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An Environmental and Hydrogeological Investigation in the South Hebgen Basin, Montana

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Abstract

This study was conducted to develop a hydrogeologic framework, and address water quality concerns in the South Hebgen Basin, near the town of West Yellowstone, Montana. The main goals of this research were to: (1) Develop a conceptual model of groundwater flow within the confined aquifer. (2) Use naturally occurring chemical tracers to investigate the confined aquifer's extent and the connectivity. (3) Identify the influence of geothermal features on water chemistry. (4) Identify water quality issues related to arsenic (As) and fluoride (F^-). Long-term static water elevation plots and surface water flow, combined with water ion chemistry were used to investigate the hydraulic gradients and the transport of chemical tracers. Statistical spatial analysis was used to generate water chemistry and temperature gradients within the confined aquifer. An observed qualitative trend between geothermal influenced areas and certain elevated chemical constituents was corroborated using multiple water chemistry analysis techniques. Water quality concerns were identified by comparing As and F^- concentration gradient models to Environmental Protection Agency human health limits. Analysis of hydrogeological data suggests a link between surface water runoff events and groundwater head levels. Generated tracer concentration gradient models provide evidence of a large, interconnected confined aquifer, with multiple recharge sources. Groundwater chemistry and temperature analysis indicate the subsurface geothermals significantly impact water chemistry, and quality within the confined aquifer. Arsenic and F^- concentrations were found to exceed the human health limits at numerous locations within the project site, and should be considered a human health concern in the area.

Introduction

The environmental impacts of surface water flow from geothermal areas in Yellowstone National Park (YNP) on the aquifers of the Madison River Valley are an established problem. Studies have shown widespread contamination of the lower Madison River alluvial aquifers due to irrigation techniques [Sondregger et al., 1989; Nimick., 1998]. The problem stems from the source of the Madison River. The Main Stem of the Madison River (Main Stem), which originates in the western portion of YNP, is influenced by geothermal geysers and springs which impact water chemistry and flow. [Thompson., 1979; Knapton et al., 1987; Nimick et al., 1998; Gardner et al., 2010]. These geothermal tributaries are of particular interest due to their high As and F^- concentrations. By the time the Main Stem exits YNP, As levels range from 120-370 μg/L, and account for approximately 110,000 kg of arsenic entering Montana each year [Nimick 1998]. The fluoride levels range from 2.9-8.2 mg/L, and account for approximately 2.67 million kg annually (USGS). To the west of the Main Stem, the South Fork of the Madison River (South Fork) drains a remote corner of Montana located between YNP and the Idaho border. Like the Main Stem, the South Fork drainage contains numerous springs, some of which exhibit geothermal characteristics [Metesh et al. 2003]. In 2000, the Montana Department of Environmental Quality (MTDEQ) designated the South Fork as an impaired stream in need of further study, with arsenic as the primary pollutant of concern [MTDEQ. Madison Use Assessment. 2012].

Although each geothermal source has unique chemistry related to the geologic origin, there are common chemical constituents typical of geothermally sourced waters [Sonderegger et al., 1981]. For the YNP geothermal features, linear ionic-concentration relationships have been established for combinations of As, F^-, Li^+, Cl^-, B, Si, Sb and HCO_3

[Thomspon., 1979; Sonderegger., 1981; Stauffer et al., 1984; Nimick 1998]. These relationships are valuable for identifying geothermal systems, and evaluating the influence of geothermals on surrounding waterbodies. For the upper Madison River Watershed, the relationships between As, F^-, Li^+ and Cl^- are of particular interest due to data availability, as well as water quality concerns associated with As and F^-.

Near the town of West Yellowstone, MT both the Main Stem and the South Fork exit mountainous terrain and enter the broad, South Hebgen Basin (SHB). Within the SHB, the Main Stem and the South Fork meander for approximately eight and five miles respectively before flowing into Hebgen Lake (Figure 1). Although groundwater concerns relating to YNP geothermals are well documented downstream of Hebgen Lake, similar studies have not been performed upstream of the lake. Given the known and alleged As and F^- loading on the rivers, contamination in the groundwater of the SHB was suspected and supported by some of the available groundwater chemistry data [Metesh et al. 2000].

The human health concerns associated with As and F^- are well established. Chronic As exposure has been linked to skin, internal organ and lung cancer, as well as cardiovascular disease and neuropathy [Abernathy et al., 1999; Kapaj et al., 2007; Saha et al., 2010]. Chronic F^- exposure has been linked to dental and skeletal fluorosis, decreased birth rates, and various types of cancer [Freni, 1993; World Health Organization., 1996; Ozvath, 2008]. Both As and F^- have been linked to reduced test scores in children [Wang et al., 2007]. Recent investigations are now researching the possibility that As and F^- may act synergistically to impair human health [Chouhan et al., 2010; Swaran et al., 2011].

Prior to developing a municipal drinking water supply in 1989, over 100 wells were drilled into the SHB aquifer within the West Yellowstone city limits. Approximately 150 additional wells are still in use outside of West Yellowstone. Despite this heavy usage there is limited understanding of the SHB confined aquifer or the contaminant distribution therein. It is known that confining conditions exist in large areas along both the Main Stem and the South Fork, but the extent of these conditions is poorly understood. It is known that some wells have tested above the EPA human health limits for As and F^- (10 μg/L and 4 mg/L respectively), and the vast majority of wells exceeded the median As concentration for groundwater in the Rocky Mountains (≤ 1 μg/L) [Welch et al., 2000]. Despite these trends no comprehensive research has been performed on the contaminant distribution in the SHB. With development expected to continue near West Yellowstone, understanding of the water resources is increasingly important.

In 1994, the State of Montana and the National Park Service established the Yellowstone Controlled Groundwater Area (YCGA) to study the relationship between Yellowstone's geothermal resources and the surrounding watersheds. Water resources in the YCGA are monitored by the Montana Bureau of Mines and Geology (MBMG).Data collected includes groundwater level, spring discharge and water chemistry. The YCGA spans YNP's northern and western borders within Montana and includes the SHB. This project was performed in conjunction with the MBMG to gain further insight into the western portion of the YCGA.

The purpose of this study was to generate an improved understanding of water resources in the SHB. The main objectives of the research were to:

1. Develop a conceptual model of groundwater flow within the confined aquifer.
2. Use naturally occurring chemical tracers to investigate the extent of the confined aquifer.
3. Identify the influence of subsurface geothermals on water chemistry.
4. Identify human health issues related to drinking water, primarily concerning As and F^-.

<u>Area Description</u>

The Project Site

The project site focuses on the southern portion of the Hebgen Basin (also referred to as the West Yellowstone Basin), in the southern end of Gallatin County, Montana (Figure 1). It is located between Hebgen Lake to the north, the Lionshead Mountains to the west, the Montana/Wyoming border to the east and the Henry's Lake Mountains to the south. The project site is primarily composed of a relatively flat basin, as well as portions of the surrounding foothills. The study area is approximately 20 square miles, and includes the town of West Yellowstone, Montana. The project site is bisected by U.S. Highway 20, which runs between West Yellowstone, MT and Henry's Lake, ID.

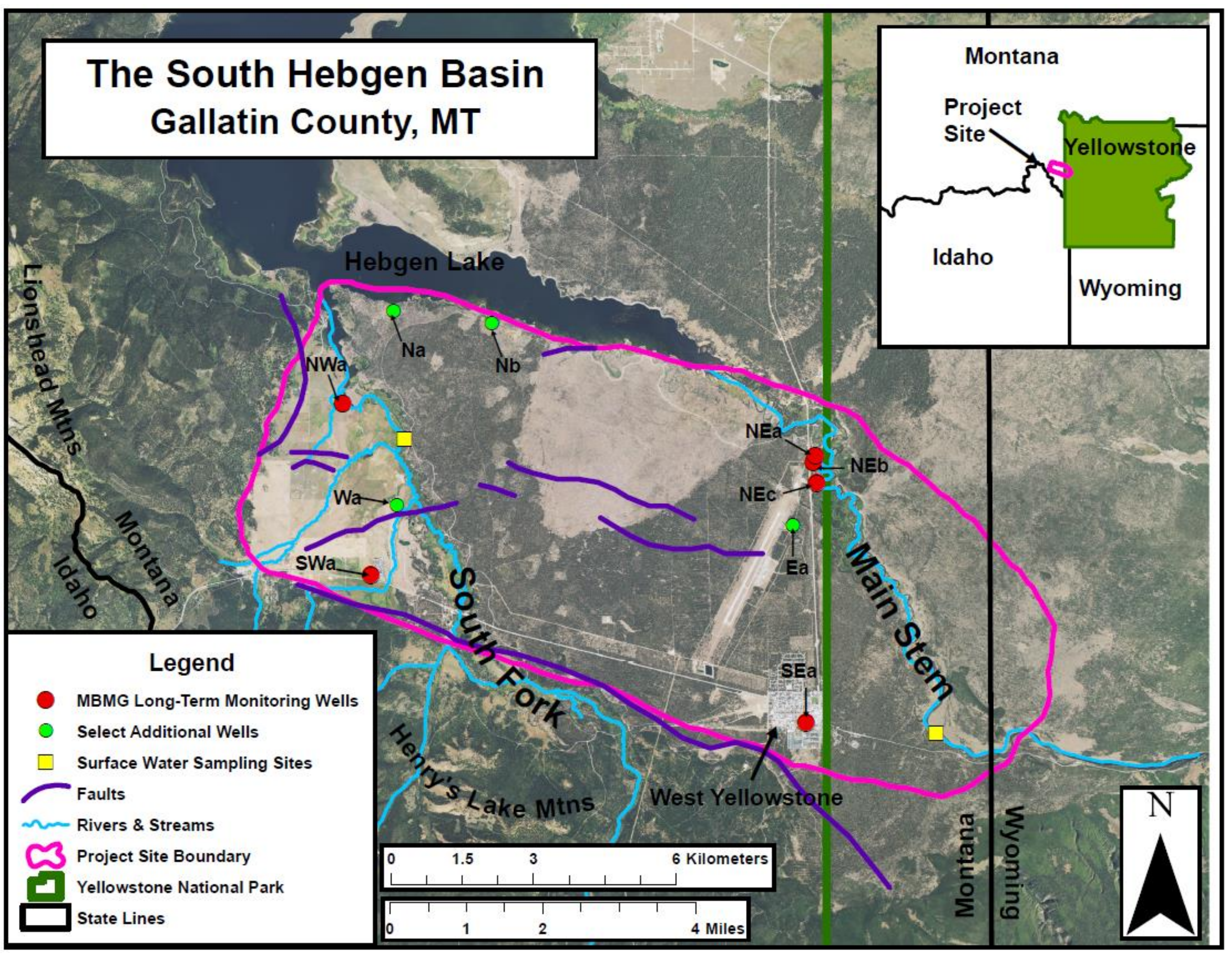


Figure 1. The South Hebgen Basin project site, regional faults and Montana Bureau of Mines and Geology long-term monitoring wells [USGS, 2006. Lonn et al., 2007].

Land Use

Outside of West Yellowstone, most residences are private recreational properties. A number of commercial hotels and campgrounds exist in the area. As of 2015, there were approximately 150 active wells in the SHB. The majority of these wells are for private domestic use, though many used for commercial hotels. With development expected to continue, more wells will likely be drilled.

Geology

The SHB is primarily comprised of alluvium and glacial outwash and is surrounded by numerous volcanic formations in the neighboring hills and mountains. The SHB basin bottom is exceptionally flat. The SHB is described as “a broad plain, sloping gently northwestward and underlain by obsidian sand and gravel several hundred feet thick” [Witkind et al 1959]. The basin fill is the result of glacial expansion and retreat with periods of alluvial, fluvial, glaciofluvial and glaciolacustrine deposition. These episodes resulted in an obsidian sand plain on the surface and regionally varied and highly stratified lithology below. The two most important glacial periods in the formation of the SHB were the Bull Lake and the Pinedale [K. Pierce., 1969]. The Bull Lake glacial period occurred 200,000 to 130,000 years ago and began shaping what would become the SHB. The ice receded for approximately 60,000 years before moving back in during the Pinedale glacial period which lasted from 110,000 to 12,000 years ago. The Pinedale ice sheet terminated just a few miles east of the Montana/Wyoming border. Streams flowing from the terminus of the ice sheet deposited glacial outwash in the SH, forming the obsidian sand plain [Pierce., 1969].

The combination of glaciation and stream deposition resulted in numerous clay horizons which create confining conditions in the aquifer (Figure 2). Owing to inconsistent well records it is difficult to compare the lithology of well sites. The majority of wells located in the basin bottom appear to be drilled into a confined aquifer. Wells located along the northern and southern portions of the project site appear to be confined but not flowing artesian. Wells located more centrally in the basin are often flowing artesian. This pattern exists along both the Main Stem and the South Fork. It is difficult to assess whether confining conditions exist across the SHB or merely along the respective rivers, due to a lack of wells on the Forest Service land between the Main Stem and the South Fork. Additionally, the absence of wells in YNP means that the eastern extent of the confining conditions cannot be determined.

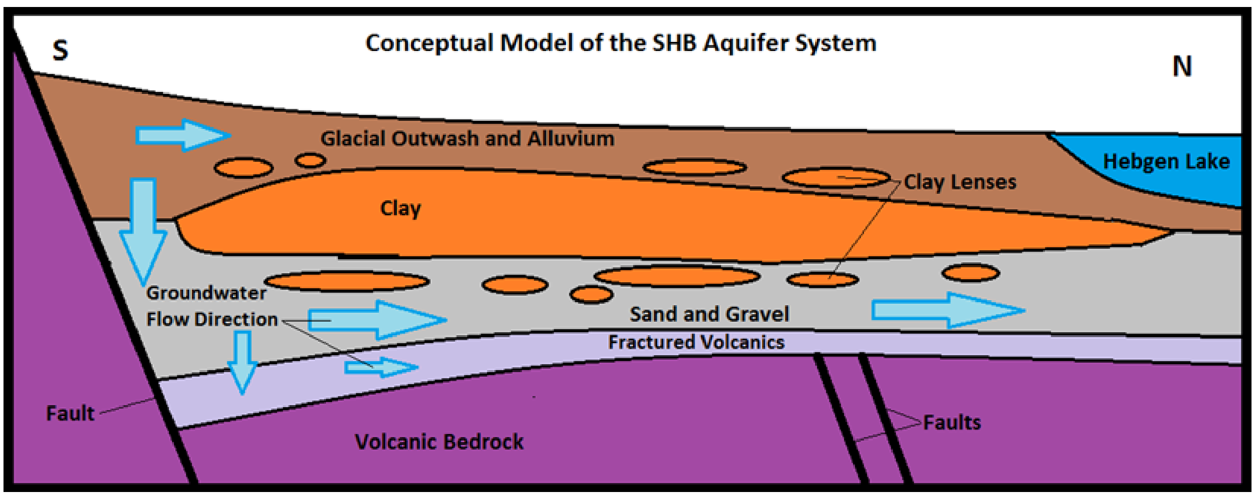


Figure 2. A conceptual model of the geologic framework in the South Hebgen Basin aquifer system.

The SHB contains numerous fault scarps within the basin bottom and along the foothills, and is seismically active. During the 1959 Hebgen Lake earthquake, fault movement in the SHB tilted the basin floor northward, and deformed the sand plain with subsidence measuring up to 4.5 m (15 ft) [Witkind., 1959]. Wells in the area recorded changes in head up to 2.75 m (9.5 ft) and an increase in turbidity [De Costa., 1959; Swenson., 1959]. Studies in the YNP geyser basins found that localized fracture systems, such as faults, are a likely source of mixing between deeper geothermal and shallow groundwater system [Gardner et al., 2011]. Groundwater systems in the SHB are likely affected by seismic activity and bedrock structure.

The SHB contains numerous wells and springs which exhibit geothermal influences. For the purposes of this study, geothermal waters (or waters influenced by geothermal activity) are defined as those with a temperature greater than 10 °C. Within the confined aquifer, some wells have recorded temperatures ranging between 15-25 ^{o}C [Metesh et al., 2000]. Along the periphery of the SHB, fault springs located in the southern foothills register an average temperature of 17 ^{o}C and exhibit a unique geothermal chemistry, which includes elevated strontium and hydrogen sulfide concentrations and a heavy odor [Metesh., 2003]. Although the source of heat in the SHB is not investigated in this study, it may be due to convection from warmer, deeper systems below the study area.

The Rivers

The SHB contains the northern stretches of the Main Stem and the South Fork rivers before they empty into Hebgen Lake (Figure 1). The Main Stem of the Madison begins in the western portion of YNP at the confluence of the Firehole River and the Gibbon River. These tributaries drain Norris, Gibbon, and Pocket Basins, which comprise the largest geothermal area in YNP. These geothermal sources result in higher flow volume during base flow periods than strictly snowmelt fed streams [Gardner et al., 2010]. Where the Main Stem exits Wyoming, just east of West Yellowstone, stream flows range from 10-60 m^3/s (400-2000 cfs). The Main Stem then meanders northwest for approximately five miles before draining into the Madison Arm of Hebgen Lake.

The South Fork is a snowmelt dominated mountain river that originates in the southern most corner of Montana, between Idaho to the west and YNP and Wyoming to the east. The watershed's western and southern boundaries are formed by the Continental Divide. The South Fork originates high in the Henry's Lake Mountains as a small stream, and flows into the SHB (Figure 1). Stream flows on the South Fork range from 0.5-1.5 m^3/s (20-50 cfs), at the southern edge of the project site (GWIC ID #278603). When the South Fork enters the SHB its course becomes drastically more meandering and sinuous. Due to numerous springs and tributaries from the Lionshead Mountains the river flow increases to between 2.5-6 m^3/s (100-200 cfs) by the time it empties into the South Fork Arm of Hebgen Lake (GWIC ID #278607).

Methods

Field Methods

Water quality field parameters (temperature, specific conductivity, pH and dissolved oxygen) were measured at all sites during sample collection. Samples were analyzed for trace metals, major anions and alkalinity. Trace metal and major ion sample water was filtered through a 0.45 micron filter. Isotope and alkalinity samples were unfiltered. Samples were collected in clean, opaque, high density polyethylene bottles and stored at 4 °C. Samples for metals analysis were preserved with nitric acid.

Surface water samples were collected on the South Fork using depth integration across the width of the stream. Flow measurements were recorded when samples were collected, using a Marsh-McBirney Flo-Mate and the USGS midsection method (Turnipseed et al., 2010). The South Fork was sampled at seven sites within the SHB to account for flow and chemistry changes from entering tributaries. Samples were collected at high, medium and low flow. Flow and water quality data for the Main Stem was obtained from the U.S.Geological Survey's gauging station near West Yellowstone (station #06037500). Numerous studies have been carried out in the past on the Main Stem and therefore additional sampling was deemed unnecessary.

Groundwater and spring information was compiled using existing data when possible, and collecting additional samples to fill in data gaps. Archived records for well information and water quality data were gathered from MBMG's Groundwater Information Center (GWIC). Samples were collected after three well volumes of water were purged, and field parameters had stabilized. Samples were collected from a flow chamber. All wells were measured for static water level or shut-in pressure when possible.

Analytical Methods

Trace metals were analyzed using an Inductively Coupled Plasma Atomic Emissions Spectrometer (ICP-AES). Major anions were analyzed using an Ion Chromatography instrument (IC). Alkalinity was measured using a digital titrator.

Modeling Methods

<u>Confined Aquifer Head vs. River Flow Plots</u>

Comparisons of confined aquifer head to river discharge were generated using publically available water monitoring data. Head values were obtained from MBMG long-term monitoring wells. Four wells (NEc, NWa, SEa and SWa in Figure 1) were selected for geographic distribution (GWIC ID's #106775, #230654, #106842, and #165852). Wells SEa and SWa have continuous level-logger monitoring data. Head levels for wells NEc and NWa are sampled at regular site visits. River discharge measurements were obtained from the USGS gauging station located near West Yellowstone. Although the western portion of the SHB confined aquifer is likely being recharged from the South Fork and its tributaries, records from the Main Stem were used to represent runoff conditions due to the similarity of the river systems and the available temporal data.

Geothermal Constituent and Main Stem Dilution Line Plots

Plots comparing concentrations of noted YNP geothermal constituents were created to analyze the sources and mixing trends of the Main Stem recharge system following methods used in Nimick, 1998. Only wells drilled into the confined aquifer along the Main Stem were selected, as plots were designed to investigate the Main Stem tracer sources. A dilution line was created for the Main Stem using water chemistry data collected between 1989 and 2004, at the USGS West Yellowstone gauging station. Multiple datasets at high, medium and low river flows were used to develop the dilution line.

Gradient Models

Potentiometric surface maps, temperature gradients, and tracer concentration gradient, were created in ArcGIS® using the "Natural Neighbors" interpolation method. The Natural Neighbors interpolation method determines the closest subset of input samples to a point and weights them using proportionate areas to interpolate values (Sibson et al., 1981). Natural Neighbors is considered equally as accurate when using data points with an uneven geographic distribution (Watson et al., 1992). Numerous interpolation techniques were attempted but Natural Neighbors generated the fewest false positives in the model contouring, as interpolated values cannot be outside of the sample dataset.

Gradients were developed using archived MBMG GWIC data and supplementing with information gathered from site visits. Well data for the center of the SHB is limited due to a large section of U.S. National Forest located between the Main Stem and the South Fork. Additionally, the portion of the project site located within YNP is largely absent of well data. Owing to these limitations, wells were chosen to supply as even a geographic distribution as possible. Wells were selected for models only when driller's logs indicated the well was drilled into the confined aquifer. Thirty wells were selected for the potentiometric surface model, 23 wells were selected for the temperature gradient model, and 20 wells were considered for the tracer concentration gradient model. Discrepancy in the number of wells used for creating the various model types is due to data availability for the various parameters of interest. For wells sampled on multiple occasions and containing numerous data sets, the most recent data set was used in model construction.

Tracer Concentration Gradients (TCG) were created by using naturally occurring tracers. Tracers were selected for their conservative nature and relative abundance within their hypothesized recharge area. Water chemistry data for the confined aquifer were limited to twenty wells. Lithium and fluoride were selected as chemical tracers for the Main Stem recharge system. These elements, along with chloride and boron are known to travel conservatively in groundwater and have been used previously in the lower Madison River alluvial aquifer to identify geothermally sourced water systems [Nimick., 1998]. Chloride was not used in these models due to regionally anomalous concentrations and B was excluded due to the limited available chemistry data [Nimick., 1998]. All the Main Stem recharge system tracers appear in concentrations above regional background levels. For the South Fork recharge system, strontium was selected as the chemical tracer. Strontium is known to travel relatively conservatively in groundwater and occurs at levels significantly higher than regional background levels in the southwest portion of the SHB.

Gradient models were also used to analyze human health concerns for As and F^-. For these models, the main focus was to create a contour for the EPA human health standard (10 μg/L for As, and 4 mg/L for F^-). Models also included all wells registered with the MBMG GWIC which exceeded or at risk of exceeding the human health standard.

Stiff Patterns and Piper Diagrams

Stiff patterns are a graphical method for depicting major-ion chemistry data. Chemical concentrations are presented as meq/L. Stiff patterns were generated using Schlumberger's Aquachem® software. Stiff patterns were created for 12 wells in the SHB aquifer. Wells were chosen to supply an even geographic distribution. Stiff patterns were then placed on the map next to their corresponding well using ArcGIS. Piper Diagrams were also created. Major-ion concentrations are presented as a percentage of all evaluated ionic species. The piper diagram for the SHB confined aquifer was created by grouping the wells into three categories by region; wells located near the Main Stem, wells located near the South Fork, and wells located along Hebgen Lake. The piper diagram was generated using the USGS' GW-Chart ® software.

Results

Table I. Select water chemistry results for groundwater within the SHB.

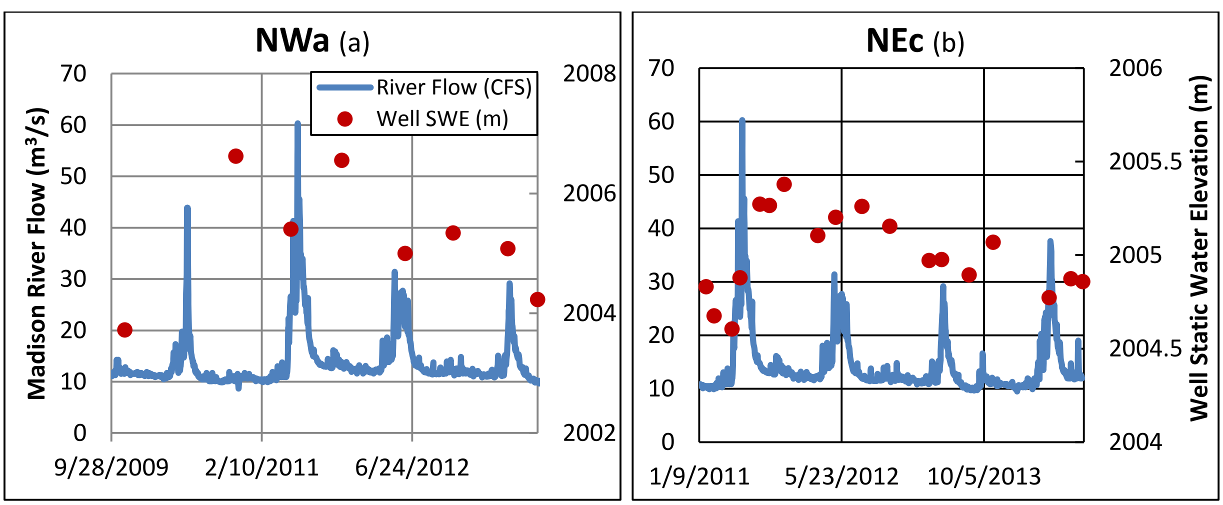
	Well ID	Temp °C	pH	eH	As	Cl^-	F^-	Li^{+2}	Sr
South Fork Wells	Nwa	14.88	7.28	-176.1	7.36	6.69	3.98	94.62	38.19
	Wa	7.90	7.71	49.00	1.02	2.6	2.15	75.13	58.20
	SWa	6.10	7.14	47.30	0.22	1.04	0.30	2.34	235.10
Main Stem Wells	NEb	22.01	6.88	229.86	27.70	10.5	4.71	157.21	11.62
	Ea	12.50	8.30	138.00	15.40	11.5	4.2	111.23	28.42
	SEa	8.99	7.03	114.66	1.73	3.94	2.94	50.18	7.69
Hebgen Lake Wells	Na	8.00	7.44	-	6.80	2.90	1.40	30.00	-
	Nb	12.2	7.6	-	10.70	3.30	3.78	63.00	23.10

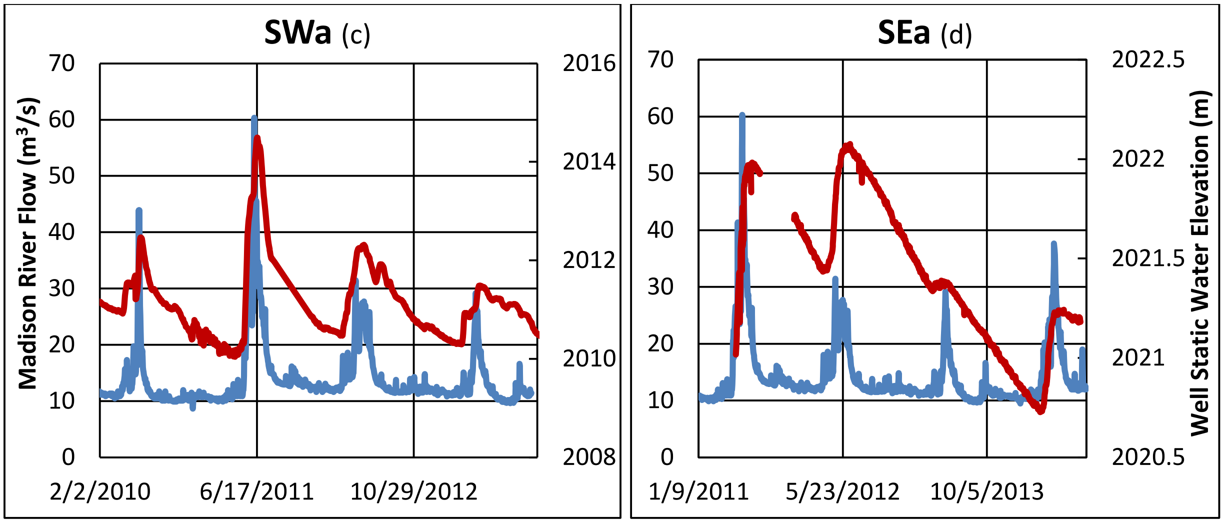
Table II. Select water chemistry results for surface water within the SHB.

		As	Cl^-	F^-	Li^{+2}	Sr
Main Stem	Mean	248.76	49.52	5.96	499.18	-
	STDEV	81.00	16.22	1.65	165.19	-
South Fork	Mean	2.00	2.52	2.34	33.83	21.43
	STDEV	1.31	0.14	0.12	3.39	3.21

Physical Hydrogeology Results

Plots of confined aquifer head levels vs. Main Stem river flows showed the aquifer responsiveness to surface water events (Figures 4a, 4b, 4c & 4d). Three wells, located in the northeastern, southeastern and southwestern portions of the project site (wells NEc, SEa and SWa in Figure 1), displayed a distinct correlation between well head and surface water flow. High river flow (runoff) events correspond to increases in well head, while low river flows (base flow periods) correspond to decreases in well head. The well located in the northwest portion of the project site (well NWa in Figure 1) displayed no visible correlation to the Main Stem surface water flows, though data for this well was substantially more limited. Well NWa's deviation from the trend seen in the other wells is possibly due to its relatively deep borehole, and unusual well construction.





Figures 4 a-d. River flow in the Main Stem of the Madison River (m^3/s) compared with static water elevation in SHB confined wells (m above sea level). River flow data are from the USGS National Water Information System (gauging station 06037500). Well data are from the MBMG GWIC data base.

The generated potentiometric surface gradient depicts a single, basin-wide confined aquifer (Figure 5a). Two distinct recharge areas contribute to the confined aquifer and flow towards a confluence, located approximately between the Main Stem and the South Fork, beneath Hebgen Lake. The first recharge area is located to the southeast and flows parallel to the course of the Main Stem. The second recharge area is located near the base of the Lionshead and Henry's Lake Mountains, and travels roughly perpendicular to the course of the South Fork towards the confluence. When the potentiometric surface is overlain on a geological map, the potentiometric surface matches with the alluvium and glacial outwash as expected (Figure 5b).

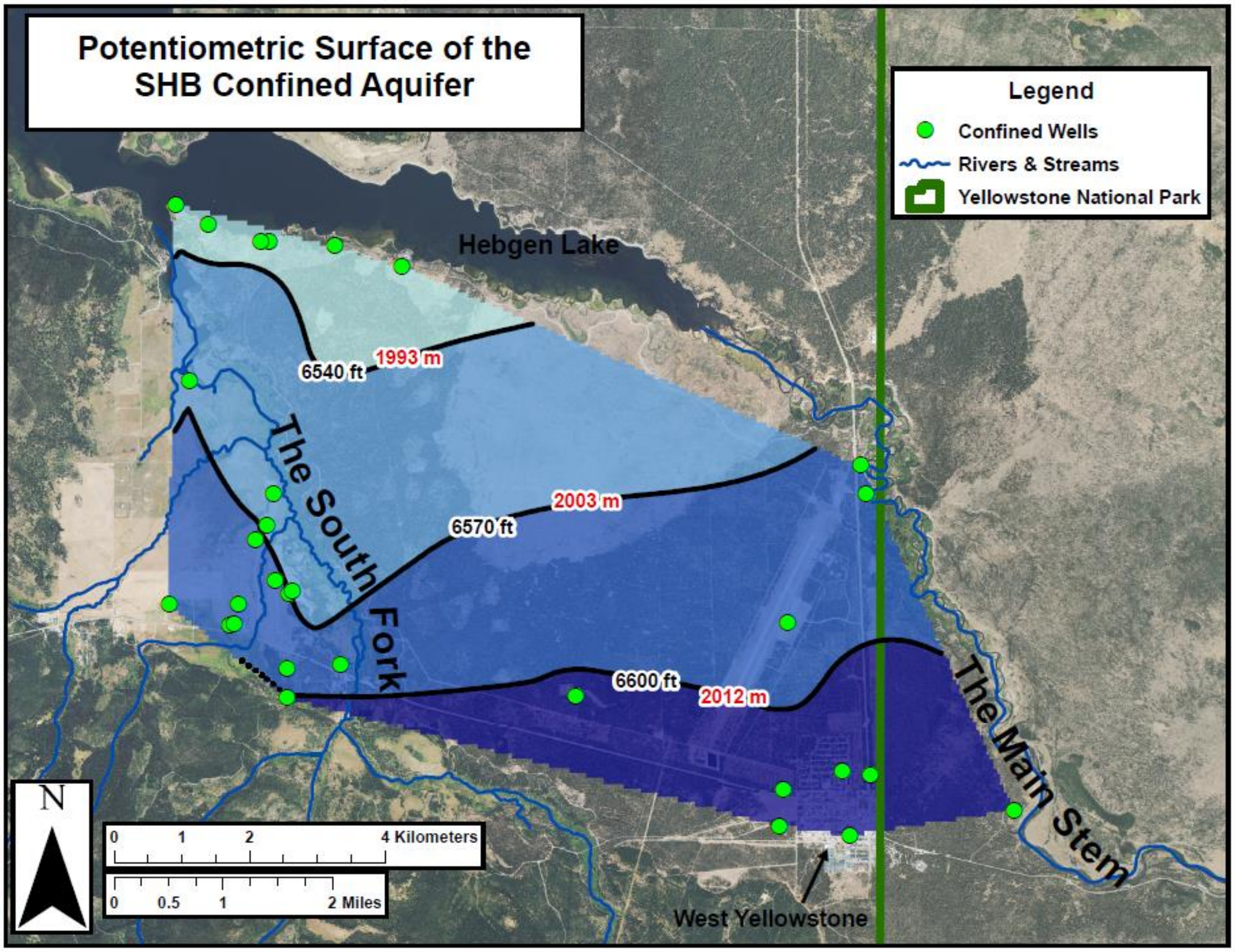


Figure 5a. Potentiometric Surface of the SHB confined aquifer (displayed in m and ft) as calculated using natural neighbor interpolation. Well data are from the MBMG GWIC data base.

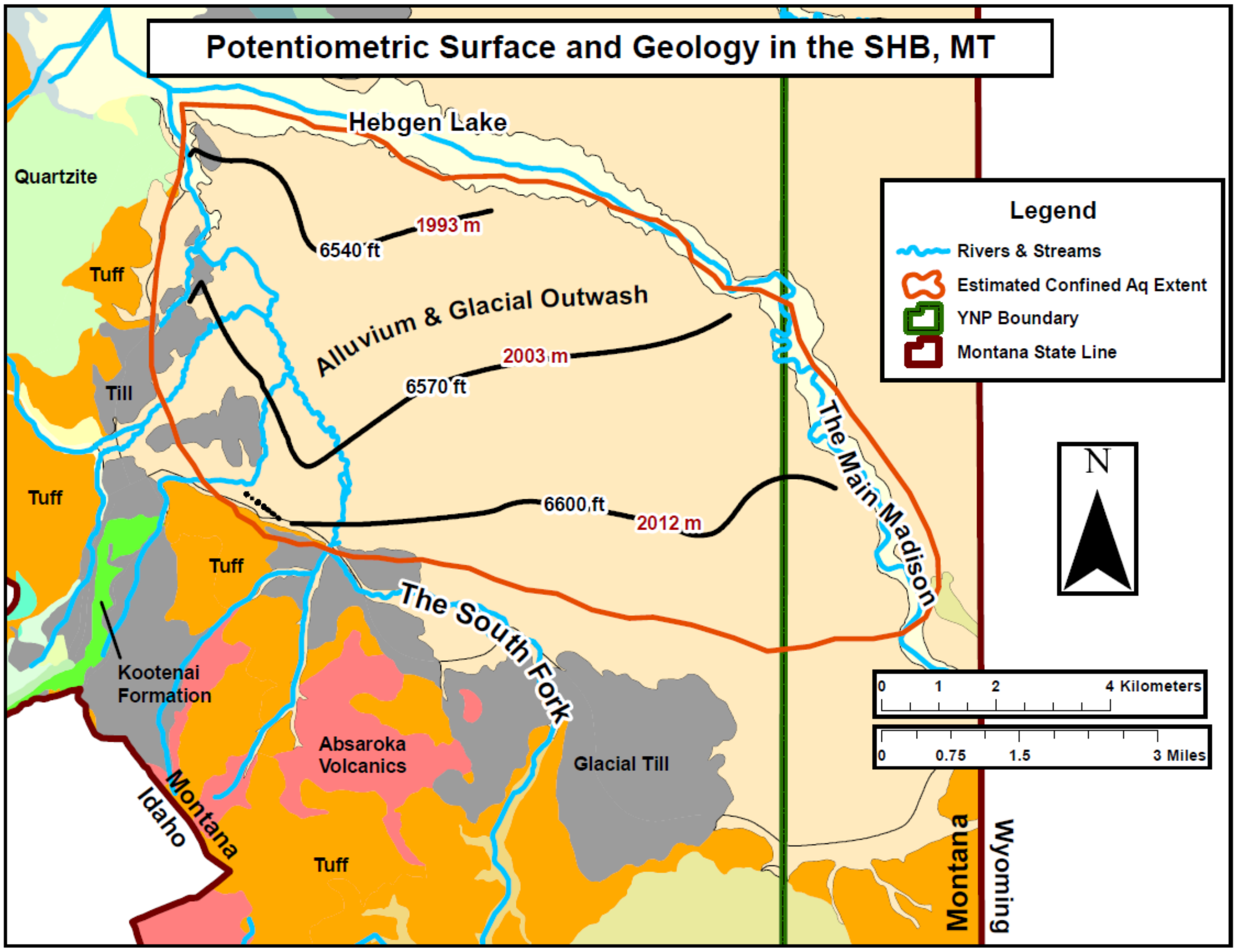


Figure 5b. Potentiometric Surface of the SHB confined aquifer (displayed in m and ft) overlayed on the MBMG 100k Hebgen lake geologic map (O'Neill et al., 2002). Well data are from the MBMG GWIC data base.

Hydrogeochemistry Results

The temperature gradient appears to depict two distinct areas of warmer groundwater; however, the western area is highly influenced by a single deep well (Figure 6). The warmer geothermal area is located along the Main Stem, in the northeastern portion of the project site, and has temperatures reaching upwards of 20 °C. This geothermal area extends into YNP which has limited data points, and therefore the eastern extent of the geothermal area cannot be predicted. A slightly cooler geothermal area is located along the South Fork in the northwestern portion of the project site. Temperatures in this area reach up to 15 °C.

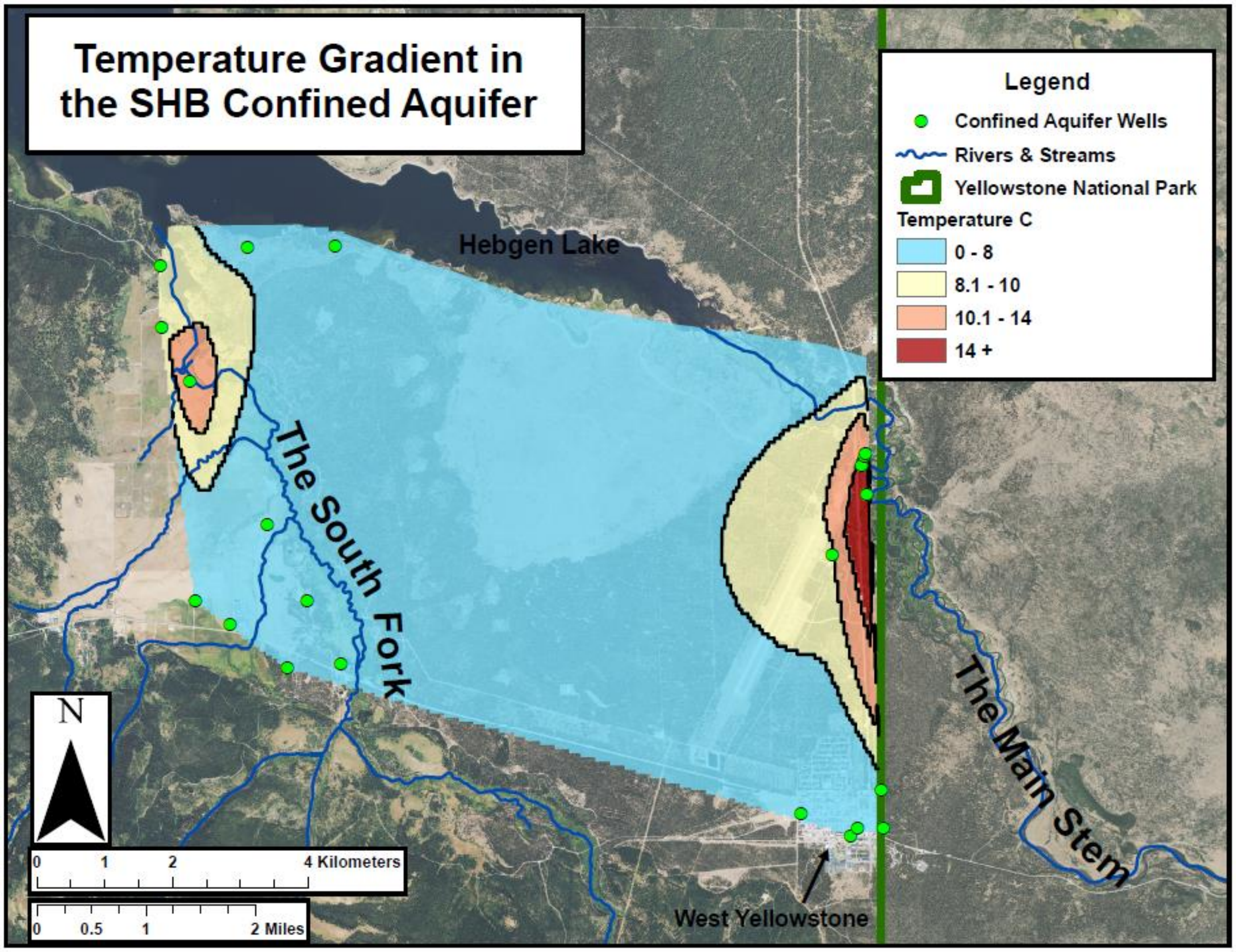


Figure 6. Temperature (°C) gradient in the SHB confined aquifer as calculated using natural neighbor interpolation. Well data are from the MBMG GWIC data base.

Well temperature vs. tracer concentration suggests a relationship between geothermal water and groundwater chemistry (Figure 7). For wells containing multiple data sets, temperature and tracer concentration values were averaged from all available datasets. The plots of the two Main Stem tracers (Li^+ and F^-), as well as the constituent of concern (As), depict a strong correlation between water temperature and concentration. The R^2 values ranged from 0.7773 to 0.8754.

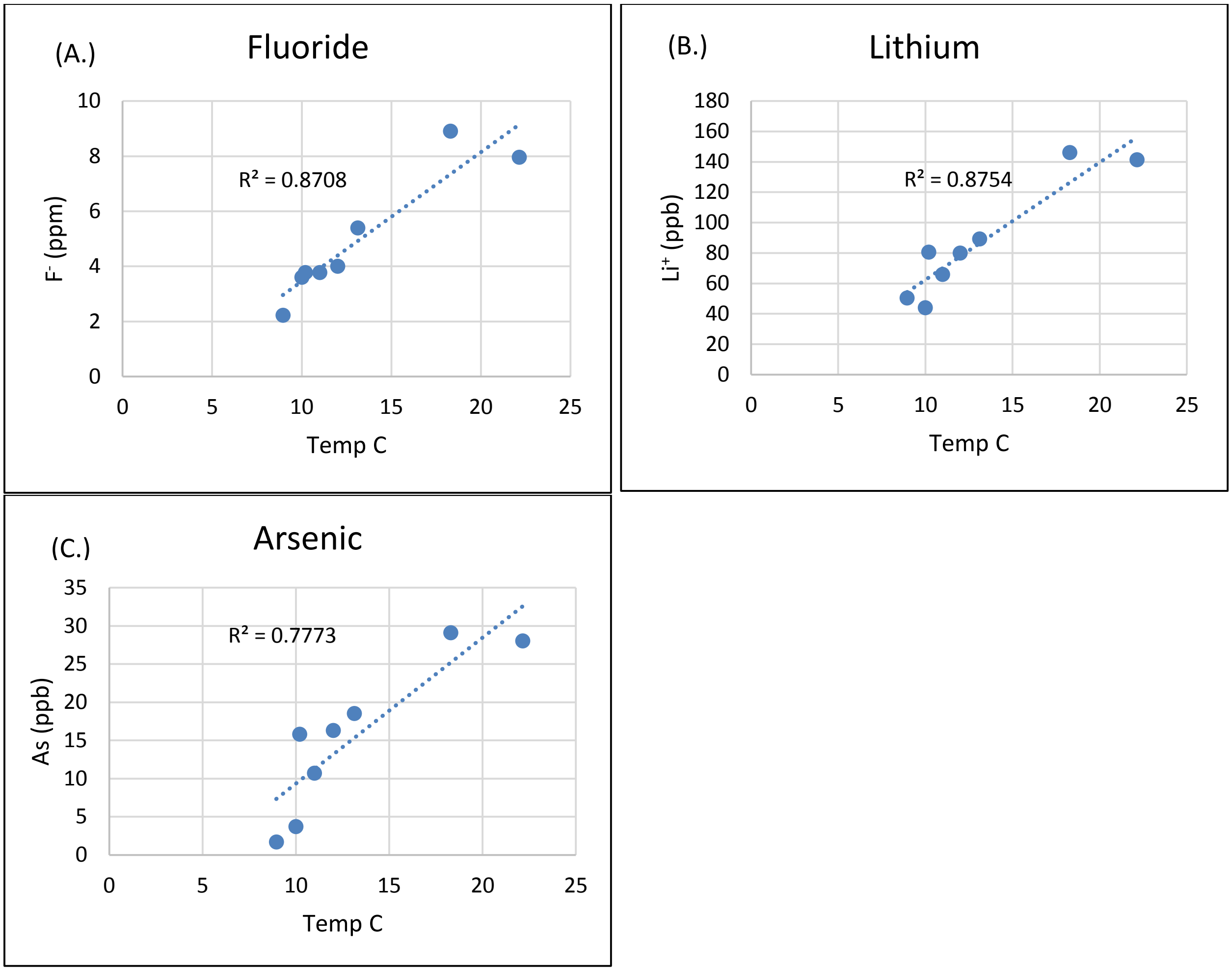


Figure 7 a-c. Geothermal tracer (and constituent of concern) concentrations vs. temperature (°C). Well data are from the MBMG GWIC data base.

Figure 8 depicts the Main Stem dilution line and selected geothermal constituents plotted against each other. Plots compare concentrations of As, F^-, Li^+, and Cl^- for wells located in the eastern portion of the project site (near the Main Stem). For wells containing multiple data sets, concentration values were averaged from all available datasets. The Main Stem dilution line predicts how elemental ratios will dilute as the geothermally influenced river water mixes with more typical waterbodies. The Main Stem dilution line is plotted with the geothermal constituents to analyze the groundwater's relationship to the surface water. The plot of known conservative constituents (Li^+ and Cl^-) lies generally along the Main Stem dilution line, which suggests that the Main Stem is a source of recharge for the confined aquifer. However, the groundwater concentrations are approximately 20% of those found in the Main Stem surface water which indicates that other sources of recharge are likely diluting the Main Stem water (Figure 3a & 3b). When As is plotted against the other constituents, the data points generally lie off the dilution line with As concentrations less than predicted by the dilution line. When F^- is plotted against the other constituents, the data points generally lie off the dilution line with F^- concentrations greater than predicted by the dilution line.

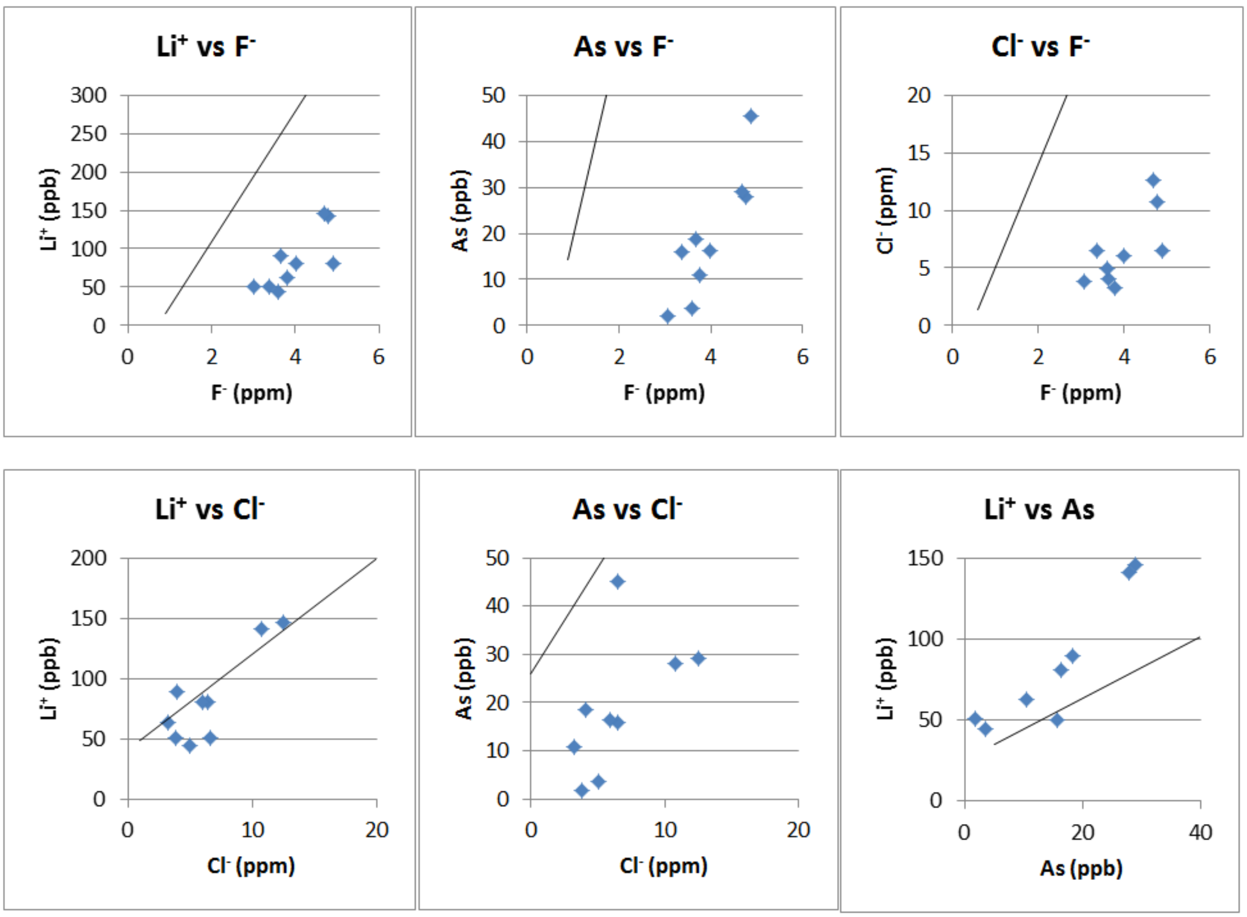


Figure 8. Geothermal constituent comparisons and Main Stem dilution lines. Geothermal constituent concentration data are from the MBMG GWIC data base. Dilution lines were generated from National Water Information System water quality data (gauging station 06037500).

When tracer concentration gradient maps were generated using the Main Stem tracers (Li^+ and F^-), tracer flow direction matches that depicted in the potentiometric surface model (Figure 9a & 9b). Tracers appear to flow from areas with higher concentrations (wells located near the Main Stem) toward the northwest. Lithium and F^- concentration also appear to be most elevated in areas exhibiting elevated groundwater temperatures (Figure 6). When a TCG map was generated using Sr concentration, tracer flow direction again roughly matches that depicted in the potentiometric surface model (Figure 5a and 9c). Strontium appears to flow from higher concentrations in the southwest of the SHB towards the theoretical confluence of the recharge systems.

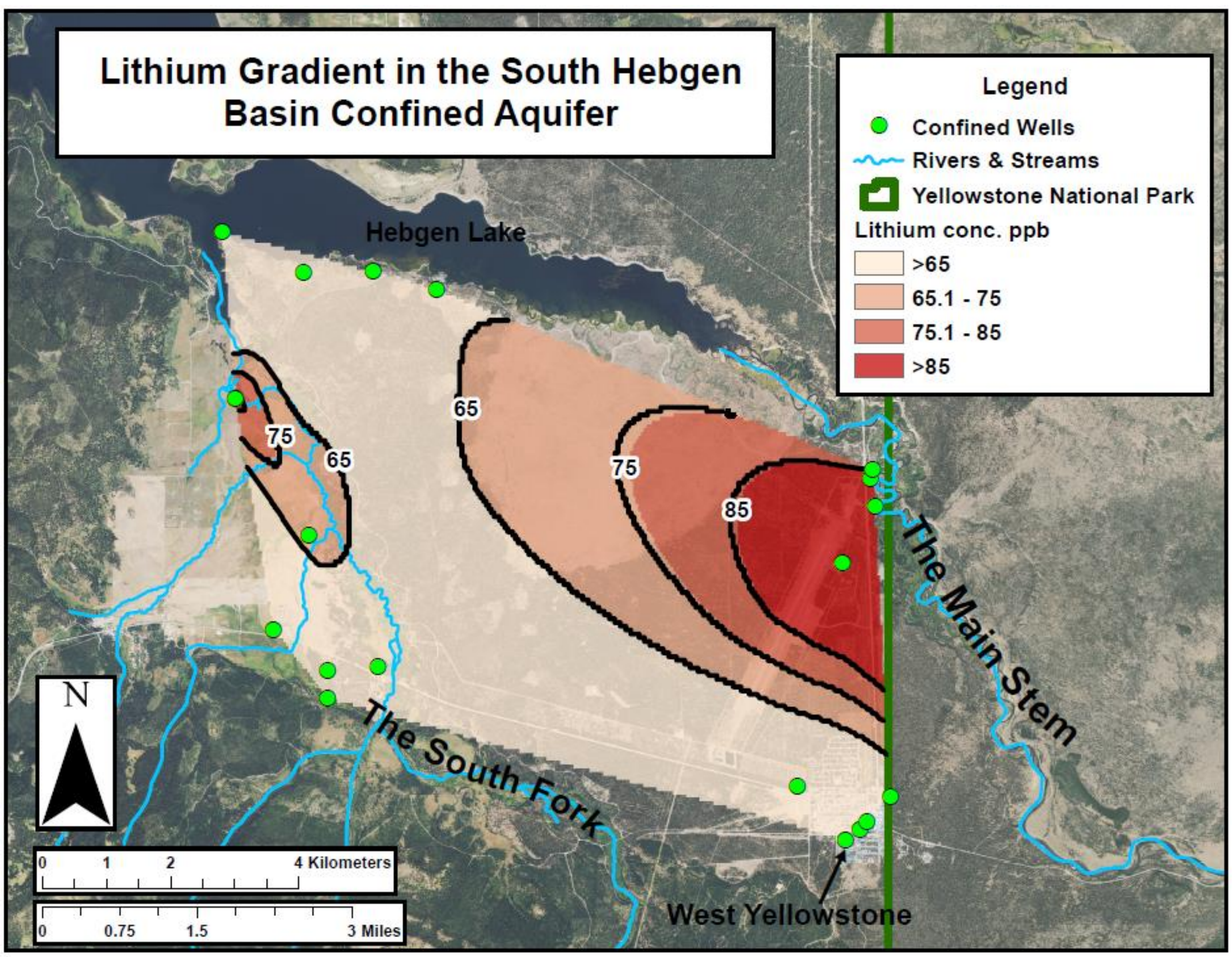


Figure 9a. Lithium concentration (µg/L) gradient in the SHB confined aquifer as calculated using natural neighbor interpolation. Well data are from the MBMG GWIC data base.

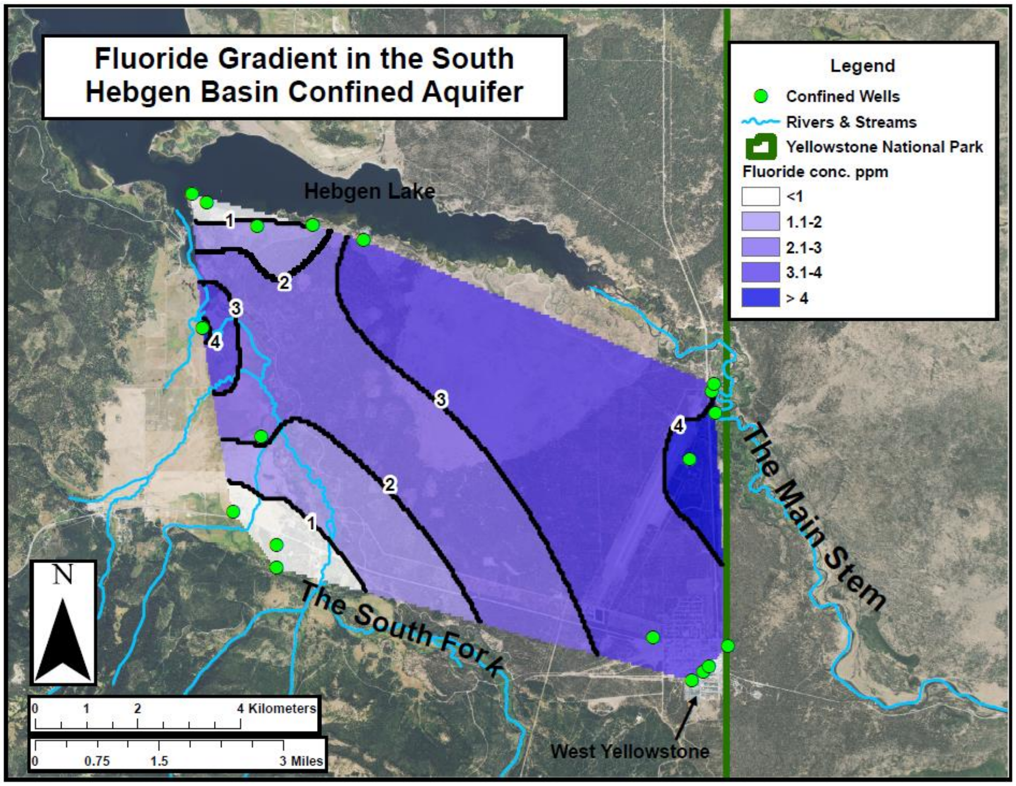


Figure 9b. Fluoride concentration (mg/L) gradient in the SHB confined aquifer as calculated using natural neighbor interpolation. Well data are from the MBMG GWIC data base.

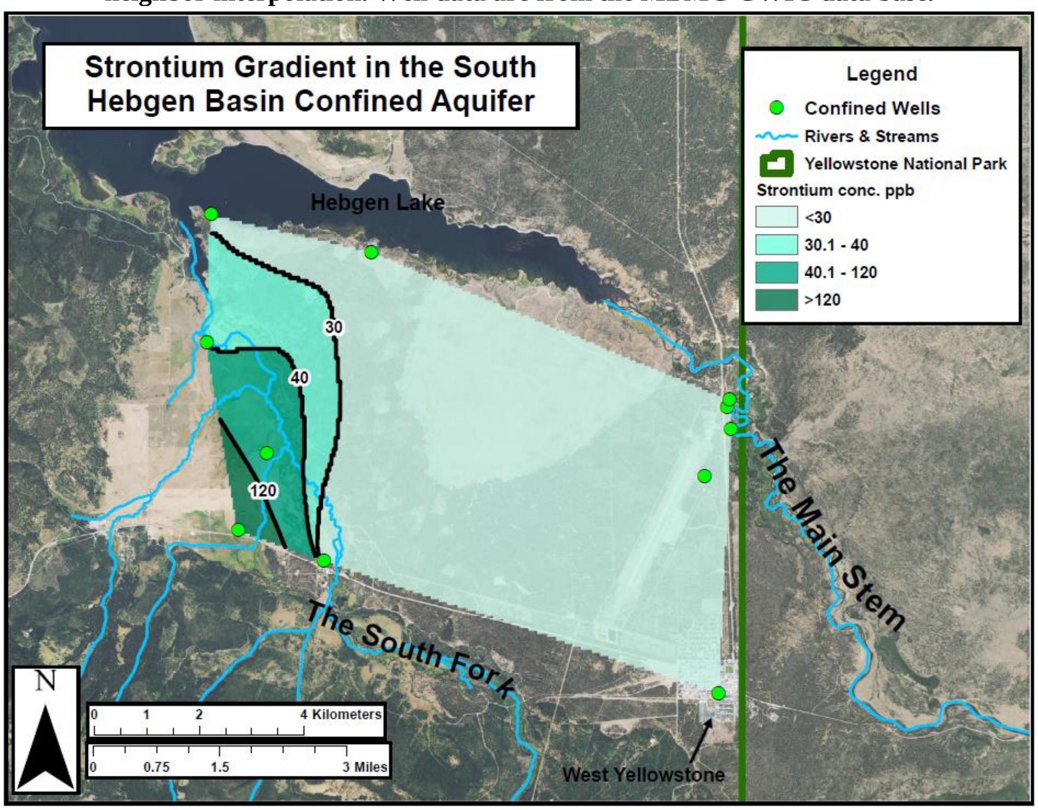


Figure 9c. Strontium concentration (µg/L) gradient in the SHB confined aquifer as calculated using natural neighbor interpolation. Well data are from the MBMG GWIC data base.

The stiff patterns map appears to also suggest two distinct recharge areas (Figure 10). Major-ion chemistry of the groundwater near the Main Stem is dominated by Mg^{+} and HCO_3^-, while major-ion chemistry near the South Fork is dominated by Ca^{2+} and HCO_3^- . Geothermal systems appear to heavily influence the groundwater chemistry. Wells with temperatures greater than 10 °C have increased concentrations of Mg^{2+} and HCO_3^-. Cold wells along the Main Stem depict the same basic shape as their warm counterparts, but with less elevated concentrations. The sole geothermal well located along the South Fork also depicts a shape typical of the Main Stem wells, which is likely a function of its deeper borehole.

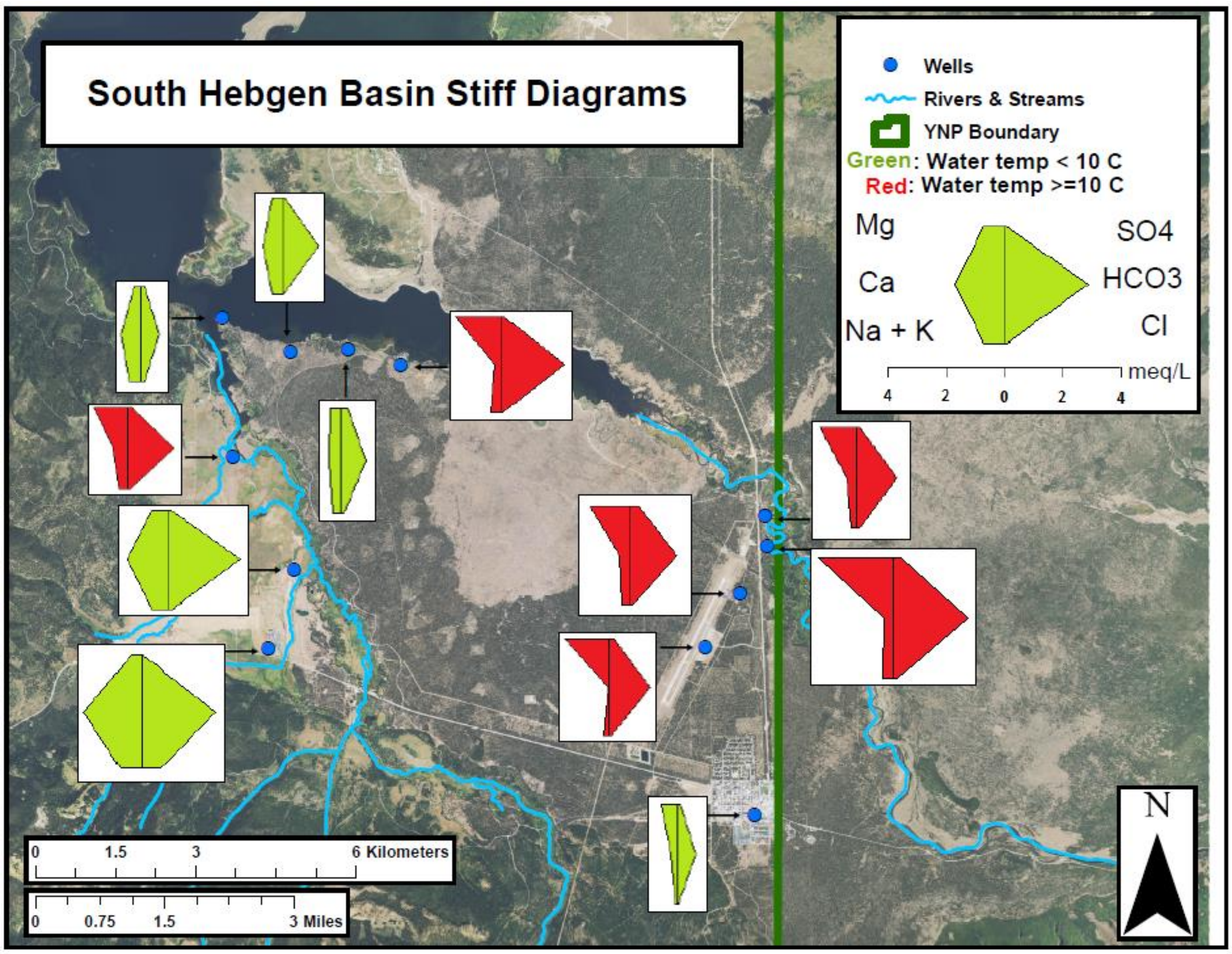


Figure 10. Stiff patterns for wells drilled in the SHB confined aquifer, categorized by temperature range. Well data are from the MBMG GWIC data base.

The piper diagram depicts two distinct chemistry trends (Figure 12). The Main Stem wells are more influenced by Na^+ and K^+, while the South Fork wells are more influenced by Ca^{2+}. As seen in the Stiff patterns, the lone geothermal well located near the South Fork, plots more similarly to the Main Stem wells. The plot position of the Hebgen Lake wells varies depending geographic location. The well located farthest east tends to plot similar to the Main Stem wells, while western Hebgen Lake wells tend to plot similar to the South Fork wells.

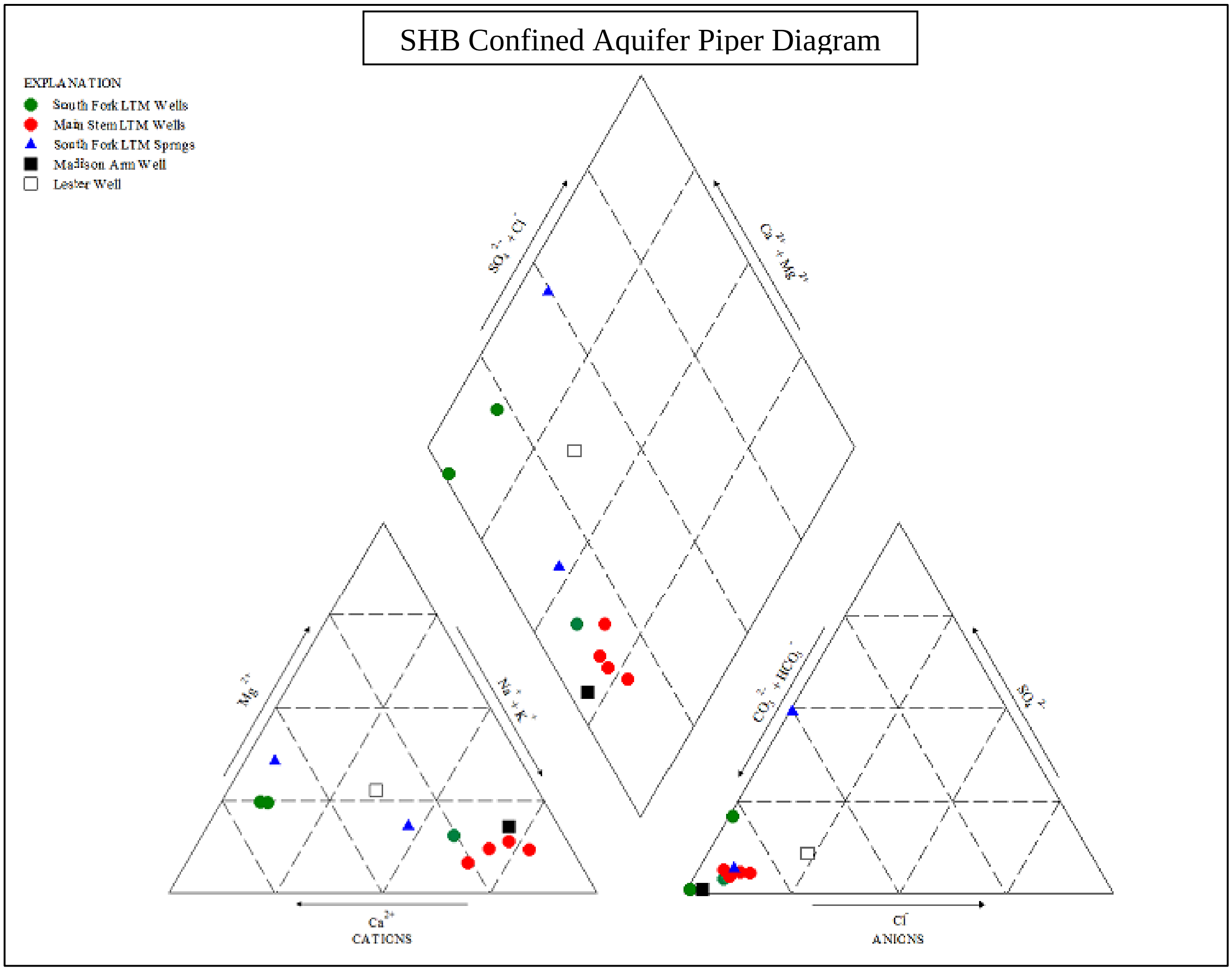


Figure 11. Piper diagram for wells drilled in the SHB confined aquifer, delineated by temperature. Well data are from the MBMG GWIC data base.

Figures 13a and 13b depict where the interpolated As and F^- concentration gradients exceed the EPA human health standard. These figures also display wells with known or potential As and F^- chronic exposure concerns. Eleven wells were found to exceed the EPA human health standard for As, and seven wells were found to exceed the standard for F^-.

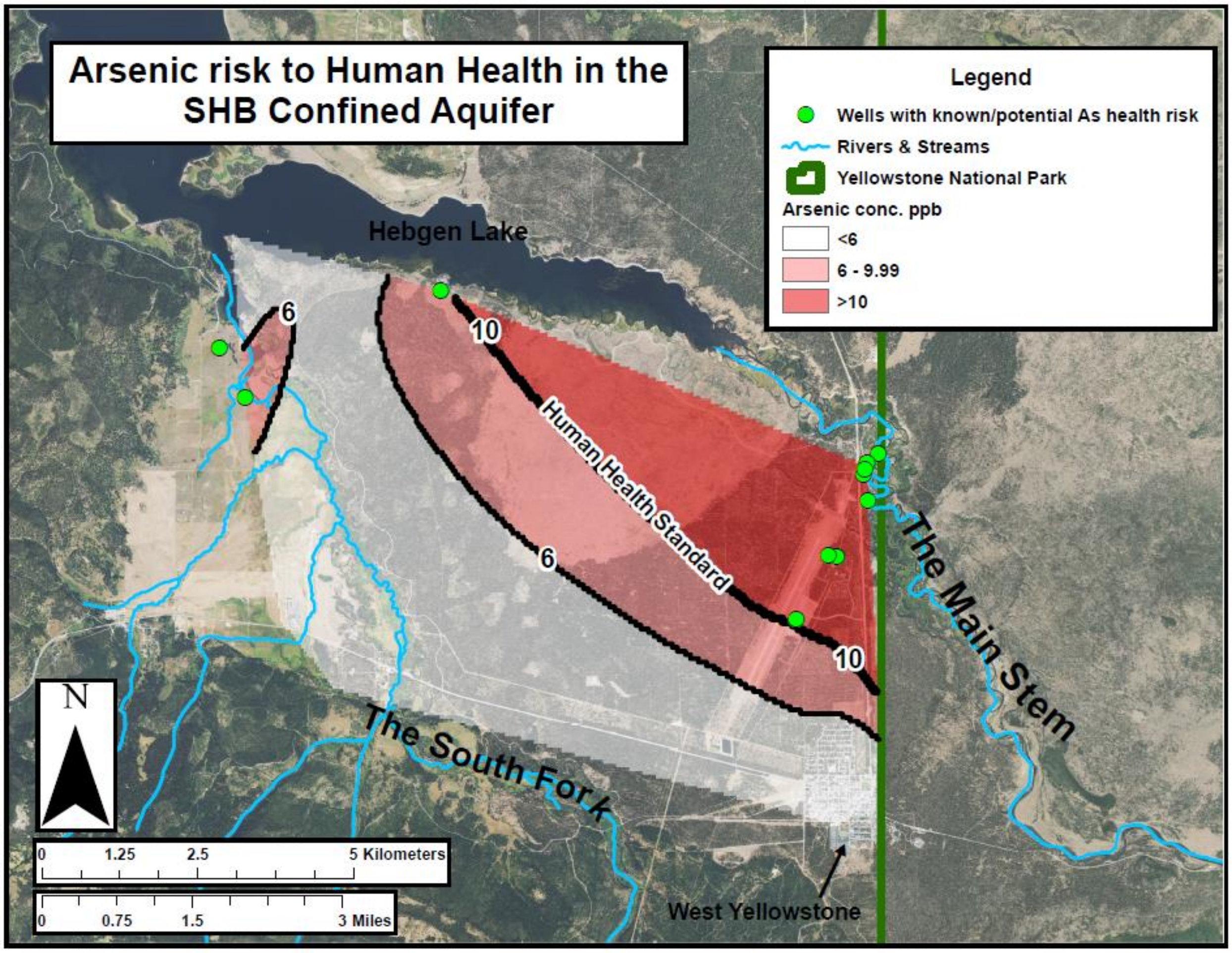


Figure 12a. Groundwater posing a health risk from As in the SHB confined aquifer. Well data are from the MBMG GWIC data base.

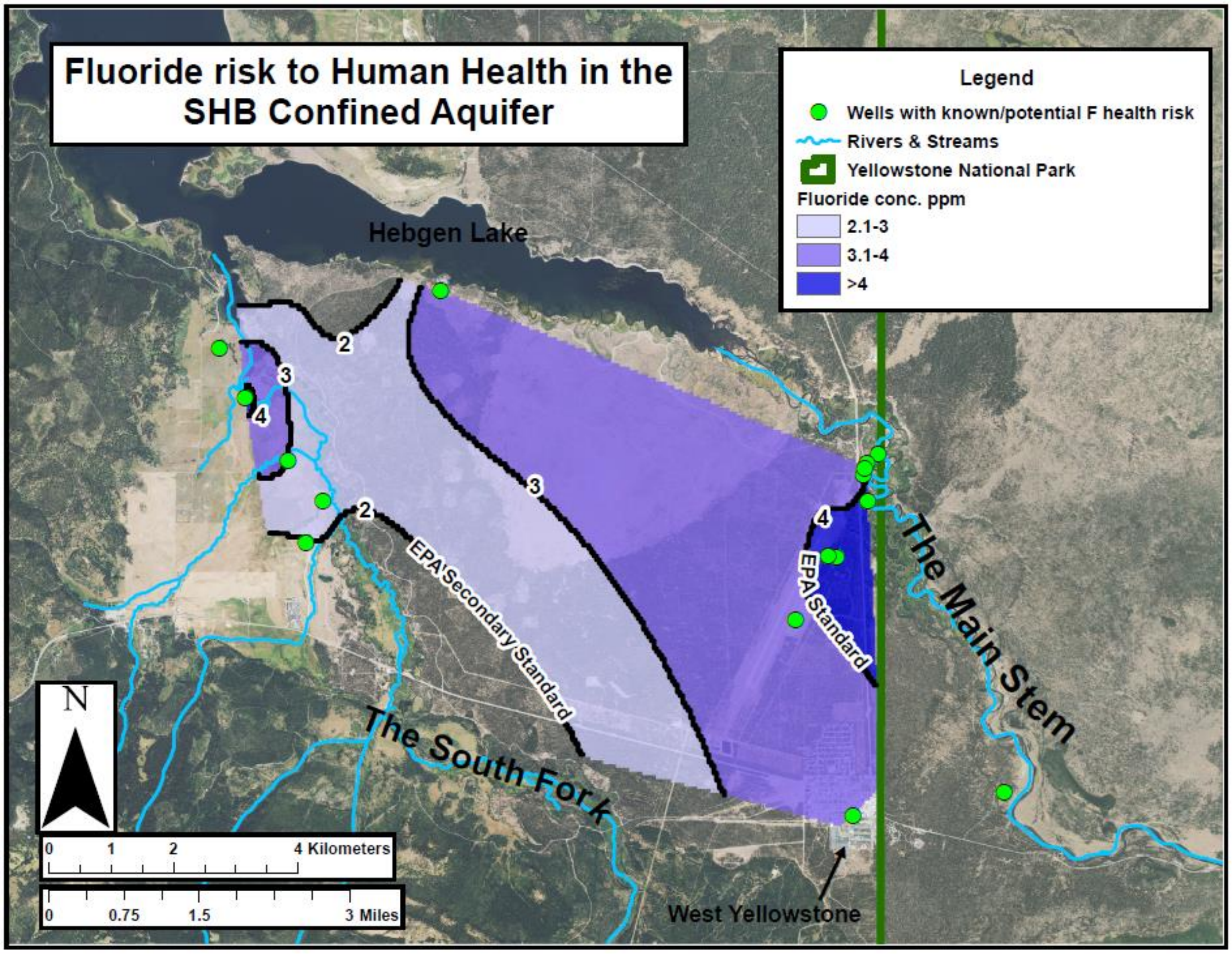


Figure 12b. Groundwater posing a health risk from F in the SHB confined aquifer. Well data are from the MBMG GWIC data base.

Discussion

Groundwater Flow System

The correlation between surface water flow and head in three of the four LTM wells suggests that the surface water is influencing the SHB confined aquifer (Figure 4). Because both LTM wells located near the Main Stem displayed a correlation between the river flow and head, a strong likelihood exists that the Main Stem, and or surface runoff events, is a source of recharge for the eastern portion of the SHB confined aquifer. The well located in the southwest portion of the SHB also appeared to be influenced directly by surface water conditions. The northwest well head levels did not appear to correlate with the Main Stem discharge measurements, though this is possibly due to a lack of reliable data. It is also possible that this well is recharged primarily from runoff from the Lionshead Mountains or due to its relatively deep borehole. In general, both southern wells displayed large fluctuations in head levels which were more tightly correlated to river discharge. This suggests that the southern portion of the SHB is more influenced by surface water runoff events. This supports the theory of recharge areas at the base of the Henry's Lake and Lionshead mountains, and may also indicate semi-confining conditions.

As mentioned earlier, the extent and connectivity of the SHB confined aquifer was poorly understood. Although a lack of wells within YNP prevent this study from determining the eastern extent of the confined aquifer, a working potentiometric surface model of the confined aquifer outside of the park was created (Figure 5a). The potentiometric surface depicts a single confined aquifer which is recharged from regions along both the Main Stem and the South Fork of the Madison Rivers. It is likely that the confined aquifer extends east into YNP, and north under Hebgen Lake, though these speculations cannot be verified. This model suggests that confining conditions located along each river are part of a single confining layer and not separate confined aquifers. Although limited well distribution prevents the potentiometric surface map from achieving a high level of confidence, it is supported by additional analysis.

TCG maps support the generated potentiometric surface. Both the Main Stem and the South Fork tracers appear to flow from the recharge areas towards the hypothetical confluence in the confined aquifer. TCG models depict high tracer concentrations near the respective recharge zones that gradually decrease in concentration as they flow northeast and northwest (respectively), within the confined aquifer. As with the potentiometric surface model, uneven distribution of water chemistry data limits the accuracy of the TCG maps. However, they do provide supplemental information that supports the validity of a basin-wide confined aquifer as predicted by the potentiometric surface model.

The Stiff patterns map and Piper diagram appear to support the TCG models and the potentiometric surface (Figure 10). In the Stiff patterns map, two distinct water chemistries are represented on either side of the project site. The Mg^{2+} rich Main Stem system and the Ca^{2+} rich South Fork system both generally appear to follow their predicted gradient toward the hypothetical confluence. Along the Main Stem, warm wells exhibit higher Mg^{2+} and HCO^{-} concentrations when compared to their colder counterparts near West Yellowstone. Similarly, the only warm well located near the South Fork exhibits a Stiff pattern closely resembling the warm Main Stem wells. This is likely related to the previously asserted temperature influence on groundwater chemistry. The Piper diagram depicts very similar trends to the Stiff patterns. The two recharge systems can be discerned, with the South Fork wells and the Main Stem wells plotting separately in two of the three Piper diagram plots. The geothermal influence on water chemistry can also be identified. This reaffirms the distinct chemical nature of the two recharge systems.

It is hypothesized that the eastern portion of the confined aquifer is recharged by the Main Stem upstream of the clay confining layers, as well as a series of small streams, which flow out of the southern Gallatin Mountains and the eastern Henry’s Lake Mountains. This would explain the conservative tracers (Cl^{-} and Li^{+}) for wells located near the Main Stem, plotting along the dilution line, but with concentration levels only 20% of those found in the surface water. The confined aquifer in the western and southwestern portion of the SHB is hypothesized to be recharged by the South Fork as well as the numerous streams and springs which drain from the Lionshead and Henry’s Lake Mountains.

Temperature Gradient

It is known that geothermal features significantly impact water chemistry and quality. Mapping the distribution of geothermally influenced groundwater within the SHB confined aquifer was considered important for comprehending the water chemistry therein. The geothermal regions (temperature ≥ 10 °C) shown by the temperature gradient modeling visually appear to align with the high concentration areas depicted in the Li^+ and F^- TCG maps (Figures 9a and 9b). This relationship is significant. It was initially hypothesized that the Main Stem chemical tracers, as well as As, originated from the river's geothermal source waters in YNP. This qualitative assessment appears to depict that Li^+, F^- and As are leaching from geothermal hotspots within the SHB confined aquifer. This assessment was quantitatively supported by plotting groundwater temperature against Li^+, F^- and As concentration (Figure 7).

Solute Transport and Geothermal Influences

By plotting temperature against the Main Stem tracer (and As) concentrations, a clear positive correlation was discerned (Figure 7). Increased groundwater temperature corresponds to increased tracer concentrations. This suggests that the tracers, including those that pose a risk to human health, are being leached from sediments within the confined aquifer. Chaffee (2007) noted that elevated anomalies of As sediment concentrations in the Main Stem, were likely the result of "fossil geothermal areas" or the result of, "unusually high background values in some of the felsic volcanic rock" [Chaffee et al., 2007]. Additional analysis has found that obsidians and other felsic volcanic rocks from YNP are often a source of F^- [Hem et al.,1970; Chaffee., 2007]. The SHB sediments are then a possible source of the elevated F^- concentrations. The generation of Li^+, F^- and As within the SHB contradicts the initial assumption that these elements were entering the confined aquifer solely as a result of groundwater recharge from the geothermally sourced Main Stem.

The relatively tight grouping of Cl^- and Li^+ on the scatter plot along the dilution line suggests that these constituents are conservative in groundwater and are at least partially sourced from the Main Stem (Figure 8). However, Cl^- and Li^+ concentrations in the confined aquifer near the Main Stem are only approximately 20% of the average concentrations in the surface water (Figures 3a & 3b). The relatively low Cl^- and Li^+ concentrations in the groundwater compared to the surface water suggest that other recharge sources are likely also contributing to the eastern portion of the confined aquifer. Likely sources of additional recharge are a series of small streams which flow from the eastern Henry's Lake Mountains, and the southern Gallatin Mountains, to the south and west of West Yellowstone. Arsenic repeatedly plotted below the Main Stem dilution line, which suggests that As moves less conservatively in the SHB groundwater (Figure 8). Arsenic mobility is possibly retarded through sorbtion onto the aquifer sediment. This assessment seems to be qualitatively affirmed in Figure 12a, in which As transport appears to be comparatively retarded. Fluoride plotting off the dilution line possibly suggests that F^- exists in the SHB confined aquifer in high concentrations, with sources besides the Main Stem. This supports the assertion that F^- is being leached from the volcanic sediments in geothermally influenced areas.

Human Health Risks

Arsenic and F^- concentrations in the SHB confined aquifer register near or slightly above the respective EPA human health standards near areas influenced by geothermal activity (Figures 12a and 12b). Residences in these areas, which use wells for domestic consumption are at risk of chronic exposure to As and F^-. Fluoride contamination was found to be more wide spread in the

SHB. Although only seven wells were found to be at risk of exceeding the primary EPA human health standard of 4.0 mg/L, the majority of the SHB registered above 2.0 mg/L for F^-. The EPA sets 2.0 mg/L F^- as the secondary standard above which cosmetic effects may occur. The Center for Disease Control identifies 2.0 mg/L as the F^- concentration at which the occurrence of dental fluorosis is greatly increased. Eleven wells were identified as at risk for exceeding the As chronic human health standard of 10 μg/L. It is likely that the As and F^- contaminant areas are relatively steady, though regular monitoring is recommended.

Fortunately, the majority of residences located near the highest As and F^- concentration area are used as seasonal cabins. Because these cabins are generally used intermittently, the likelihood of health problems from long-term exposure is lowered.

Conclusions

The models produced demonstrate a single, basin-wide confined aquifer in the South Hebgen Basin. The potentiometric surface model depicts two distinct recharge systems originating on either side of the basin. Both recharge systems flow towards a hypothetical confluence located between the South Fork and the Main Stem. TCG models depict the flow of recharge systems through the confined aquifer, and closely resemble the aquifer system hypothesized by the potentiometric surface map. This assertion is further supported from Stiff patterns and the Piper Diagram. Tracer concentration gradient models and the Stiff patterns also qualitatively depict the relationship between geothermals and water chemistry. This relationship was further supported by temperature-tracer concentration analysis, which suggests that the geothermal regions within the SHB confined aquifer are a source of the eastern recharge system tracers. This geothermal influence on water chemistry is significant due to the leaching of elements hazardous to human health. Geothermal features within the SHB confined aquifer are releasing As and F^- in quantities above the EPA human health standard. These elements represent serious water quality concerns within the SHB.

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Appendix

Select Groundwater Well Chemistry

GWIC ID	Lat	Long	Last sample date	temp	pH	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Si (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	F (mg/L)	As (µg/L)	Li (mg/L)	Sr (µg/L)
6582	44.681	111.208	8/24/79	7.5	7.26	29.2	8.8	9.7	2.1	33.6	22.6	2.2	2.6	0.24	0.5	5	-
8913	44.743	111.229	8/22/79	7	7.3	16.5	6.1	4.8	2.8	43.6	23.1	6.3	6.7	0.14	0.9	-	-
8925	44.735	111.186	6/11/98	12.2	7.6	6.43	5.8	42.2	3.91	53.8	155.7	3.3	-	3.78	10.7	-	23.1
8926	44.737	111.199	8/20/96	8	8.28	8.7	3.8	7.1	3.7	27.4	25.4	8.2	5.1	0.96	6.3	18	-
8927	44.737	111.213	8/24/79	8	7.44	16.7	5.4	8.4	3.3	41.3	91.9	2.9	1.1	1.4	6.8	30	-
8935	44.687	111.218	8/16/10	6.1	7.32	41	9.1	6.39	1.07	16.7	152.5	0.895	26.79	0.291	0.231	6.5	243
8939	44.677	111.208	8/27/79	5	6.7	5.9	1.6	7.9	1.8	28.4	8.3	1.7	3.9	0.22	0.3	25	-
8943	44.708	111.101	11/6/13	18.1	6.97	11.89	7.34	-	8.1	75.34	223.8	12.16	9.1	3.83	28.8	152.52	23.42
8948	44.664	111.097	8/27/79	7	7.5	5.6	1.5	13.8	2.4	47	49.4	4.3	1.9	3.6	3.3	53	
8950	44.660	111.101	8/22/79	6	6.32	5.2	1	6.9	2	40.6	44.5	5.4	1.9	3.6	0.9	25	-
8959	44.657	111.105	8/23/79	9	7	5.2	0.9	14.6	1.7	41.4	44.8	4.3	2.4	3.8	2.6	0.055	-
106775	44.704	111.100	8/6/14	21.9	7.08	6.26	4.34	51.77	6.1	81.68	154.6	10.82	7.94	4.81	26.74	142.3	10.58
106778	44.709	111.100	8/10/11	14.6	6.74	8.27	3	29.84	4.34	64.46	99.3	4.16	4.98	3.76	18.08	80.62	15.3
106781	44.696	111.106	8/20/14	12.5	8.3	7.23	3.5	35.55	3.9	44.2	112.1	11.5	3.9	4.2	15.4	111.23	28.42
106842	44.659	111.103	8/6/14	8.9	7.11	5.37	0.99	14.37	1.57	36.78	46.58	4	2.18	3.25	1.78	51.88	7.6
158035	44.741	111.225	6/16/98	8.2	7.2	15.31	4.3	4.1	2.22	41.1	80.5	1.2	4.08	0.17	3.97	-	29.8
165852	44.687	111.218	8/6/14	5.9	7.3	41.86	9.46	7.65	0.98	17.6	164.34	1.09	32.7	0.32	0.27	0.53	216.2
230654	44.719	111.226	8/7/14	15.9	7.05	14.76	5.34	36.33	3.55	52.04	150.23	6.97	-	4.38	9.14	89.14	38.38
259182	44.700	111.211	7/7/14	7.9	7.71	33.56	8.35	13.75	4.66	45.6	174.43	2.6	5.3	2.15	1.02	75.13	58.2

Select South Fork Surface Water Chemistry

Date	GWIC ID	Site ID	Discharge	Cl (mg/L)	F (mg/L)	Li (µg/L)	As (µg/L)	Sr (µg/L)
6/9/2014	278603	SF1	42.932	0.8078	1.7312	14.2	0	10.2
6/9/2014	278604	SF2	150.557	2.4362	2.5045	31.4	0.7	10.9
6/9/2014	278605	SF3	155	2.4625	2.5207	31.5	1.8	10.7
6/9/2014	278606	SF4	169.8025	2.4666	2.3519	31.8	1.2	23
6/9/2014	278607	SF5	157.094	2.4561	2.3285	31.8	1.3	24
6/9/2014	278608	SF6	156.562	2.3846	2.2158	30.3	1.8	25.8
6/9/2014	278609	SF7	-	2.383	2.214	30.2	1.2	25.6
8/1/2014	278603	SF1	40.3	0.7787	1.7361	14	0	10.2
8/1/2014	278604	SF2	98.1	2.745	2.665	33.9	0.6	9.3
8/1/2014	278605	SF3	101.3	2.729	2.686	34.4	0	9.2
8/1/2014	278606	SF4	112.6	2.7111	2.5327	33.8	0.3	16.9
8/1/2014	278607	SF5	123.5	2.707	2.5078	33.2	0	17.4
8/1/2014	278608	SF6	134.7	2.6467	2.4494	32.1	0.5	17.6
8/1/2014	278609	SF7	-	2.629	2.4467	32	1.4	18
11/1/2014	278603	SF1	27.2	-	-	15.3	2	10.7
11/1/2014	278604	SF2	100.2	-	-	40.9	3.4	9.7
11/1/2014	278605	SF3	94.3	-	-	41.1	1.9	10.1
11/1/2014	278606	SF4	99.4	-	-	40.8	3.1	16
11/1/2014	278607	SF5	116.5	-	-	40.7	4.6	17.1
11/1/2014	278608	SF6	116.5	-	-	38.4	3.7	20.9
11/1/2014	278609	SF7	-	-	-	39.3	3.7	22.4

Select Main Stem Surface Water Chemistry

Date	Cl (mg/L)	F (mg/L)	Li (µg/L)	As (µg/L)
4/14/1989	64	8.2	-	-
4/20/1989	40	5	-	-
5/17/1989	28	3.5	-	-
6/8/1989	33	4.5	-	-
7/6/1989	53	6.7	-	-
8/4/1989	59	6.7	-	-
8/24/1990	63	7.5	630	310
8/25/1990	62	7.4	620	310
5/26/1993	21	2.9	210	110
8/17/1993	63	6.4	430	200
2/15/1994	64	-	443	300
4/5/1994	63	-	670	290
5/9/1994	25	-	280	120
5/16/1994	28	-	320	140
6/2/1994	37	-	420	190
7/5/1994	53	-	600	270
8/22/1994	60	-	620	340
10/13/1994	64	-	670	340
1/10/1995	69	-	700	330
4/5/1995	64	-	690	320
6/6/1995	19	-	200	120
8/8/1995	47	-	540	270
4/19/2004	60	6.75	443	269
mean	49.52174	5.959091	499.1765	248.7647

Photos

South Fork of the Madison upstream sampling site

South Fork of the Madison River

Stream gauging on the South Fork

“Blue Hole” spring

Stinky Spring

Povah flowing artesian well