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Characterizing groundwater–lake interactions and its impact on lake water quality

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SUMMARY

Geochemical tracers were used to investigate groundwater–lake interactions and to map nutrient concentrations within Georgetown Lake, a 1219 ha lake situated at 1960 m above sea level between two mountain ranges in western Montana. Radon-222 was used to identify locations and relative amounts of groundwater inflow to the lake, and nutrients were sampled to investigate the role of groundwater on nutrient dynamics occurring within the lake. Sampling primarily took place during late winter and early spring when the lake was frozen, stratified and relatively anoxic, and all lake samples were collected near the bottom of the lake. Radon concentrations in the lake varied spatially from less than 3.5–194.0 pCi/L. Radon results show that groundwater enters the lake through fractured Paleozoic karst limestone situated near a major thrust fault. No groundwater flows were noted on the western side of the lake, which is underlain by west-dipping Precambrian metasedimentary rocks. The western two-thirds of the lake is anoxic near the bottom of the water column with H_2S and NH_4^+ concentrations as high as 1.99 mg/L and 4.0 mg/L respectively. Along the eastern side of the lake, H_2S was absent and NH_4^+ was generally low, suggesting that groundwater inflows improve water quality. Pore water diffusion samplers show that there is an internal source of NH_4^+, H_2S, and PO_4^{3-} to the lake originating from decay of organic carbon in the lake sediments.

1. Introduction

Groundwater and surface water are accepted as being a single complex and interconnected system (Cook et al., 2008; Loveless et al., 2008; Owor et al., 2011). In order to responsibly develop and manage lakes it is important to understand fluxes into and out of lakes (Barr et al., 2000; Cherkauer and Nader, 1989). Groundwater and surface water inflow play an important role in controlling lake water chemistry, water quality, aquatic habitat and biodiversity (Hagerthey and Kerfoot, 1998). Surface water inflows to lakes are relatively easy to characterize, but the role of groundwater–lake interactions and how they influence water quality remains less obvious. Several cases have been observed where contaminant and/or nutrient-rich groundwater entering lakes has led to lake pollution and/or eutrophication (Hagerthey and Kerfoot, 1998; Zhang et al., 2010; Zhu and Schwartz, 2011). Improvements to lake water quality from groundwater–lake interactions are less well documented, but certainly occur.

The setting for this paper is Georgetown Lake, Montana. Georgetown Lake is the most highly recreated lake of its size in Montana, and it is under intense pressure to rapidly subdivide and develop. The lake has experienced a decline in water quality, which has been attributed to the high use and growth at the lake (Knight, 1981). In the 1980s, the status of Georgetown was classified as eutrophic or mesotrophic (Knight, 1981) and there were concerns with decreased dissolved oxygen (DO) during winter months when the lake is ice-covered because of the increased nitrogen and phosphorous loading (Garrett; 1983; Knight, 1981; USEPA, 1983). Recent work suggests that the DO decreases in late winter months are becoming more severe with time (Henne, 2011). The exact sources of nutrients to the lake are not well known, but could include tributary streams and springs, septic effluent, fertilizer application, previous grazing, or geologic sources. Characterizing the groundwater–lake interactions may provide some insight into the possible sources of nutrients or processes controlling nutrient dynamics within Georgetown Lake.

Groundwater flow to lakes can be especially difficult to determine using traditional techniques, such as well hydraulics and Darcy's Law, because of the large degree of heterogeneity in geologic material—especially in fractured, faulted, and folded terrain such as that surrounding Georgetown Lake. Darcy's Law estimates generally cannot be made unless there is sufficient information about aquifer parameters, especially the hydraulic conductivity, which varies over thirteen orders of magnitude in natural geologic

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material (Freeze and Cherry, 1979) and local heterogeneities can lead to vastly different results (Fetter, 2001). The use of naturally occurring environmental tracers coupled with physical methods has proven to be particularly useful in characterizing groundwater interactions with surface water (Maloszewski and Zuber, 1982; Maloszewski et al., 1983; Mattle et al., 2001). In this study ^{222}Rn was used to characterize groundwater-surface water interactions (Cook et al., 2008; Genereux et al., 1993).

Radon-222 is a dissolved radioactive gas that normally has low activity in surface water unless groundwater with elevated activity discharges to the surface water (Brooklin, 1991; Isam et al., 2002; Szabo and Zapecza, 1993). Degassing and radioactive decay (half-life of 3.8 days) prevents ^{222}Rn from persisting in surface water for much more than 10–30 days (Cecil and Green, 2000; Hoen and Von Gunten, 1989; Krishnaswami and Seidemann, 1988; Torgerson et al., 1992; Wanty et al., 1991) so it is an ideal tracer for identifying point locations, or reaches, where groundwater may discharge to surface water. Radon-222 has been used to identify groundwater seepage in numerous surface water bodies, such as small streams (Genereux et al., 1993; Wanninkof et al., 1990) large tropical streams (Cook et al., 2003) infiltration of surface water to groundwater (Hoen and Von Gunten, 1989) and submarine discharge from coastal aquifers to the ocean (Burnett and Dulaiova, 2003; Cable et al., 1996; Top et al., 2001). There have also been several previous studies using radon to quantify groundwater discharge to lakes. Schmidt et al. (2010) used Rn^{222} to estimate the percent groundwater discharge relative to the entire water budget within typical boreal lakes in Alberta, Canada. Kluge et al. (2012) used Rn^{222} in a multi-box model to estimate groundwater discharge to lakes. Dugan et al. (2011) used Rn^{222} to develop a conceptual understanding of how localized groundwater inputs interact with arctic lakes in the continuous permafrost zone of Northwest Territories. Rodellas et al. (2012) combined three isotopes of radium with Rn^{222} to separate four subsurface inflows to wetlands adjacent to the Mediterranean Sea. The majority of hydrologic studies using Rn^{222} focus on surface water bodies overlying unconsolidated sedimentary aquifers (Corbett et al., 1997; Schmidt et al., 2009).

Characterizing groundwater–lake interactions in terrain with complex fractured, faulted, and folded rocks, such as in montane watersheds, has been understudied. Springs were detected using Rn^{222} in a lake overlying volcanic rock in Cuitzeo Lake, Mexico (Alfaro et al., 2002). Radon-222 has also been used to investigate Lake Roseland in the French Alps, where seepage from the lake through fractures to underlying tunnels was monitored (Provost et al., 2004; Trique et al., 1999).

The objectives of the present study were to (i) obtain spatial concentrations of ^{222}Rn in Georgetown Lake and surrounding groundwater to develop a conceptual understanding of how groundwater interacts with Georgetown Lake, (ii) spatially assess nutrient concentrations within the lake and infer the role of groundwater in helping to regulate nutrient concentrations within Georgetown Lake, and (iii) investigate the role of internal production of nutrients from within lake sediments.

2. Study area

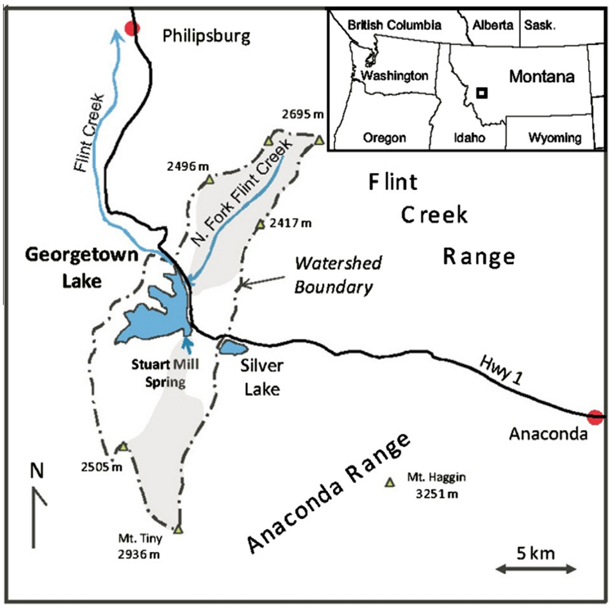

Fig. 1. Map of the Georgetown Lake area relative to the state of Montana. (modified from Henne, 2011). The gray shaded areas show sub-watersheds drained by the North Fork of Flint Creek and Stuart Mill Spring.

Georgetown Lake is a high elevation lake sitting at 1960 meter above sea level. It is located near the Flint Creek drainage situated on a high plateau between the Anaconda-Pintler Range and the Flint Creek Range in the upper Clark Fork watershed of western Montana (Fig. 1). The plateau was emplaced by the Georgetown Thrust Fault, a low angle, westward dipping fault consisting of allochthonous mid-Proterozoic sedimentary rocks of the Belt Basin on top of mid-Paleozoic sedimentary rocks (Lonn et al., 2003). Georgetown Lake is underlain by the Georgetown Thrust which separates the bedrock geology of the lake into the eastern and western sides. The west side of the lake is dominated by the middle Belt carbonate (Yc) which consists of dolomitic siltite and quartzites. The east side of the lake is comprised of sedimentary rocks of the Madison Group and Amsden Formations (PMs), which are dominated by limestone. Surficial deposits, including alluvium and glacial till (Qgtk), form a thin, discontinuous layer above the bedrock. The Madison Group is an important karst aquifer in Montana and neighboring states, and includes a massive, locally brecciated and cavernous limestone (Mission Canyon Fm.) underlain by thin-bedded limestone with silty interbeds (Lodgepole Fm.) (Fig. 2). These rock units dip ~40–60° to the northwest and strike northeast/southwest and have been folded, faulted, and metamorphosed by intrusion of late Cretaceous granitic bodies (Fig. 2).

The hydrogeology of Georgetown Lake is highly influenced by upland terrain. The reservoir is fed by two major tributaries, several springs, and groundwater within its 13,720 ha drainage area. Stuart Mill Spring maintains a year-round flow of roughly 0.5 m^3/s from a 4222 ha drainage area (Fig. 1), and it discharges from karst limestone less than 200 m from the shore of Georgetown Lake. Flint Creek discharges into the lake from an approximate drainage area of 4895 ha, and shows large seasonal variation in flow. There is a smaller spring located roughly 1 km north of Stuart Mill Spring called Emily Spring. The total flow was not measured, but is much lower than that of Stuart Mill Spring.

The study area includes 22,680 m of highly embayed lake shoreline. The deepest point in the lake is 10.7 m and the average depth is 4.9 m. The reservoir has an irregular shape with a surface area of 1219 ha and a volume of 5.9×10^7 m^3 of water at full pool (Knight, 1981). The mean annual precipitation for 1971–2000 was 536 mm and the average annual snowfall was 3973 mm. Higher elevations around the lake receive a much greater amount of precipitation in the range 890–1440 mm/yr (Western Regional Climate Center, 2011a). There are no mean annual air temperature measurements recorded at Georgetown Lake. The nearest SNOTEL site, Peterson Meadows, is located at an elevation of 2194 m above sea level, and has a mean annual air temperature of 2.4 °C from 1999 to 2012. Direct evaporation accounts for a loss of 89.8 cm/yr (Western