drainage area is approximately 12,976 ha (Knight 1981), and it is fed by a 137-km² watershed (EPA 1977). The two largest tributaries flowing into the lake are Stuart Mill Spring (SMS) and the North Fork of Flint Creek (FCI; Fig. 1). SMS originates entirely from a spring located approximately 200 m south of the lake (Knight 1981), whereas FCI originates from the highlands to the northeast of the lake with an approximate drainage

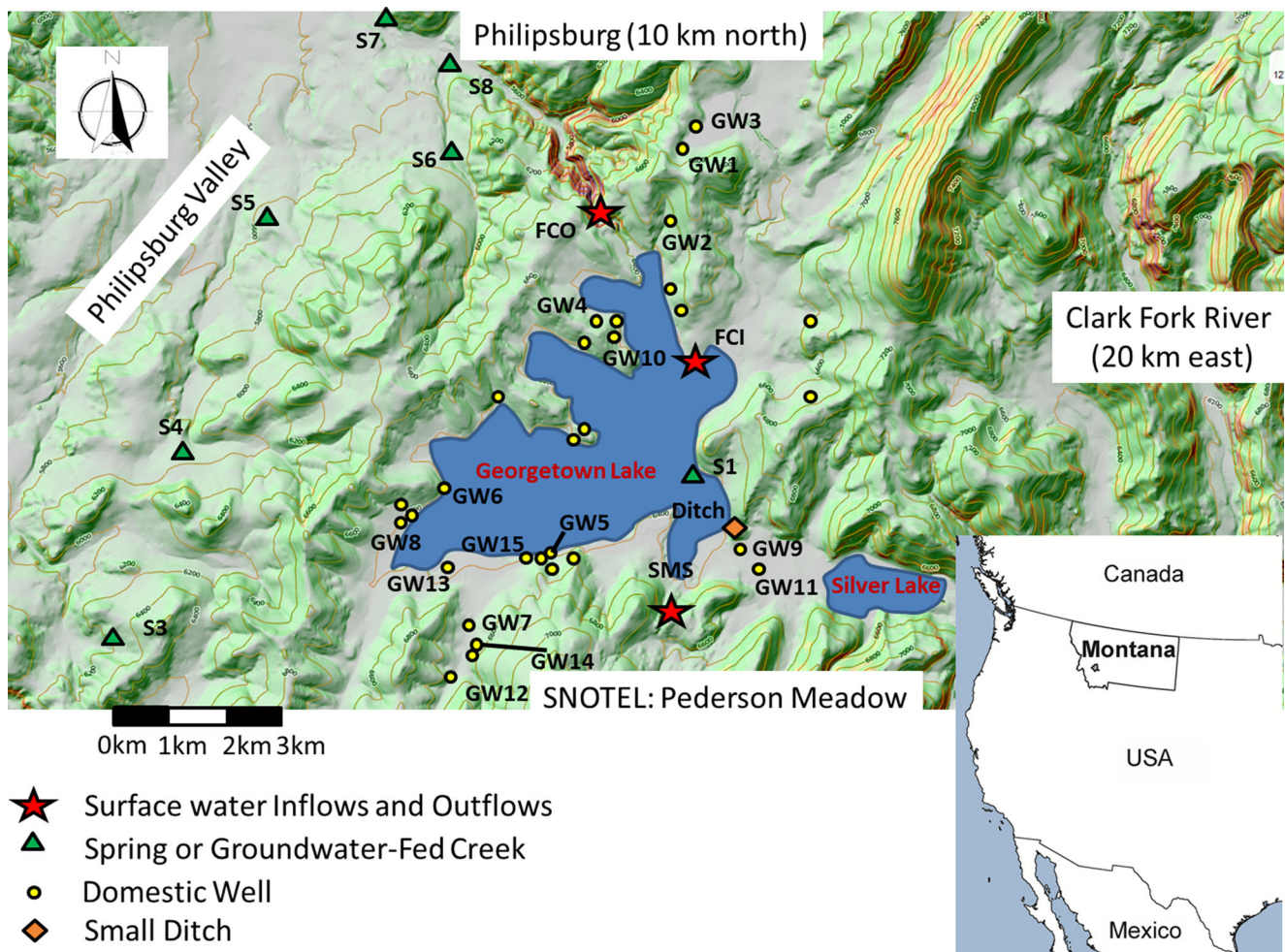


Fig. 1 Site map of the study area with sampling locations for lake inflow and outflow (*red stars*), springs and small groundwater-fed creeks (*green triangles*), domestic wells (*yellow circles*), and one small ditch (*orange diamond*). Groundwater locations used from Shaw et al. (2013) are not

labeled with sampling IDs. Stuart Mill Spring (SMS) and the North Fork of Flint Creek (FCI) and Flint Creek Out (FCO) (background image courtesy of CalTopo 2015)

area of 4,895 ha (Knight 1981). The primary surface water outflow of the lake is at the dam, which discharges lake water to Flint Creek. In this study, Flint Creek below the dam is referred to as Flint Creek Out, and is denoted FCO. A smaller range of hills (~2,060 m.a.s.l.) separates Georgetown Lake from the deeper Philipsburg Valley to the west. The floor of the Philipsburg Valley (~1,680 m.a.s.l.) is substantially below the elevation of Georgetown Lake (1,960 m.a.s.l.). Annual precipitation from 1981 to 2010 averaged 66.8 cm. The mean annual air temperature is 2.4 °C, with highs occurring during summer months (May–August) and lows occurring during winter months (November–March).

Georgetown Lake is known for its scenic views, fishing, camping, and other various outdoor activities, and it is currently the most recreated lake of its size in Montana. As recreation and housing development increase at Georgetown Lake, interest and research have increased in response to degrading lake-water quality (Shaw et al. 2013; Gammons et al. 2014). Previous studies showed

that most groundwater enters the lake through the eastern one-third of the lakebed (Shaw et al. 2013). Water in the western and central portion of the lake becomes progressively anoxic with a strong vertical chemocline throughout roughly 6 or 7 months of ice-cover (Knight et al. 1976; Garrett 1983; Stafford 2013; Gammons et al. 2014). The well-oxygenated groundwater mixes with anoxic water and thus maintains lake-water quality throughout winter months along the eastern shoreline of the lake (Shaw et al. 2013). Shaw et al. (2013) speculated that lake water seeps out through the western two-thirds of the lake. The groundwater flow-through setting of Georgetown Lake is supported by two regional potentiometric surface maps illustrating a general west-moving flow of groundwater (Waren and LaFave 2011; Mitchell 2014). Lake sediment thickness has never been determined, but Shaw et al. (2013) speculate that accumulated sediments may contribute to a decrease in groundwater inflows and leakage outflows to and from the lake.

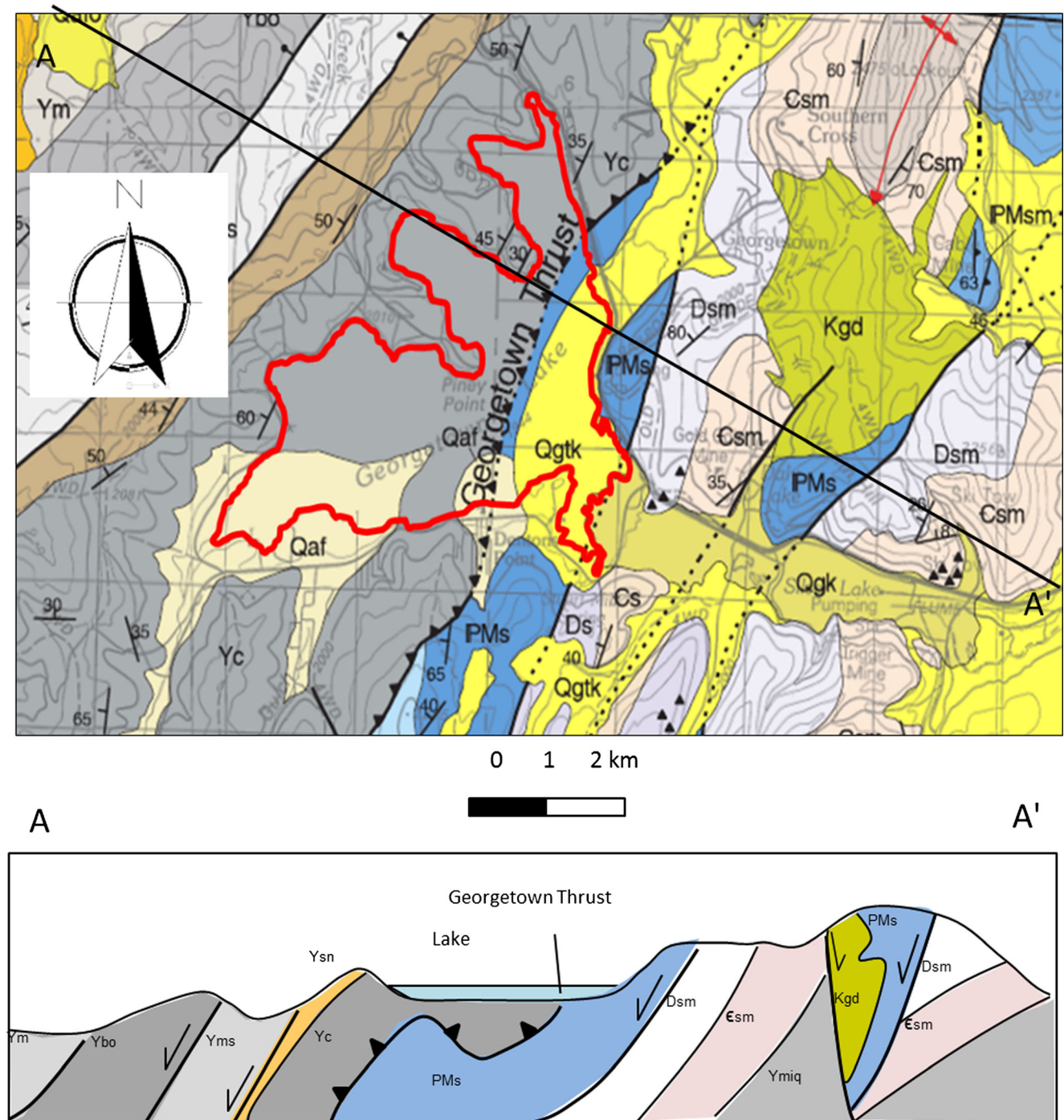


Fig. 2 Geologic map illustrating the location of Georgetown Lake and the Georgetown Thrust Fault where Precambrian metasedimentary rocks are upthrown over Mississippian and Pennsylvanian carbonates. The map

is modified from Lonn et al. (2003) and the section is taken from Shaw et al. (2013)

Methods

Lake-water balance

A lake-water balance was created by measuring monthly lake inflows, outflows, and changes in storage from December 2012 to November 2013. Stream flows at SMS and FCI were

determined by recording monthly staff gage heights, once per month mid-day, and converting to flow using a previously calibrated rating curve (courtesy of Montana Department of Natural Resources and Conservation). To ensure the data represented the months where it was collected, data were collected between storm events. Nearby hydrographs for the region were also followed to ensure field measurements were not

conducted during an anomalously high or low flowing conditions. FCO flow measurements were obtained from the United States Geological Survey (USGS) Flint Creek gaging station near Southern Cross (Station ID 12325500).

Monthly evaporation was calculated using local meteorological data (average monthly air temperature, dew point temperature, relative humidity, wind speed, and incoming solar radiation), and incorporated in lake evaporation diagrams presented by Kohler et al. (1955), where monthly free water evaporation rates could be estimated. The Philipsburg, MT station meteorological data were obtained from the Western Regional Climate Center (Western Regional Climate 2015). The Philipsburg station is roughly 20 km northwest of Georgetown Lake at an elevation of 1,606 m.a.s.l.

Precipitation for this study was taken from the Natural Resource Conservation Service Pederson Meadows SNOTEL site located approximately 4 km away at an elevation of about 2,200 m.a.s.l. (NOAA station ID PTNM8).

The following mass balance equation was used for major inflows and outflows including changes in storage for Georgetown Lake

$$P + S_i + G_i = E + S_o + G_o \quad (1)$$

where

P	Precipitation for the area of the lake
E	Evaporation for the area of the lake
S_i	Surface water into the lake
S_o	Surface water out of the lake
G_i	Groundwater into the lake
G_o	Groundwater out of the lake

and all variables have units of m^3/day (both E and P were multiplied by the lake surface area).

Using Eq. (1), the net groundwater flow through the lake (G_{NET}) can be determined as follows

$$G_{\text{NET}} = G_i - G_o = E + S_o - P - S_i \quad (2)$$

which provides insight to the short-term and seasonal changes in groundwater flux into and out of the lake (Sacks et al. 2014).

Isotope balance

A lake isotope balance was created by measuring or calculating monthly ^{18}O and D values for all of the inflows and outflows to the lake and combining in an isotope balance. The isotopic values were expressed using the following δ notation

$$\delta = \left[\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right] \times 1,000 \quad (3)$$

where R is an isotopic ratio (in this case $^{18}\text{O}/^{16}\text{O}$ or $^2\text{H}/^1\text{H}$), subscripts “sample” and “standard” refer to the ratio of the

sample collected and the ratio of standard respectively. The isotopic abundance ratio is generally small, so each measurement is expressed as per mil (‰). The standard used in this study is Vienna Standard Mean Ocean Water (VSMOW), which has a value of 0‰ for both $\delta^{18}\text{O}$ and δD .

Isotope samples were analyzed by the Montana Bureau of Mines and Geology (MBMG) analytical lab using a Picarro Isotopic Water Analyzer, L2130-i. The samples were run with at least three of the following standards, VSMOW, USGS 48, USGS 47, Greenland Ice Sheet Precipitation (GISP), Standard Light Antarctic Precipitation (SLAP), and a local standard called Lone Mountain. The $\delta^{18}\text{O}$ values for VSMOW, USGS 48, USGS 47, GISP, SLAP and Lone Mountain are 0, -2.24, -19.8, -24.78, -55.5 and -27.1‰ respectively. The δD values for VSMOW, USGS 48, USGS 47, GISP, SLAP, and Lone Mountain are 0, -2, -150.2, -189.5, -428, and -201.2‰ respectively. Analytical uncertainty was ± 1 and ± 0.2 ‰ for δD and $\delta^{18}\text{O}$ respectively.

Monthly samples of $\delta^{18}\text{O}$ and δD were measured from December 2012 to November 2013. The two inflows, FCI and SMS, and the outflow, FCO (Fig. 1), were collected in 10-ml borosilicate bottles with plastic conical lids. Each sample was filtered using a 60-ml high-density polyethylene syringe and 0.2- μm PES syringe filter. The syringe was triple rinsed and the samples were also triple rinsed with filtered water. Specific conductivity (SC) and temperature were also recorded during every field visit at each surface water site using an MS5 Hydrolab.

Water isotopes ($\delta^{18}\text{O}$ and δD), SC, and temperature were also collected from 15 wells surrounding the Georgetown Lake perimeter to determine the groundwater isotopic composition. Isotope samples from an additional 17 wells published in Shaw et al. (2013) was also used as part of this study. Locations for all past and current well samples are shown in Fig. 1. Seasonal groundwater sampling was not conducted because the majority of wells are deep (~25–100 m) and seasonal sampling of SMS showed minimal seasonal variations in $\delta^{18}\text{O}$, δD and flow (see the ‘Results’ section and Fig. 3). The domestic well samples were collected from the outside hose connection in houses with no treated or softened water. Samples were taken after approximately three well volumes had been purged.

In order to do an isotope mass balance, the isotopic compositions for both precipitation and evaporation are needed. Isotopic composition of precipitation was estimated using a correlation of the isotopic compositions of precipitation versus temperature established by Gammons et al. (2006) during a study using 43 precipitation samples at a site roughly 60 km southwest of Georgetown Lake. Gammons et al. (2006) defined the following relationships of temperature to $\delta^{18}\text{O}$ and δD

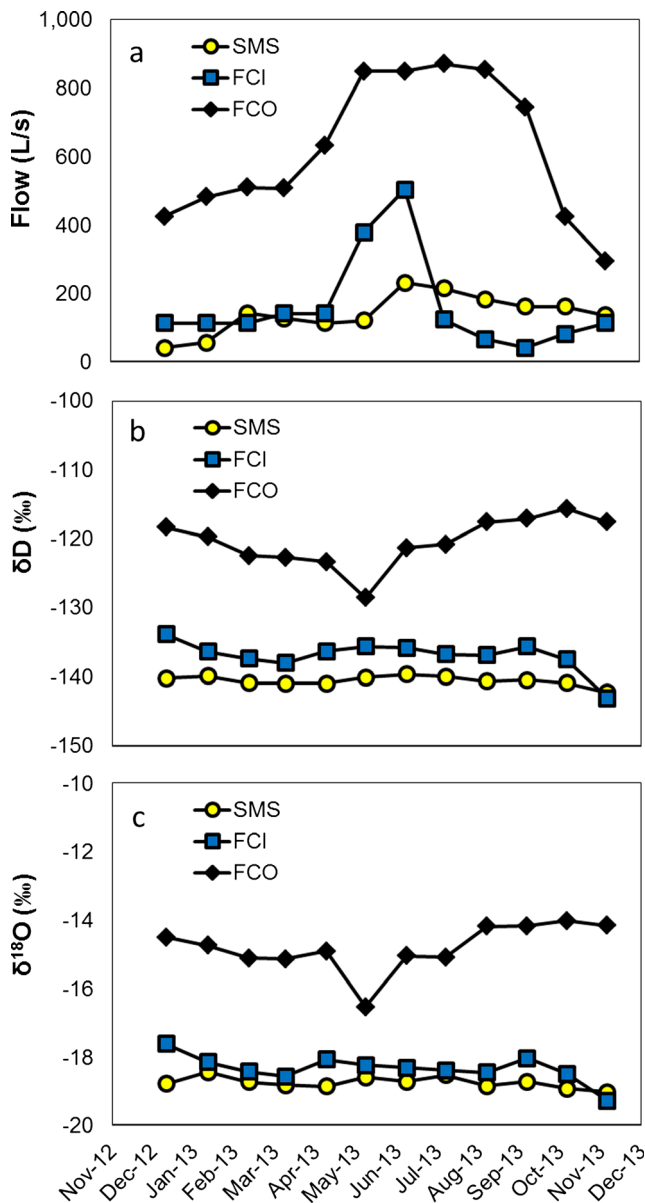


Fig. 3 Temporal variations in **a** flow rates (L/s), **b** δD (‰), and **c** δ¹⁸O (‰) for Stuart Mill Spring (SMS) and Flint Creek inflow (FCI) and outflow (FCO)

$$\delta^{18}\text{O} = 0.58T - 19.6 \tag{4}$$

or

$$\delta\text{D} = 4.25T - 151 \tag{5}$$

where *T* is temperature in °C. *R*² values for Eqs. (4) and (5) are 0.67 and 0.66 respectively.

The Craig-Gordon model was used to determine the isotopic composition of water vapor from lake evaporation (Craig and Gordon 1965). The following equation from Clark and Fritz (1997) was used to solve for the isotopic value for evaporation

$$\delta_v = \delta_L - \varepsilon_{l-v} - \Delta\varepsilon_{bl-v} \tag{6}$$

where the following terms are as defined:

- δ_L Isotopic value for the lake
- δ_v Isotopic value for evaporated water vapor
- ε_{l-v} Fractionation factor for equilibrium, liquid–water–vapor exchange
- Δε_{bl-v} Kinetic fractionation factor for evaporation

To solve for Δε_{bl-v} the following equations from Clark and Fritz (1997) were utilized for oxygen and hydrogen isotopes

$$\Delta\varepsilon^{18}\text{O}_{bl-v} = -14.2 \times (1-h)\text{‰} \tag{7}$$

or

$$\Delta\varepsilon^2\text{H}_{bl-v} = -12.5 \times (1-h)\text{‰} \tag{8}$$

where *h* is the relative humidity.

In order to separate and quantify groundwater inflows from outflows, a lake isotope mass balance, similar to those presented by Krabbenhoft et al. (1990) and Sacks et al. (2014), was derived. Known isotopic composition for major inflows and outflows are multiplied by the quantity of each major inflow and outflow.

$$P\delta_P + S_i\delta_{S_i} + G_i\delta_{G_i} = E\delta_E - S_o\delta_{S_o} - G_o\delta_{G_o} \tag{9}$$

δ denotes the corresponding isotope value for each major inflow or outflow. A steady state isotope mass balance was used instead of transient because changes in lake-water level were not significant, and Mitchell (2014) showed that changes in storage were negligible to the total water balance. The isotopic composition of δ_{G_i} was determined by averaging the isotopic composition of all groundwater wells collected from the Paleozoic carbonate aquifer, which was determined to be the inflowing aquifer to the lake (Shaw et al. 2013). Equations (1) and (9) can be rearranged and combined to solve for both groundwater inflows and outflows. Equation (10) shows how Eq. (1) is solved for groundwater outflows

$$G_o = P + S_i + G_i - E - S_o \tag{10}$$

The isotopic composition of Georgetown Lake was analyzed at 70 locations during winter 2011 (see Shaw et al. 2013), and there is spatial variability of isotopes. Gammons et al. (2014) also illustrate temporal variations of isotopes within the lake. Therefore, the isotopic composition at FCO is assumed to be an integration of isotopic variability within the lake, and monthly samples at FCO capture the temporal variations occurring within the lake. Presentation of lake samples collected in Shaw et al. (2013) is later discussed in section ‘Comparison to previous studies of Georgetown Lake’ and presented in Fig. 5 in this report. By assuming

$\delta_L = \delta_{G_o} = \delta_{S_o}$, Eq. (10) can be incorporated into Eq. (9) and simplified to the following equation

$$G_i = \left[(P\delta_P - E\delta_E + S_i\delta_{S_i} - (P - E + S_i)\delta_L) \div (\delta_L - \delta_{G_i}) \right] \quad (11)$$

Once G_i is calculated the result can be used in the physical mass balance equation (Eq. 2) to solve for G_o .

Watershed isotopes

Shaw et al. (2013) showed that groundwater inflows to the lake are predominantly located on the east side of the lake. Regional springs and small, primarily groundwater-fed creeks were sampled for $\delta^{18}\text{O}$ and δD between September and October of 2013 and compared with the 70 lake samples presented in Shaw et al. (2013). The same field and analytical methods were used as explained in section ‘Isotope balance’. Samples of the springs and streams were collected both within the site catchment and near the base of the lower valley adjacent to the west of the lake (Fig. 1). The purpose of collecting these regional spring and stream samples is to compare with groundwater samples and see if there is any insight in where Georgetown Lake is losing lake water to groundwater recharge. The lake has a strong evaporation signal, and regional groundwater and springs with an evaporated signal may suggest areas where lake water has mixed with groundwater (Shaw et al. 2013).

Results

Lake mass balance

Monthly inflows and outflows to Georgetown Lake from December 2012 to November 2013 are presented in Table 1. Precipitation ranged from 1.0 to 15.7 cm/month. Evaporation ranged from 1.6 to 19.7 cm/month during months with no ice cover. Evaporation was assumed to equal zero during months with ice-cover (November through April). Major surface water inflows and outflows show that monthly flow at FCO was greater than the sum of FCI and SMS (Table 1; Fig. 3). After dividing through by the lake area, the flows at FCO, FCI, and SMS averaged 13.6, 3.5, and 3.1 cm/month from December 2012 to November 2013. Annual values for lake inflows and outflows are found in Table 1.

FCI and SMS flows exhibit natural conditions with low steady flows during the majority of the year and increased flows resulting from snowmelt during May–July (Fig. 3c). Peak inflow from Flint Creek is larger and arrives earlier (May–June) than SMS and dissipates more rapidly. The lesser, sustained response to snowmelt at SMS is typical of a large groundwater spring as opposed to a mountain stream. Flows at FCO remain elevated between May and September, which is

Table 1 Summary of the total monthly inflows, outflows, and changes in storage (cm) at Georgetown Lake from December 2012 until November 2013. *SD* standard deviation

Date (m/year)	Total inflows			Total outflows		Net groundwater flow	
	<i>P</i> (cm)	FCI (cm)	SMS (cm)	<i>E</i> (cm)	FCO (cm)	G_{NET} (cm)	G_{NET} (m ³)
Dec-12	5.8	2.5	0.9	0	9.3	0.1	1.3×10^4
Jan-13	5.3	2.5	1.2	0	10.6	1.5	1.9×10^5
Feb-13	2.0	2.5	3.1	0	11.2	3.6	4.3×10^5
Mar-13	4.3	3.1	2.8	0.0	11.2	0.9	1.1×10^5
Apr-13	3.0	3.1	2.5	0.0	13.9	5.2	6.3×10^5
May-13	11.2	8.4	2.7	9.4	18.7	6.0	7.3×10^6
Jun-13	10.7	11.1	5.1	13.1	18.7	4.9	6.0×10^6
Jul-13	1.0	2.7	4.7	19.7	19.2	30.4	3.7×10^6
Aug-13	5.6	1.5	4.0	13.4	18.8	21.1	2.6×10^6
Sep-13	15.7	0.9	3.6	7.9	16.4	4.0	8.1×10^5
Oct-13	7.4	1.8	3.6	1.6	9.3	-1.9	-2.3×10^5
Nov-13	3.0	2.5	3.0	0.0	6.5	-2.0	-2.5×10^5
Annual	75.2	42.6	37.3	42.6	163.8	73.8	9.0×10^6
Average	6.3	3.5	3.1	5.4	13.6	6.2	7.5×10^5
Median	5.5	2.5	3.1	0.8	12.6	3.8	4.6×10^4
SD	4.3	3.0	1.2	7.0	4.5	9.7	1.2×10^6
Maximum	15.7	11.1	5.1	19.7	19.2	30.4	3.7×10^6
Minimum	1.0	0.9	0.9	0.0	6.5	-2.0	-2.5×10^5

The difference between groundwater inflows and outflows is also presented (cm and m³/month)

P precipitation; *FCI* Flint Creek inflow; *SMS* Stuart Mill Spring; *E* evaporation; *FCO* Flint Creek outflow; G_{NET} net groundwater flow

an artifact of Georgetown Lake outflows being controlled by the dam.

Using the physical mass balance equation (Eq. 2), net groundwater flow through the lake between December 2012 and November 2013 ranged between -2.5×10^5 and 3.7×10^6 m³/month, with an average value of 7.5×10^5 m³/month, with an annual value of 9.0×10^6 m (Table 1). October through November were the only months that displayed negative net groundwater flow (Fig. 4a). July and August had the largest positive net groundwater inflow, which appears to correlate with the largest month in releases of lake water at FCO (Fig. 3c).

Isotope mass balance

Values of $\delta^{18}\text{O}$ and δD for evaporation, precipitation, surface water inflows, outflows, and groundwater are presented in Table 2. The estimated precipitation had the largest variation in values, with $\delta^{18}\text{O}$ ranging from -11.4 to -22.7‰. The most depleted values were during winter and the most isotopically enriched values were during the warmer summer months, similar to values observed in other areas of southwest Montana

Fig. 4 **a** Net groundwater flow at Georgetown Lake, with *positive values* reflecting greater groundwater inflows than groundwater outflows; **b** percent inflows, **c** percent outflows at Georgetown Lake

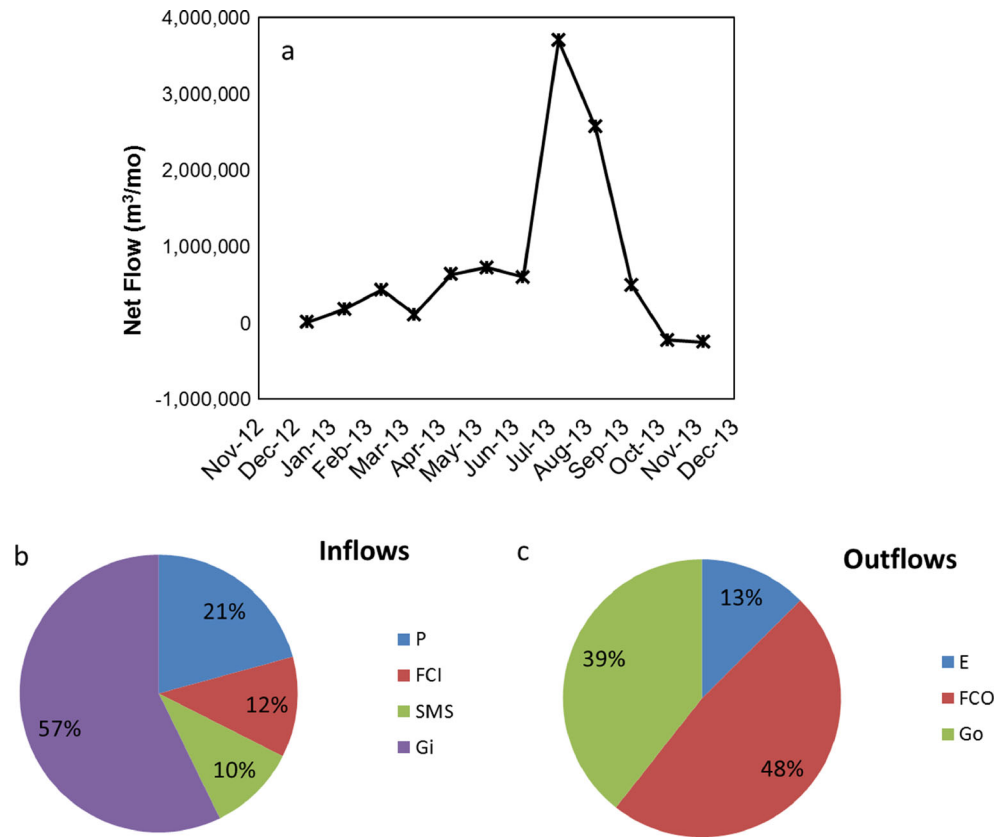


Table 2 Isotopic composition for major inflows and outflows used in the isotope mass balance. *SD* standard deviation

Date (month-year)	Total inflows						Total outflows			
	<i>P</i>		FCI		SMS		<i>E</i>		FCO	
	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)
Dec-12	-174	-22.7	-134	-17.6	-140	-18.8	-236	-31.0	-118	-14.5
Jan-13	-173	-22.7	-136	-18.1	-140	-18.4	-238	-31.9	-120	-14.8
Feb-13	-170	-22.2	-137	-18.4	-141	-18.7	-240	-32.5	-122	-15.1
Mar-13	-162	-21.1	-138	-18.6	-141	-18.8	-237	-32.7	-123	-15.1
Apr-13	-151	-19.7	-136	-18.1	-141	-18.9	-240	-33.3	-123	-14.9
May-13	-130	-16.7	-136	-18.2	-140	-18.6	-233	-32.9	-129	-16.5
Jun-13	-112	-14.3	-136	-18.3	-140	-18.7	-221	-31.3	-121	-15.1
Jul-13	-91	-11.4	-137	-18.4	-140	-18.5	-217	-32.4	-121	-15.1
Aug-13	-97	-12.2	-137	-18.5	-141	-18.8	-215	-31.8	-118	-14.2
Sep-13	-114	-14.5	-136	-18.0	-140	-18.7	-217	-30.1	-117	-14.2
Oct-13	-149	-19.3	-137	-18.5	-141	-18.9	-226	-30.7	-116	-14.0
Nov-13	-159	-20.7	-143	-19.3	-142	-19.0	-231	-31.5	-118	-14.2
Average	-140	-18.1	-137	-18.3	-141	-18.8	-229	-31.8	-120	-14.8
Median	-150	-19.5	-137	-18.4	-141	-18.8	-232	-31.9	-120	-14.8
SD	30	4.1	2	0.4	1	0.2	10	1.0	4	0.7
Maximum	-91	-11.4	-134	-17.6	-140	-18.4	-215	-30.1	-116	-14.0
Minimum	-174	-22.7	-143	-19.3	-142	-19.0	-240	-33.3	-129	-16.5

(Gammons et al. 2006; Abdo et al. 2013). Shaw et al. (2013) show that FCO is isotopically similar to Georgetown Lake and appears to be an integration of lake-water chemistry sampled spatially around the lake. As a result, the lake was assumed to be identical to FCO values for this study, and FCO was the most isotopically enriched water sampled with mean $\delta^{18}\text{O}$ and δD of -14.8 and -120‰ respectively. Evaporated water vapor was the most isotopically depleted, with mean $\delta^{18}\text{O}$ and δD of -31.8 and -229‰ respectively. Precipitation, FCI and SMS had $\delta^{18}\text{O}$ and δD values in between evaporation and FCO values (Table 2).

Results from the isotope mass balance combined with the physical mass balance (Eqs. 10 and 11) were used to determine gross groundwater inflows and outflows to Georgetown Lake. Annual groundwater inflow to the lake was estimated to be 207.7 cm/year (2.5×10^7 m³/year) using $\delta^{18}\text{O}$, and 279.1 cm/year (3.4×10^7 m³/year) using δD values (Table 3). Total mean groundwater outflow was 133.8 cm/year (1.6×10^7 m³/year) using $\delta^{18}\text{O}$ and 205.3 cm/year (2.5×10^7 m³/year) using δD . The oxygen isotope analysis ($\delta^{18}\text{O}$) has an analytical precision of $\pm 0.2\text{‰}$, whereas the deuterium isotope has an analytical precision of $\pm 1\text{‰}$. For this reason, the isotopic mass balance results using $\delta^{18}\text{O}$ were considered the most reliable and were the results that were analyzed throughout the rest of the analytical portion of this study. In comparison with all of the inflows to Georgetown Lake, and using the oxygen isotope results, approximately 57% of the total inflow to the lake is a result of inflowing groundwater (Fig. 4b). Total annual groundwater outflows are roughly 64% of the total groundwater inflows, and roughly 39% of the total outflows measured in the water balance.

The isotope mass balance equation results were recalculated with uncertainty ranges in the water budget terms (Table 4). Evaporation was both increased and decreased by 10 and 20%. Precipitation was only decreased because the SNOTEL site where the precipitation data came from is at a higher elevation and would more likely exhibit more

Table 3 Physical and isotopic mass balance values and isotope mass balance results for groundwater inflow and outflow

Type of flow	Parameter	Flow (m ³ /year)
Inflows	Precipitation	9.1×10^6
	FCI	5.2×10^6
	SMS	4.5×10^6
Outflows	Evaporation	8.1×10^6
	FCO	2.0×10^7
Calculated groundwater flows	G_i ($\delta^{18}\text{O}$)	2.5×10^7
	G_o ($\delta^{18}\text{O}$)	1.6×10^7
	G_i (δD)	3.4×10^7
	G_o (δD)	2.5×10^7

Table 4 Sensitivity analysis of the isotope mass balance

Parameter change in water and isotope balance with the percent increase/decrease	Increase or decrease	Total G_i (m ³ /year)	Total G_o (m ³ /year)	G_i % of total inflow
Original		2.53×10^7	1.63×10^7	57%
Precipitation 10%	↓	2.59×10^7	1.60×10^7	59%
Precipitation 20%	↓	2.65×10^7	1.57×10^7	61%
Evaporation 10%	↓	2.12×10^7	1.30×10^7	53%
Evaporation 10%	↑	2.94×10^7	1.97×10^7	61%
Evaporation 20%	↓	1.71×10^7	9.64×10^6	47%
Evaporation 20%	↑	3.36×10^7	2.30×10^7	64%
Surface water inflows 10%	↑	2.63×10^7	1.63×10^7	59%
Surface water inflows 10%	↓	2.43×10^7	1.63×10^7	55%
Surface water inflows 20%	↑	2.73×10^7	1.64×10^7	62%
Surface water inflows 20%	↓	2.33×10^7	1.63×10^7	53%

The arrows indicate an increase or decrease in each parameter

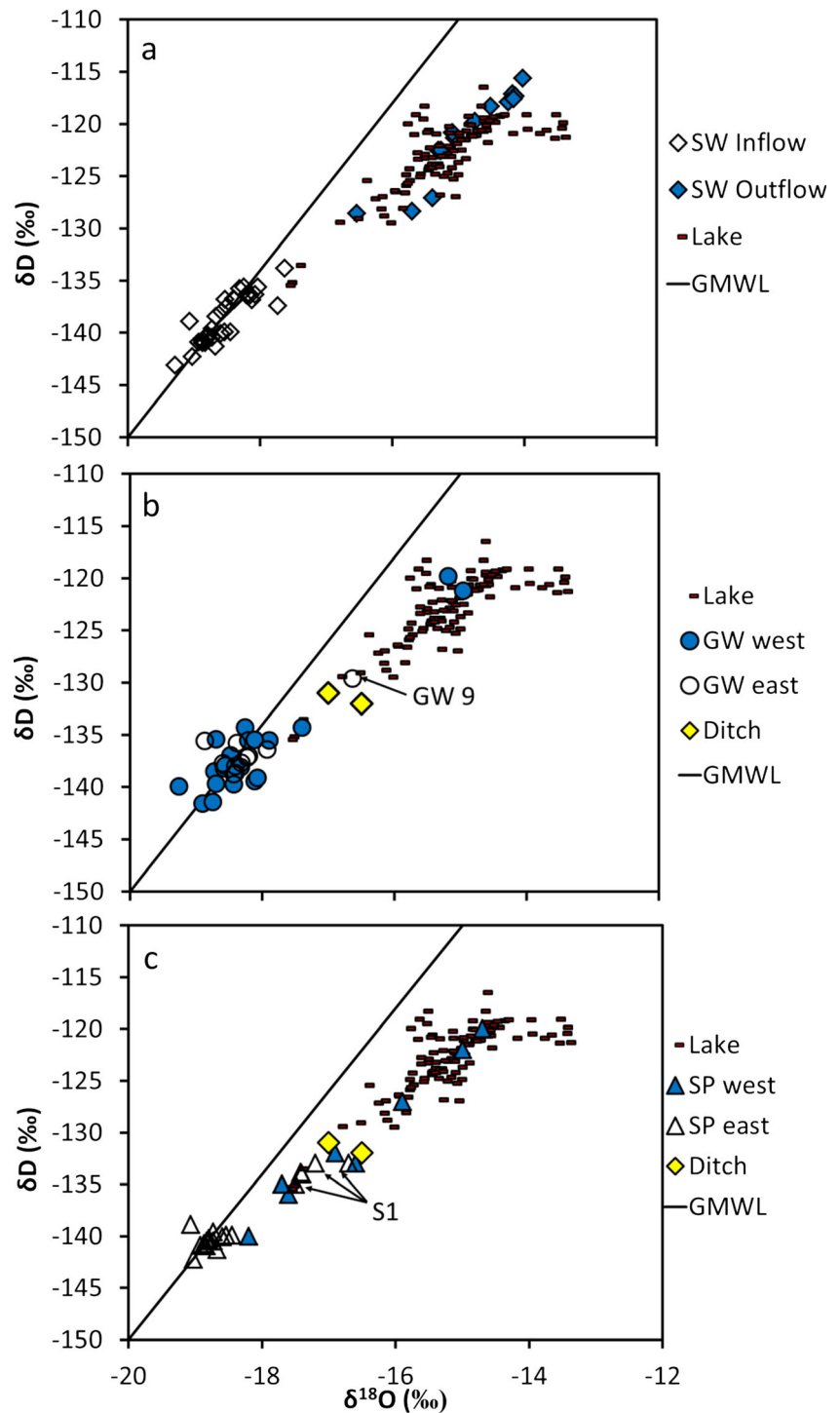
precipitation than the lake area (NOAA SNOTEL site PTNM8). Surface water inflows were both increased and decreased by 10 and 20%. The sensitivity analysis showed that the isotope mass balance was most sensitive to the amount of evaporation. When evaporation was changed by $\pm 20\%$ groundwater inflows ranged between 47 to 64% of total inflows, which corresponds to a decrease of 10% and an increase of 7% from the results presented in this study. Changes in precipitation and surface water inflows resulted in percent groundwater inflows varying by less than or equal to 5% variation.

Watershed isotopes

Water isotope results ($\delta^{18}\text{O}$ versus δD) for all surface water, springs, and groundwater are presented in Table S1 of the electronic supplementary material (ESM). Lake-water samples presented in Shaw et al. (2013) are also used for comparison of inflow and outflow samples used in this study. Individual lake-water chemistry samples are in the supplementary material of Shaw et al. (2013). Surface water inflows (FCI and SMS) and outflows (FCO) plotted with lake samples show a distinct separation in grouping (Fig. 5a). FCO and lake samples are isotopically similar and deviate significantly from the GMWL suggesting the samples have undergone significant evaporation. FCI and SMS (labeled as SW Inflow) are isotopically depleted and generally plot on or near the GMWL suggesting a meteoric water source with little to no evaporation.

The isotopic composition of groundwater for 15 domestic wells surrounding Georgetown Lake combined with 17 previous well samples presented by Shaw et al. (2013) are plotted in Fig. 5b with lake samples for comparison. In general, groundwater samples are clustered near the GMWL with

Fig. 5 Water isotope values (δD and $\delta^{18}O$) for **a** major inflows (*SW Inflow*) and outflows (*SW Outflow*) in comparison with the lake, **b** domestic well samples located west (*GW west*) and east (*GW east*) of the Georgetown Thrust Fault in comparison to the lake, and **c** spring and baseflow small tributary samples located west (west springs) and east (east springs) in comparison to lake samples. The Global Meteoric Water Line (*GMWL*) is shown for reference (Craig 1961). Ditch water (labeled *Ditch*) carrying Silver Lake water is also shown (**b** and **c**)



relatively depleted values in comparison to lake samples. Groundwater samples collected east and west of the Georgetown Thrust Fault are labeled *GW east* and *GW west* respectively. The majority of groundwater samples are isotopically depleted relative to lake samples and plot near the GMWL; however, a few samples (4–6) appear to plot along a local evaporation line (LEL) that trends toward the lake samples. All but one of these groundwater samples along this

apparent LEL are from wells sampled along the west side of the lake. The one *GW east* sample plotting along the apparent LEL (*GW-9*) is a shallow well (~2 m) placed in alluvium near a small ditch where Silver Lake water is sometimes routed to Georgetown Lake. Ditch water plots very near *GW-9* (labeled as “ditch” on Fig. 5b,c). The evaporative signal in *GW-9* may be attributed to local recharge of ditch water to shallow groundwater. Isotopically enriched well samples on the west

side of the thrust fault were collected from relatively deep (e.g. ~100 m depth) domestic wells located at homes with lakeside or very close to lakeside properties.

Isotope results for springs and small groundwater fed creeks (Fig. 1 for locations) show varying amounts of mixing between depleted meteoric values close to the GMWL and evaporated lake samples (Fig. 5c). In particular, separation of springs sampled to the west and east of the Georgetown Thrust Fault are plotted on Fig. 5c (labeled SP west and SP east respectively). SMS and spring S1 are the only two springs located to the east of the thrust fault, and were sampled several times. Generally, they have isotopically depleted chemistry with little evaporation, but spring S1 appears to sometimes receive water from a ditch connected to Silver Lake (labeled S2 on Fig. 5c). Although FCI samples are presented with surface inflows and outflows (Fig. 5a), the isotopic composition of FCI is also significantly depleted and during much of the year could be classified as a low-flowing groundwater-fed creek. Springs and groundwater-fed creeks sampled west of the Georgetown Thrust Fault were generally sampled only once or twice, and consistently show varying degrees of evaporation (Fig. 5c). Generally, the west side springs tend to be more isotopically enriched and have evaporated signatures more similar to the lake than on the east side.

Discussion

Summary of the water balance for Georgetown Lake

Results from this study combined with results from Shaw et al. (2013) and Gammons et al. (2014) can be used to develop a conceptual understanding of groundwater flow to and from Georgetown Lake (Fig. 6). Both net groundwater and

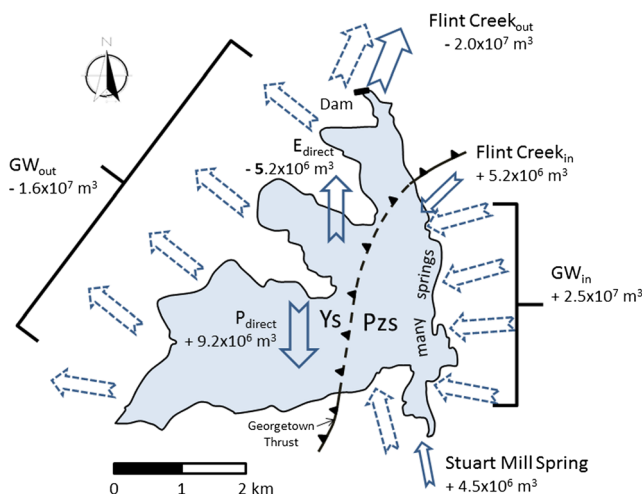


Fig. 6 Schematic illustrating annual flow volumes for inflows, outflows, and changes in storage during the 2012/2013 water year. *Arrows* show the directions of flow, with subsurface flows illustrated by *hashed lines*

estimates of groundwater inflows and outflows to and from the lake show that groundwater inflows (2.5×10^7 m³/year) are nearly twice as high as groundwater outflows (1.6×10^7 m³/year). Shaw et al. (2013) show that groundwater inflows occur through karst carbonates located to the east of the Georgetown Thrust Fault. Due to the karst nature of groundwater flow in the area, groundwater inflow most likely enters the lake through many submarine springs discharging at fractures and/or karst voids instead of a spatially continuous specific discharge that may be expected from unconsolidated alluvium. An unpublished map showing spring locations prior to creating Georgetown Lake confirms that there are several springs along the east side with varying amounts of flow (not quantified). Some are listed as “large” flows. $\delta^{18}\text{O}$ and δD from groundwater sampled along the east side of the lake are isotopically depleted and plot on the BMWL suggesting a meteoric source of water with little to no evaporation (Fig. 5). While groundwater inflow rates may seem large in comparison to surface-water inflows, the total surface and groundwater flow rates fall well within the expected incoming precipitation for the entire catchment that drains to Georgetown Lake. SMS is treated as surface water in this study because it discharges to ground surface above the lake, but it is an example of the types of the magnitude of karst spring flow that may occur within the lake system, and its magnitude is nearly the same as FCI (Fig. 4).

Two seepage meters coupled with minipiezometers installed from August 17 to September 24, 2011 measured groundwater discharge fluxes of 339.1 and 23.8 g/m²/day and vertical hydraulic gradients (directed upwards) of roughly 0.03 and 0.01 respectively (Shaw and White, unpublished data), which also suggests inflow of groundwater to the lake along the eastern shore. However, with only two seepage meter estimates, the spotty nature of groundwater flow to the lake, and limited knowledge of the water table near the lake, it is nearly impossible to make reasonable Darcy flux calculations to support the calculated groundwater inflows from the isotope balance.

Silver Lake may recharge some of the shallow Quaternary alluvium located between Silver and Georgetown Lakes and that water may later discharge to Georgetown Lake (Figs. 1 and 2). Shallow groundwater located between Georgetown and Silver Lake shows isotopic enrichment similar to Silver Lake water chemistry, and could be from direct seepage inflow of Silver Lake, which sits at a slightly higher elevation than Georgetown Lake (Garrett 1983; Fig. 5bc).

While groundwater outflow from Georgetown Lake is less than total incoming groundwater flow to the lake, it was a magnitude roughly 75% of the total surface water outflow measured at FCO (Fig. 6). Shaw et al. (2013) suggested that groundwater outflow occurs through the bedding and fractures located on the western side of the Georgetown Thrust Fault over the western approximately two-thirds of the lake.

Not all of the groundwater wells located along the western perimeter of the lake show similar evaporated water as Georgetown Lake, a handful of the western wells do have a similar evaporated isotopic signature (Fig. 5). It may be that this evaporated signature is a result of Georgetown Lake water recharging groundwater at discrete fracture zones. White (2012) showed similar water quality and major ion concentrations in at least one of the wells located near the southwestern portion of the lake which strongly suggested lake water recharges groundwater in some portions of the lake. The west-dipping rock, lower valley to the west of the lake, and regional potentiometric surface map (estimated by Waren and LaFave 2011) support a westward flow of groundwater away from the lake. Furthermore, all springs and small tributaries located near the eastern edge of the lower valley (west of the lake) show some evidence of evaporation relative to local meteoric water, which strongly suggests that Georgetown Lake provides some recharges of groundwater to the west of the lake. Regional groundwater mixed with Georgetown Lake water appears to discharge lower in the valley as springs or baseflow to small creeks flowing from the hills situated between Georgetown Lake to the lower valley to the west. No other literature used for this study was found to use regional isotopes to illustrate leakage outflow locations.

During sampling, flows were sometimes measured at some of the springs and creeks. Spring S8 flow was approximately $6.1 \times 10^5 \text{ m}^3/\text{year}$ ($1.98 \times 10^{-2} \text{ m}^3/\text{s}$) in September, and spring S4 flows were $6.2 \times 10^5 \text{ m}^3/\text{year}$ ($2.0 \times 10^{-2} \text{ m}^3/\text{s}$) and $3.1 \times 10^5 \text{ m}^3/\text{year}$ ($1.1 \times 10^{-2} \text{ m}^3/\text{s}$) for July and September respectively (Fig. 1 for locations). The combination of flow from these two springs results in 11% (using July S4 flows) and 5% (using September flows) of the total calculated groundwater outflow from Georgetown Lake (Table 3), which is well within the total lake outflow budget. Unaccounted flow could be supplying regional groundwater to the semiarid, agricultural valley to the west without discharging as discrete springs. A more comprehensive study should be conducted to advance and test this idea, but it would be complicated by rugged terrain and limited wells available for testing.

Groundwater underflow exiting below the dam may also account for a substantial amount of groundwater outflow from Georgetown Lake. The dam is located in a tight canyon that may very well be underlain by coarse-grained sediment and a dense fracture network below the sediment.

Sources of uncertainty

Results from the sensitivity analysis show that the isotope balance is most sensitive to evaporation. Evaporation estimates for this study may also have more uncertainty because of the lack of direct estimates taken from Georgetown Lake. Instead, empirical relationships taken from temperature data were used in this study. Temperature data were collected from

the Philipsburg station located ~20 km from the lake and at roughly 300 m lower elevation. The higher elevation of the lake would result in cooler temperatures (less evaporation), but the lake nearly always has a strong breeze relative to surrounding lower valleys. The elevated wind would result in an increase in evaporation which would counteract the cooler temperature. In previous studies at certain times of the year lake water displays a strong isotopic evaporation signal, especially the western portion of the lake which has no inflows (Shaw et al. 2013; Gammons et al. 2014).

Precipitation taken from SNOTEL sites at elevations ~240 m higher than the study site would suggest that the precipitation rates may be slightly lower than what was used in this study. If evaporation is higher and precipitation lower than values used in this study, a higher groundwater inflow rate to Georgetown Lake would result. When evaporation is increased by 20% and precipitation decreased by 20% groundwater inflow relative to total inflow increases by 7 and 4% respectively. The calculated groundwater inflow rate (m^3/year) increases by ~30 and 4% when evaporation is increased and precipitation is decreased respectively.

Using the regression that was developed between average daily temperature vs. isotopic composition of rain and snow for Butte, MT, developed by Gammons et al. (2006), to estimate the isotopic composition of precipitation may also add uncertainty in the isotope mass balance. However, other sites in southwest Montana appear to have the same or a similar meteoric water line as the regression developed by Gammons (Abdo et al. 2013; Thomson 2016). The similarity of Butte's precipitation with that of other nearby regions in Montana suggests that the use of the Butte temperature vs. isotope regression may be adequate for this study, but collection of precipitation in the Georgetown Lake watershed would be more accurate.

The use of a steady-state isotope balance at Georgetown Lake also requires some caution. Monthly inflows and outflows clearly show temporal variation (Table 1; Fig. 3), but in general the total lake volume remains essentially constant. Net groundwater flow also changes significantly throughout the study period, and even shows groundwater outflows exceeding groundwater inflows during the months of October and November 2012 (Fig. 4). Mitchell (2014) showed that changes in monthly lake stage values were small in comparison with other inflow and outflow measurements. Mitchell (2014) also showed that these small changes in lake storage resulted in negligible changes on a lake-water balance, suggesting that a steady-state isotope balance is appropriate for this study and may even decrease overall uncertainty.

Isotope balances require an isotopically well-mixed lake. While this is true at Georgetown Lake during months with no ice cover, a chemocline gradually forms throughout the periods of time with ice covering the lake (Gammons et al. 2014), and isotopic values of lake water also vary spatially

by the end of the “ice-on” period (Shaw et al. 2013). This may result in error to the isotope balance conducted, but the use of FCO as δ_L is assumed to be the most accurate method for integrating the isotopic variations within the lake. Considering the uncertainty that exists in the isotope balance, the classification of Georgetown Lake being a high groundwater inflow lake likely remains.

Comparison to previous studies of Georgetown Lake

Previous methods used to estimate annual groundwater inflow to Georgetown Lake prior to this study did not consider groundwater outflows. In other words, the net groundwater inflow was solved and since outflow was assumed to be zero, net inflow was taken as actual inflow. Two estimates for the 1974 water year gave net groundwater values of 50 and 55% of total inflows (Knight et al. 1976; Garrett 1983, 1984). Three attempts for the 1975 water year consistently showed lower net groundwater gains with values of 38, 40, and 42% (Knight et al. 1976; EPA 1977; Garrett 1983, 1984). Garrett (1983, 1984) also showed that the net groundwater gain for the 1982 water year was 43%.

The current study improves on past studies by (1) illustrating monthly variations in net groundwater gains (Fig. 4a), and (2) separating both groundwater inflow to Georgetown Lake and leakage outflow from the lake. The current study shows actual groundwater inflow was 57% of total inflows and net groundwater inflow was 32%, which falls just below the EPA (1977) estimate for the 1975 water year. In a previous attempt to separate groundwater inflow and outflow to Georgetown Lake (White 2012), Cl^- and specific conductivity mass balances yielded estimates of 24 and 31%, respectively, for total inflows from groundwater. However, the estimates of White (2012) are considered less reliable, as they were based on sampling conducted in March and April 2011 when the lake experiences a relatively strong chemocline under ice cover.

Comparison to other lakes

While the isotope mass balance approach is useful for quantifying groundwater inflows and outflows, there may be uncertainty in estimating exact groundwater flow rates and/or percentages of the total water balance. Sacks (2002) used a similar isotope mass balance approach and categorized lakes into three groups based on the influence of groundwater. They are low, medium, and high groundwater input lakes which have percent groundwater inflows relative to total inflows of <25, 25–50, and >50% respectively. Based on these ranges, Georgetown Lake would be considered a medium to high groundwater input lake. Groundwater outflows are volumetrically lower than groundwater inflows and also reflect only 39% of the total outflows from Georgetown Lake (Fig. 4).

Rosenberry et al. (2015) tabulates over 100 separate lake studies where groundwater inflow to lakes and leakage outflow from lakes are quantified and compared with lake size. They show a general relationship with lake size and percent groundwater inflow or leakage outflow. Generally, the percent of total flow into or out of the lake as groundwater decreases as lake size increases. They show that no lake with an area greater than 100 ha had more than 35 and 40% groundwater inflow to lakes and leakage outflow respectively. Rosenberry et al. (2015) argues that the majority of groundwater inflow or leakage outflow occurs along the lake perimeter and as lake area increases, the surface area to perimeter ratio decreases. The percent groundwater inflow to Georgetown Lake nearly doubles the maximum expected values presented by Rosenberry et al. (2015). The high percent of groundwater inflow might be explained from the discontinuous nature of karst hydrology on the lake with numerous springs discharging to the lake (Garrett 1983; Shaw et al. 2013). Leakage outflow from Georgetown Lake is 39% of total outflows, which is at the high end of what Rosenberry et al. (2015) show for a lake the size of Georgetown Lake. The nature of leakage from Georgetown Lake through fractures and bedding planes of the underlying metasedimentary rocks is different from karst voids that have the potential to create large springs, which may keep outflow rates within the expected range.

The large fluxes of groundwater inflow and leakage outflow to and from Georgetown Lake are important quantities to know for the entire water balance. Shaw et al. (2013) and Gammons et al. (2014) suggest that groundwater through flow may be very important for buffering lake-water quality to near-optimal levels for the fishery, while preventing the entire water column from going anoxic/suboxic in winter.

Conclusions

This report presents a groundwater–surface water investigation of Georgetown Lake that (1) quantified groundwater inflows and outflows to and from the lake and classifies the relative role of groundwater inflow to the lake, and (2) addresses the location and processes that control groundwater inflow and outflows to and from the lake. The use of isotopes was crucial for accomplishing both major objectives. Combining an isotope balance with a water balance using physical measurements of surface water inflows and outflows provided reasonable estimates of groundwater inflows and outflows rather than simply estimating net groundwater inflow rates. The physical mass balance approach showed that groundwater inflow is greater than groundwater outflow year-round except for the months of October and November. The isotopic mass balance showed that groundwater contributes approximately 57% of the total inflow into Georgetown

Lake, and the lake can be categorized as a medium-high to high groundwater inflow Lake. Uncertainty in precipitation and evaporation measurements suggest that groundwater inflow rates may actually be elevated with total inflows relative to total inflows increasing by 7% for evaporation and 4% for precipitation.

The use of water isotopes from groundwater and springs to help characterize where and how groundwater inflow and outflow occur through the lake is particularly useful. In the case of Georgetown Lake, springs and groundwater sampled where groundwater is known to discharge to the lake showed no evaporation. The lake, on the other hand, had a strong evaporated isotopic signature. Some of the groundwater samples, and several of the springs located downgradient from the lake where groundwater was expected to discharge showed partial or significant evaporation similar to Georgetown Lake. The setting is too complex to definitively identify lake water recharging groundwater to the west of the lake, but the west dipping metasedimentary rocks underlying the lake may provide a conduit for lake water to exit and recharge groundwater.

Considering, (1) the large amounts of groundwater inflows and outflows relative to the total water budget for the lake, (2) current water quality issues with nutrients and anoxia (Shaw et al. 2013; Stafford 2013; Gammons et al. 2014), and (3) current pressures for expanding subdivision around the lake, management considerations based on the amount and locations of groundwater inflow and outflow might be considered during planning. For example, septic systems located on the east side of the lake where groundwater flows to the lake might result in providing a nutrient source, or domestic wells placed on the west side of the lake where lake water appears to recharge groundwater might result in drinking water with elevated nutrients and/or pathogens.

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References

- Abdo G, Butler J, Myse T, Wheaton J, Snyder D, Metesh J, Shaw G (2013) Hydrogeologic investigation of the Beaverhead River Study Area, Beaverhead County, Montana. Montana Bureau of Mines and Geology Open-File Report 637. Montana Bureau of Mines and Geology, Butte, MT
- Ameli AA, Craig JR (2014) Semianalytical series solutions for three-dimensional groundwater–surface water interaction. *Water Resour Res* 50(5):3893–3906
- Bocanegra E, Quiroz Londoño OM, Martínez DE, Romanelli A (2013) Quantification of the water balance and hydrogeological processes of groundwater–lake interactions in the Pampa Plain. *Argentina Environ Earth Sci* 68:2347–2357
- CalTopo (2015) Topography data. <http://www.caltopo.com>. Accessed March 2016
- Cartwright I, Hall S, Tweed S, LeBlanc M (2009) Geochemical and isotopic constraints on the interaction between saline lakes and groundwater in southeast Australia. *Hydrogeol J* 17:1991–2004
- Clark ID, Fritz P (1997) Environmental isotopes in hydrogeology. CRC, Boca Raton, FL
- Corbett DR, Bernett WC, Cable PH, Clark SB (1997) Radon tracing of groundwater input into Par Pond, Savannah River site. *J Hydrol* 203: 209–227
- Craig H (1961) Isotopic variations in meteoric waters. *Science* 133:1702–1703
- Craig H, Gordon LI (1965) Deuterium and oxygen 18 variations in the ocean and marine atmosphere. In: Tongiogi E (ed) Stable isotopes in oceanographic studies and paleotemperatures, Spoleto, Italy. V. Lishi e F, Pisa, Italy
- Dessie M, Verhoest NEC, Pauwels VRN, Adgo E, Deckers J, Peosen J, Nyssen J (2015) Water balance of a lake with floodplain buffering: Lake Tana, Blue Nile basin. *Ethiopia J Hydrol* 522:174–186
- Elsawwaf M, Feyen J, Batelann O, Bakr M (2014) Groundwater–surface water interaction in Lake Nasser. *Southern Egypt Hydrol Process* 28:414–430
- Environmental Protection Agency (1977) National eutrophication survey. Working Paper Series, Report of Georgetown Lake Deer Lodge and Granite counties Montana EPA Region VIII, Working paper no. 793, Montana EPA, Helena, MT, 12 pp
- Gammons CH, Poulson SR, Pellicori DA, Reed PJ, Roesler AJ, Petrescu EM (2006) The hydrogen and oxygen isotopic composition of precipitation, evaporated mine water, and river water in Montana. *USA J Hydrol* 328:319–330
- Gammons CH, Henne W, Poulson SR, Parker SR, Johnston TB, Dore JE, Boyd ES (2014) Stable isotopes track biogeochemical processes under seasonal ice cover in a shallow, productive lake. *Biogeochemistry* 120:359–379
- Garrett PA (1983) Relationships between benthic communities, land use, chemical dynamics, and trophic State in Georgetown Lake. PhD Thesis, Montana State University, Bozeman, MT, 149 pp
- Garrett PA (1984) Georgetown Lake Clean Lakes Project. Phase I. Final Report to EPA, US EPA, Washington, DC, 243 pp
- Gurrieri JT, Furniss G (2004) Estimation of groundwater exchange in alpine lakes using non-steady mass-balance methods. *J Hydrol* 297:187–208
- Hagerthy SE, Kerfoot WC (1998) Groundwater flow influences the biomass and nutrient ratios of epibenthic algae in a north temperate seepage lake. *Limnol Oceanogr* 43(6):1227–1242
- Hood JL, Roy JW, Hayashi M (2006) Importance of groundwater in the water balance of an alpine headwater lake. *Geophys Res Lett* 33: L13405. doi:10.1029/2006GL026611
- Hunt RL, Haitjema HM, Krohelski JT, Feinstein DT (2003) Simulating ground water–lake interactions: approaches and insights. *Ground Water* 41(2):227–237
- Isokangas E, Rozanski K, Rossi PM, Ronkanen AK, Kløve B (2015) Quantifying groundwater dependence of a sub-polar lake cluster in Finland using an isotope mass balance approach. *Hydrol Earth Syst Sci* 19:1247–1262
- Jarosiewicz A, Witek Z (2014) Where do nutrients in an inlet-less lake come from? The water and nutrient balance of a small mesotrophic lake. *Hydrobiologia* 724:157–173
- Karan S, Kidmose J, Engesgaard P, Nilsson B, Frandsen B, Ommen DAO, Flindt MR, Anderson FØ, Pedersen O (2014) Role of groundwater–lake interface in controlling seepage of water and nitrate. *J Hydrol* 517:791–802

- Kebede S, Travi Y, Alemayehu T, Marc V (2006) Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin. *Ethiopia J Hydrol* 316:233–247
- Kluge T, Ilmberger J, von Rohden C, Aeschbach-Hertig W (2007) Tracing and quantifying groundwater inflow into lakes using a simple method for radon-222 analysis. *Hydrol Earth Syst Sci* 11:1621–1631
- Knight JC (1981). An Investigation of the General Limnology of Georgetown Lake, Montana. PhD Thesis, Montana State University, Bozeman, MT, 139 pp
- Knight JC, Garrison PJ, Wright JC (1976) An investigation into the extent and cause of eutrophication in Georgetown Lake, Montana. Report no. 77, Montana University Joint Water Resources Research Center, Bozeman, MT, 97 pp
- Kohler MA, Nordenson TJ, Fox WE (1955) Evaporation from pans and lakes. Research paper no. 38, US Department of Commerce, Washington, DC, 26 pp
- Krabbenhoft DP, Webster KE (1995) Transient hydrogeological controls on the chemistry of a seepage lake. *Water Resour Res* 31(9):2295–2305
- Krabbenhoft DP, Bowser CJ, Anderson MP, Valley JW (1990) Estimating groundwater exchange with lakes: 1. the stable isotope mass balance method. *Water Resour Res* 26:2445–2453
- Kummu M, Tes S, Yin S, Adamson P, Jozca J, Koponen J, Richey J, Sarkkula J (2014) Water balance analysis for the Tonle Sap Lake-floodplain system. *Hydrol Process* 28:1722–1733
- Lavoie R, Joerin F, Rodriguez MJ (2014) Incorporating groundwater issues into regional planning in the Province of Quebec. *J Environ Plan Manag* 57(4):516–537
- Lee TM, Sacks LA, Swancar A (2014) Exploring the long-term balance between net precipitation and net groundwater exchange in Florida seepage lakes. *J Hydrol* 519:3054–3068
- Lei Y, Yao T, Bird BW, Yang K, Zhai J, Sheng Y (2013) Coherent lake growth on the central Tibetan Plateau since the 1970s: characterization and attribution. *J Hydrol* 483:61–67
- Lewandowski J, Meinikmann K, Nutzmann K, Rosenberry DO (2015) Groundwater—The disregarded component in lake water and nutrient budgets. 2. Effects of groundwater on nutrients. *Hydrol Process* 29:2922–2955
- Lonn JD, McDonald C, Lewis RS, Kalakay TJ, O'Neill JM, Berg RB, Hargrave P (2003) Preliminary geologic map of the Philipsburg 30' × 60' quadrangle, western Montana. Open File Rep 48, Montana Bureau of Mines and Geology, Helena, MT
- Millham NP, Howes BL (1994) Nutrient balance of a shallow coastal embayment: I. patterns of groundwater discharge. *Mar Ecol Prog Ser* 112:155–167
- Mitchell KL (2014) Groundwater and surface water interactions at Georgetown Lake, Montana with emphasis on quantification of groundwater contribution. MSc Thesis, Montana Tech of the University of Montana, Butte, MT, 70 pp
- Nachiappan RMP, Kumar B, Manickavasagam RM (2015) Estimation of subsurface components in the water balance of Lake Nainital (Kumanun Himalaya, India) using environmental tracers. *Hydrological Sciences Journal* 47:S41–S54
- Ojiambo BS, Poreda RJ, Lyons WB (2001) Ground water/surface water interactions in Lake Naivasha, Kenya, using $\delta^{18}\text{O}$, δD , and $^3\text{H}/^3\text{He}$ age-dating. *Ground Water* 39(4):526–533
- Radke LC, Howard KWF (2007) Influence of groundwater on the evaporate evolution of saline lakes in Wimmera of south-eastern Australia. *Hydrobiologia* 591:185–205
- Rodellas V, Garcia-Orellana J, Garcia-Solsona E, Masqué P, Domínguez JA, Ballesteros BJ, Mejias M, Zarroca M (2012) Quantifying groundwater discharge from different sources into a Mediterranean wetland by using ^{222}Rn and Ra isotopes. *J Hydrol* 466–467:11–22
- Rosenberry DO, Lewankowski J, Meinikmann K, Nutzmann G (2015) Groundwater: the disregarded component in lake water and nutrient budgets—1. effects of groundwater on hydrology. *Hydrol Process* 29:2895–2921
- Rudnick S, Lewanski J, Nutzmann G (2014) Investigating groundwater–lake interactions by hydraulic heads and a water balance. *Ground Water* 53(2):227–237
- Sacks LA (2002) Estimating ground-water inflow to lakes in central Florida using isotope mass-balance approach. *US Geol Surv Water Resour Invest Rep* 02-4192, 68 pp
- Sacks LA, Lee TM, Swancar A (2014) The suitability of a simplified isotope-balance approach to quantify transient groundwater–lake interactions over a decade with climatic extremes. *J Hydrol* 519:3042–3053
- Schmidt A, Gibson JJ, Santos R, Schubert M, Tattrie K, Weiss H (2010) The contribution of groundwater discharge to the overall water budget of two typical boreal lakes in Alberta/Canada estimated from a radon mass balance. *Hydrol Earth Syst Sci* 14:79–89
- Schuster PF, Reddy MM, LaBaugh JW, Parkhurst RS, Rosenberry DO, Winter TC, Antweiler RC, Dean WE (2003) Characterization of lake water and ground water movement in the littoral zone of Williams Lake, a closed-basin lake in north central Minnesota. *Hydrol Process* 17:823–838
- Shaw GD, White ES, Gammons CH (2013) Characterizing groundwater–lake interactions and its impact on lake water quality. *J Hydrol* 492:69–78
- Stafford CP (2013) Long-term trends in the water quality of Georgetown Lake, Montana. University of Montana College of Forestry and Conservation. Prepared for Montana Department of Environmental Quality, Helena, MT, 127 pp
- Stets EG, Winter TC, Rosenberry DO, Striegl RG (2010) Quantification of surface water and groundwater flows to open- and closed-basin lakes in a headwaters watershed using a descriptive oxygen stable isotope model. *Water Resour Res* 46:W03515
- Swenson S, Wahr J (2009) Monitoring the water balance of Lake Victoria, East Africa, from space. *J Hydrol* 370:163–176
- Thomson C (2016) Determining groundwater sources and ages vis isotope geochemistry in big sky, Montana. MSc Thesis, Montana Tech of the University of Montana, Butte, MT, 175 pp
- Turner JV, Townley LR (2006) Determination of groundwater flow-through regimes of shallow lakes and wetlands from numerical analysis of stable isotope and chloride tracer distribution patterns. *J Hydrol* 320:451–483
- Turner JV, Allison GB, Holmes JW (1984) The water balance of a small lake using stable isotopes and tritium. *J Hydrol* 70:199–220
- Van Oel PR, Mulatu DW, Odongo VO, Meins FM, Hogeboom RJ, Becht R, Stein A, Onyando JO, van der Veen A (2013) The effects of groundwater and surface water use on total water availability and implications for water management: the case of Lake Naivasha. *Kenya Water Resour Manag* 27:3477–3492
- Waren KB, LaFave JI (2011) Potentiometric surface map of basin fill and selected bedrock aquifers: Deer Lodge, Granite, Powell, and Silver Bow Counties, Montana. Groundwater Assessment Atlas 5 B-03, Montana Bureau of Mines and Geology, Helena, MT, 1 sheet
- Western Regional Climate Center (2015) Meteorological data (average monthly air temperature, dew point temperature, relative humidity, wind speed, and incoming solar radiation) from Philipsburgh, MT. <http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?inMPHL>. Accessed March 2016
- White ES (2012) Using Naturally occurring tracers to track groundwater–lake interactions at Georgetown Lake, Granite County, Montana. MSc Thesis, Montana Tech of the University of Montana, Butte, MT, 89 pp
- Wright JB (1983) A lake on a mountain pass: land-use capability of the Georgetown Lake area, Montana. MSc Thesis, University of Montana, Missoula, MT
- Xiao J, Zhangdong J, Zhang F (2013) Geochemical and isotopic characteristics of shallow groundwater within the Lake Qinghai catchment, NE Tibetan Plateau. *Quat Int* 313–314:62–73