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Geothermal solute flux monitoring and the source and fate of solutes in the Snake River, Yellowstone National Park, WY

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ABSTRACT

The combined geothermal discharge from over 10,000 features in Yellowstone National Park (YNP) can be can be estimated from the Cl flux in the Madison, Yellowstone, Falls, and Snake Rivers. Over the last 30 years, the Cl flux in YNP Rivers has been calculated using discharge measurements and Cl concentrations determined in discrete water samples and it has been determined that approximately 12% of the Cl flux exiting YNP is from the Snake River. The relationship between electrical conductivity and concentrations of Cl and other geothermal solutes was quantified at a monitoring site located downstream from the thermal inputs in the Snake River. Beginning in 2012, continuous (15 min) electrical conductivity measurements have been made at the monitoring site. Combining continuous electrical conductivity and discharge data, the Cl and other geothermal solute fluxes were determined. The 2013−2015 Cl fluxes (5.3−5.8 kt/yr) determined using electrical conductivity are comparable to historical data. In addition, synoptic water samples and discharge data were obtained from sites along the Snake River under low-flow conditions of September 2014. The synoptic water study extended 17 km upstream from the monitoring site. Surface inflows were sampled to identify sources and to quantify solute loading. The Lewis River was the primary source of Cl, Na, K, Cl, SiO_2, Rb, and As loads (50−80%) in the Snake River. The largest source of SO_4 was from the upper Snake River (50%). Most of the Ca and Mg (50−55%) originate from the Snake Hot Springs. Chloride, Ca, Mg, Na, K, SiO_2, F, HCO_3, SO_4, B, Li, Rb, and As behave conservatively in the Snake River, and therefore correlate well with conductivity ($R^2 \geq 0.97$).

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1. Introduction

Yellowstone National Park (YNP) is well-known for its geysers, hot springs, mud pots, and steam vents. Monitoring Yellowstone's geothermal system is difficult because there are more than 10,000 geothermal features spread across nearly 9000 km^2. However, the chloride concentrations in most YNP geothermal waters are elevated (Friedman and Norton, 1990; Norton and Friedman, 1985) and because most of the water discharged from these geothermal features eventually enters a major river, the chloride flux in the major rivers has been used as a surrogate for estimating the heat flow in geothermal systems (Ellis and Wilson, 1955; Fournier, 1989). This technique has been termed an "integrated" flux because water from most geothermal features discharges into one of four major rivers (Madison, Yellowstone, Snake, and Falls Rivers) draining YNP. Fournier (1989) summarized the results and long-term trends of heat flow from YNP using the Cl flux method and found that the convective heat discharged from the Yellowstone hydrothermal system was ~5300 MW. Ingebritsen et al. (2001) investigated the time variation of hydrothermal discharge at several sites in the western U.S. including YNP and found the heat flow from YNP to be ~6100 MW. From 1983 to 2003, Friedman and Norton (2007) found that the sum of the Cl fluxes for the four rivers varies as much as 20% annually and inferred from their results that the Cl flux decreased 10% over the past 20 years.

A long-term chloride flux baseline and timely monitoring of the Yellowstone Supervolcano is fundamental to hazard assessment. In addition, the thermal activity of geysers and hot springs continually

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changes making it a challenge to manage the safety of park visitors as geothermal areas transform over time. The U.S. Geological Survey (USGS) and the National Park Service (NPS) have collaborated on chloride flux monitoring since the 1970s (e.g. Fournier et al., 1976; Hurwitz et al., 2007b; Norton and Friedman, 1985; Norton and Friedman, 1991) by periodically sampling (about 28 times per year) the rivers and analyzing chloride concentrations in discrete water samples (Hurwitz et al., 2007a, 2007b). Stream discharge is measured automatically every 15 min at a series of USGS streamgages within and outside YNP (NWIS, 2016), and for many years researchers and volunteers collected water samples at these locations (Hurwitz et al., 2007a). However, constraints of funding, winter travel, and the great distances between sites limit the number of samples collected annually. McCleskey et al. (2012a) demonstrated that electrical conductivity and chloride concentrations, as well as other geothermal solutes, have linear correlations in the Gibbon, Firehole and Madison Rivers, and thus electrical conductivity can be used as a proxy for chloride concentrations. Only a few samples per year, collected under a range of flow conditions, will need to be analyzed to ensure the electrical conductivity-solute correlations remain accurate. Continuous electrical conductivity monitoring provides a cost- and labor-effective alternative to previous protocols, whereby chloride concentrations were measured in 28 discrete water samples annually. In addition, continuous (every 15 min) electrical conductivity measurements provide high-resolution data that can be used to rapidly calculate chloride flux and the data provide insights into storms and geyser eruptions. The primary goal of this study was to develop an electrical conductivity method that can be used as a proxy for chloride concentrations, as well as other geothermal solutes, in the Snake River in southern YNP. It has been estimated that the 11–12% of the total heat flux exiting YNP, based on the chloride flux measurements, is from thermal areas in the Snake River watershed (Hurwitz et al., 2007a; Norton and Friedman, 1985; Norton and Friedman, 1991). In addition, synoptic water samples and discharge data were obtained from six sites along the Snake River and seven tributaries under the low-flow conditions of September 2014. Thus, the short-term chemical mass loading of the thermal inputs to the Snake River were systematically determined and processes of attenuation identified.

2. Study area and sample sites

The headwaters of the Snake River are located in southeastern YNP (Fig. 1) and the river flows for 1735 km before combining with the Columbia River in Washington. From its source, the Snake River flows westward for about 50 km before bending southward near the boundary between YNP and the John D. Rockefeller, Jr. Memorial Parkway. From the YNP boundary, the Snake River flows south for an additional 14 km before entering the northern most end of Jackson Lake. This study focuses on the river reach upstream from Jackson Lake. Heart Lake Geyser Basin (HLGB), Snake Hot Springs (SHS), Shoshone Geyser Basin (SGB) are the largest thermal areas within the Snake River watershed. The HLGB feeds Heart Lake, which is drained by the Heart River (Fig. 1). The SHS comprises three thermal areas on the south bank of the Snake River. Aside from one large thermal inflow (I4), most of the SHS thermal features have diffuse and relatively small discharges. The SGB drains into Shoshone Lake, which is where the Lewis River begins. The Lewis River flows through Lewis Lake and combines with Snake River about 0.7 km upstream from the southern boundary of YNP (Fig. 1). To quantify the thermal discharge into the Snake River within YNP, a long-term electrical conductivity monitoring site (S6) was established about 100 m downstream from the USGS streamgage 13010065 and about 5 km south of the YNP South Entrance (Fig. 1). In addition, synoptic water samples were collected along a 17-km reach of the Snake River beginning upstream from Red Creek (S1) and ending at the electrical conductivity monitoring site (S6). Six water samples (S1–S6) were collected along the Snake River and seven water samples (I1–I7) were collected from inflows to the Snake River. The major inflows include Red Creek (I1), Forest Creek (I3), one large thermal discharge from the Snake Hot Springs (I4), Lewis River (I6), and Sheffield Creek (I7). The latitude and longitude of each sample site are listed in Table 1.

3. Methods

3.1. Field methods

3.1.1. Electrical conductivity monitoring

The electrical conductivity of the Snake River has been continuously monitored at S6 (Fig. 1) since Sept. 28, 2012. The long-term monitoring site (S6) is located downstream and on the opposite bank from the USGS streamgage 13010065 because Sheffield Creek (I7), a small tributary, enters just upstream from the streamgage on the left bank (looking downstream). The electrical conductivity measured from the right bank is expected to be more representative of the Snake River.

An Aqua TROLL 100 (In-Situ Corporation) was deployed at the long-term monitoring site (S6) to collect electrical conductivity and water temperature measurements. Upon deployment, the Aqua TROLL 100 was programmed to collect measurements every 15 min concurrent with stage and discharge measurements from the USGS streamgage 13010065. The Aqua TROLL 100 contains a data logger capable of storing up to 380,000 data points. The probe was deployed in a 5-m section of 3.5-cm diameter PVC pipe, extending into the main flow of the channel, semi-perpendicular to the bank and anchored to the streambed with rebar. Holes were drilled into the lower 25-cm of the polyvinyl chloride (PVC) pipe to allow water to flow freely past the Aqua TROLL 100. The pipe extends out onto the stream bank such that the cabling can be accessed and data downloaded without having to move the instrument, except for occasional cleaning. The Aqua Troll 100 was periodically cleaned to minimize fouling due to mineral precipitation, sediment deposition, and algae growth. The electrical conductivity measured by the Aqua Troll 100 instrument was periodically compared to the electrical conductivity measured with a handheld conductivity meter to check for fouling of the conductivity cell. Because the pH of the Snake River and its inflows are circumneutral, the electrical conductivity referenced to 25 °C (κ_{25}) determined with both the handheld meter or the Aqua Troll 100 are within ±2% of the values determined using the temperature compensation method described in McCleskey (2013), which often better predicts the κ_{25} for some YNP waters. The Aqua TROLL 100 functioned properly with only two exceptions. In August 2013, someone removed the Aqua Troll 100 from the river and left the probe on the bank. Fortunately, the probe was reinstalled 12 days after it was removed. Then from December 2013–February 2014, there were periods of time when the conductivity measurements were unreliable likely because of ice buildup in the conductivity cell. During these relatively short time periods, the electrical conductivity was estimated based on the electrical conductivity (McCleskey, 2016) – discharge (NWIS, 2016) correlation ($R^2 = 0.9$):

$$\kappa_{25} = 736 \times Q^{-0.427} \quad (1)$$

where κ_{25} is the electrical conductivity at 25 °C and Q is the discharge in m^3/s.