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Quantity and quality of groundwater discharge in a hypersaline lake environment

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SUMMARY

Geophysical and geochemical surveys were conducted to understand groundwater discharge to Great Salt Lake (GSL) and assess the potential significance of groundwater discharge as a source of selenium (Se). Continuous resistivity profiling (CRP) focusing below the sediment/water interface and fiber-optic distributed temperature sensing (FO-DTS) surveys were conducted along the south shore of GSL. FO-DTS surveys identified persistent cold-water temperature anomalies at 10 separate locations. Seepage measurements were conducted at 17 sites (mean seepage rate = 0.8 cm/day). High resistivity anomalies identified by the CRP survey were likely a mirabilite ($Na_2SO_4{\cdot}10H_2O$) salt layer acting as a semi-confining layer for the shallow groundwater below the south shore of the lake. Positive seepage rates measured along the near-shore areas of GSL indicate that a ~1-m thick oolitic sand overlying the mirabilite layer is likely acting as a shallow, unconfined aquifer. Using the average seepage rate of 0.8 cm/day over an area of 1.6 km^2, an annual Se mass loading to GSL of 23.5 kg was estimated. Determination of R/Ra values (calculated ^{3}He/^{4}He ratio over the present-day atmospheric ^{3}He/^{4}He ratio) <1 and tritium activities of 1.2–2.0 tritium units in groundwater within and below the mirabilite layer indicates a convergence of regional and local groundwater flow paths discharging into GSL. Groundwater within and below the mirabilite layer obtains its high sulfate salinity from the dissolution of mirabilite. The δ^{34}S and δ^{18}O isotopic values in samples of dissolved sulfate from the shallow groundwater below the mirabilite are almost identical to the isotopic signature of the mirabilite core material. The saturation index calculated for groundwater samples using PHREEQC indicates the water is at equilibrium with mirabilite. Water samples collected from GSL immediately off shore contained Se concentrations that were 3–4 times higher than other sampling sites >25 km offshore from the study site and may be originating from less saline groundwater seeps mixing with the more saline water from GSL. Additional evidence for mixing with near shore seeps is found in the δD and δ^{18}O isotopic values and Br:Cl ratios. Geochemical modeling for a water sample collected in the vicinity of the study area indicates that under chemically reducing conditions, arsenic- (As) bearing minerals could dissolve while Se-bearing minerals will likely precipitate out of solution, possibly explaining why the shallow groundwater below and within the mirabilite salt layer contains low concentrations of Se (0.9–2.3 μg/L).

1. Introduction

Groundwater discharge is an important component of the hydrologic and chemical cycles of limnological systems, yet it remains difficult to locate and quantify (Healy et al., 2007; Rosenberry and Winter, 2009). Geophysical methods are often employed to help locate groundwater and understand sub-surface conditions. Examples of these methods include electrical resistivity (Keller and Frischknecht, 1966), seismic refraction (Dobrin, 1976), and aerial thermal IR imagery (Palluconi and Meeks, 1985). Fiber-optic

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distributed temperature sensing (FO-DTS), is an emerging technology with previous non-hydrologic applications in the petroleum, fire, and nuclear industries (Lane, 2007) and recently has been applied to help identify areas of groundwater discharge and observe the spatial and temporal variations in groundwater at the freshwater–saltwater interface (Henderson et al., 2009). In this study, FO-DTS technology was used in the south arm of Great Salt Lake (GSL) (Fig. 1A) as a tool in locating potential areas of groundwater discharge beneath the lake and to study the quality and source of groundwater to this system.

GSL is a hypersaline terminal lake in northwest Utah (Fig. 1A). Millions of migratory waterfowl and shorebirds utilize GSL as a source of food and rest during the migrating seasons (Caudell and Conover, 2006). GSL also supports a vibrant brine shrimp population that provides an important food source for migratory waterfowl (Aldrich and Paul, 2002). Brine shrimp cysts are harvested seasonally from GSL and used as a food source in aquaculture industries throughout the world (Bengtson et al., 1991). The lake provides significant mineral resources (sodium and magnesium chloride, potassium salts, magnesium metal, and chlorine gas), while also serving as a recreational area. GSL is a complex system that has been the subject of recent ecological studies (Stephens and Birdsey, 2002; Naftz et al., 2008a, 2008b; Belovsky et al., 2011). Despite the ecological and economic importance of GSL, little is known about the quantity or quality of groundwater discharging to the lake. The vast majority of water entering GSL is by surface flow from three major rivers – the Bear, the Provo-Jordan, and the Weber; with additional inputs from smaller tributaries, groundwater seepage and irrigation drainage (Mohammed and Tarboton, 2011). Groundwater in Salt Lake Valley generally moves from recharge areas near the mountain fronts toward the Jordan River and GSL (Thiros et al., 2010). The minimum groundwater discharge to GSL is estimated between 92 and 123 million m^3/year, which is about 3% of the total annual inflow to the lake (Arnow and Stephens, 1975).

The Jordan Valley Water Conservancy District is currently (2013) in the process of obtaining a permit to discharge byproduct water from reverse osmosis treated groundwater to the south shore of GSL. This discharge will represent an additional selenium (Se) input (Utah Department of Environmental Quality, 2012) and potentially other inputs including arsenic (As) and mercury (Hg) into GSL. In response to increasing public concern regarding Se inputs to the GSL ecosystem, the United States Geological Survey (USGS) in collaboration with other agencies estimated Se loads entering GSL from six primary inflow sites from May 2006 to March 2008 (Naftz et al., 2008b). The investigation documented a net increase in Se concentrations and indicated substantial amounts of unmeasured sources of Se (~1500 kg/year) entering the south arm of GSL. It is hypothesized that unmeasured sources of Se may come from groundwater discharge, unmeasured surface flows, diffusion from lake sediment pore water, poorly characterized Se exchange between the north and south arm of GSL, and

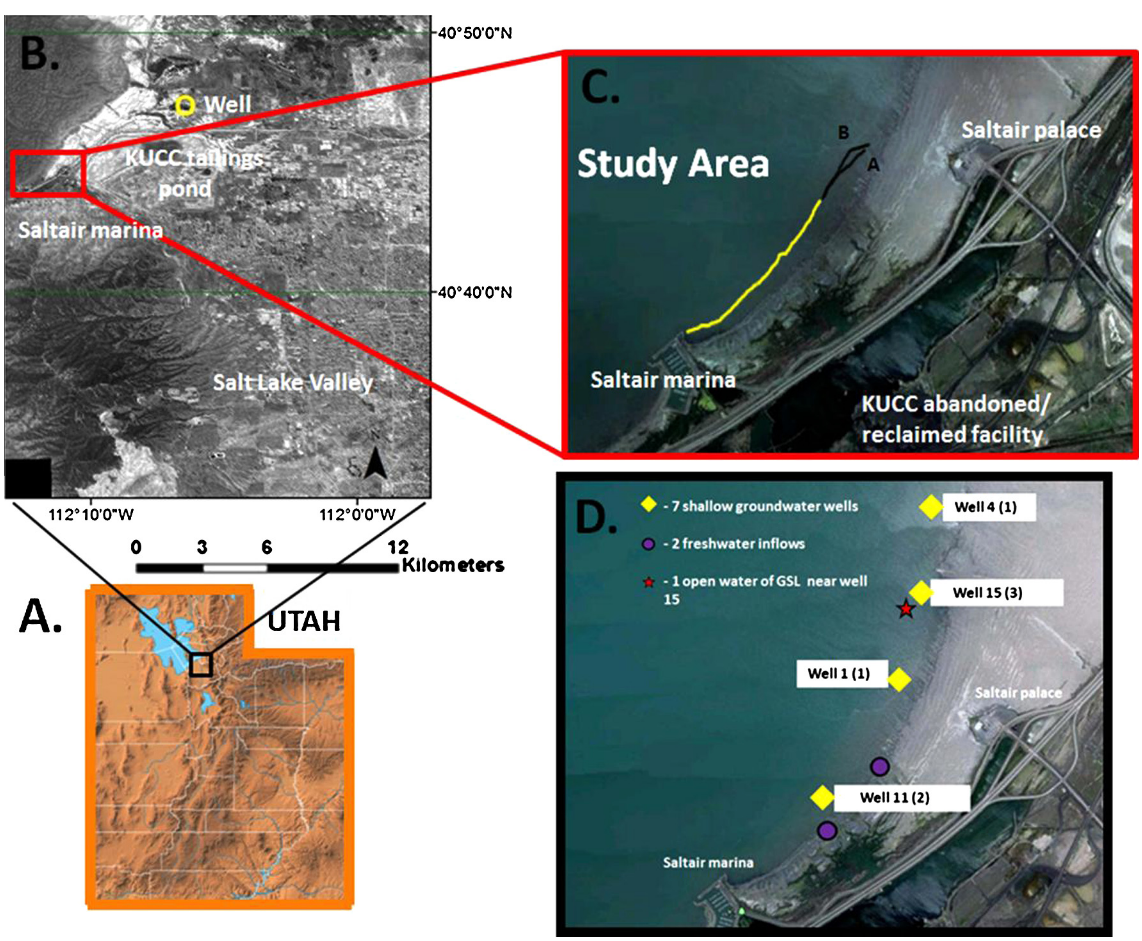

Fig. 1. The study area along the south arm of Great Salt Lake (GSL), Utah (A). Map showing the location of a monitoring well 2 km N of the KUCC tailings pond, and 9 km NE of the study area (Map B). Map showing location of the fiber-optic cable that was placed along the near-shore of GSL between the Saltair palace and Saltair marina (C). The yellow trace is the first 2 km and the black trace is the last 1 km depicting the trace before the storm (labeled as A) and after the storm (labeled as B). (C). Map showing sampling locations where water samples were collected from shallow groundwater wells, freshwater inflows, and the open water of GSL (D). Number in parentheses designate number of wells at each location. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)