

**Progress Report:
Yellowstone Controlled Groundwater Area
Technical Oversight Committee
2014 - 2018**





Contents

Yellowstone Controlled Groundwater Area (YCGA) 1

Technical Oversight Committee (TOC)..... 1

TOC Reporting Requirements 3

Water Permitting in the YCGA..... 3

Water Permitting Activities in YCGA..... 3

Summary of YCGA Monitoring, 2014 to 2018..... 7

Overview of Monitoring Trends 15

Miscellaneous MBMG Activities 16

Summary of Yellowstone National Park Monitoring, 2014 to 2018 19

Water Use Data and Analysis 24

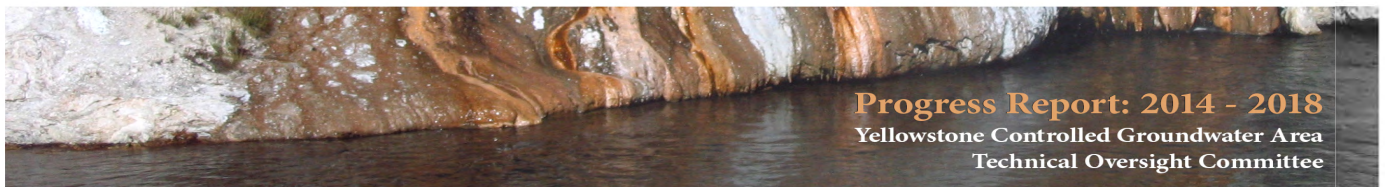
Re-evaluation of YCGA Boundary..... 25

Education and Public Outreach..... 25

References..... 26

Appendix..... 28

Yellowstone Controlled Groundwater Area Technical Oversight Committee Members 30



Yellowstone Controlled Groundwater Area

The Yellowstone Controlled Groundwater Area (YCGA) was established on January 31, 1994 under Article IV of the Water Rights Compact (Compact) between U.S. National Park Service (NPS) and the State of Montana (Montana Water Law: [MCA 85-20-401](#)). Article IV, section A of the Compact states in part:

The parties understand that knowledge of the interrelationship of hydrothermal features within YNP [Yellowstone National Park], the hydrothermal system that supports those features, and groundwater in surrounding areas of Montana will benefit from increased study. The parties agree that the hydrothermal features of YNP are a unique and irreplaceable resource and represent one of the few undisturbed hydrothermal systems in the United States.

The Compact further states that “the goal of establishment and administration of the YCGA shall be to allow no impact to the hydrothermal system within the reserved land of YNP.”

The following are roles of cooperating agencies:

- *Department of Natural Resources and Conservation (DNRC)* – administer YCGA and regulate groundwater appropriations in YCGA.
- *U.S. National Park Service (NPS)* – review and evaluate applications for beneficial groundwater use in YCGA and responsible for monitoring geothermal systems in YNP.
- *Montana University System* – advise on inventory and monitoring activities in YCGA.
- *U.S. Geological Survey (USGS)* – conduct hydrologic and geologic studies in the vicinity of YCGA, including stream flow, water quality monitoring, and geologic mapping.
- *Montana Bureau of Mines and Geology (MBMG)* – conduct hydrologic and geologic studies in the vicinity of YCGA, including stream flow, water quality monitoring, geologic mapping, data management, and mails, handles and tracks meter cards.

Technical Oversight Committee

The Technical Oversight Committee (TOC) for the YCGA was established in Article IV, section J.1.a to the Compact. The Compact specifically outlines tasks and procedures and states that “the TOC shall”:

- i. Review the boundaries of the Area and the Subareas.
- ii. Review the initial restrictions on groundwater development imposed pursuant to Article IV, and future modifications of those restrictions.
- iii. Assess the cumulative impact of all development in the Area.
- iv. Review changes in groundwater and hydrothermal systems revealed by inventory and analyses done by MBMG, and any other pertinent scientific evidence.
- v. Review new scientific evidence pertinent to the YCGA.
- vi. Consult with MBMG or the DNRC on request.
- vii. Present evidence and make recommendations to DNRC in accordance with Article IV, section J.2.
- viii. Review applications for a permit to appropriate groundwater with a temperature greater than 60 degrees Fahrenheit (°F) or on request by the DNRC as set forth in Article IV, section G.2.c.
- ix. Take any additional action necessary to implement Article IV of the Compact.

Members of the TOC are from the NPS, USGS, DNRC and Montana University System (Table 1 and Figure 1). An additional at large member is selected by the other members. The representative for the Montana University System is appointed by the Montana State Geologist and typically is from MBMG, part of Montana Technological University. Also, note that David Susong is an Emeritus USGS Hydrologist serving as the NPS representative.

Table 1. The 2019 TOC members and representation.

Member	Representation
Stephan Custer (Chair)	TOC members
John Kilpatrick	USGS
Marvin Miller	Montana University System
David Susong	NPS
Attila Folnagy	DNRC

The past five years saw Russell Levens retire from his appointment to the TOC and the appointment of Attila Folnagy as the DNRC member. In addition to Mr. Folnagy’s appointment, all other members of the TOC were formerly reappointed to five-year terms in 2018 by the appropriate official. The Committee expressed their deep appreciation for Russell Levens service and dedication to seeing that the TOC complete its work. Dr. Stephan Custer was elected to continue serving as the Chair of the TOC.



Figure 1. Left to Right: Montana State Geologist Dr. John Metesh, Montana University System TOC Representative Marvin Miller, DNRC TOC Representative Russell Levens, USGS TOC Representative John Kilpatrick, and TOC Chair Dr. Stephan Custer.



TOC Reporting Requirements

Article IV, section J.1.g. of the Compact states that an initial review shall take place within one year of the inventory report done by the Montana Bureau of Mines and Geology followed by subsequent reviews every five years. The initial report was completed in 2001 covering the period from 1994 through 2000. Subsequent reports were completed by the TOC in 2008 and 2013. This report covers the five years from 2014 through 2018.

Water Permitting in the YCGA

Applicants wishing to appropriate water in the YCGA must apply for a Permit for Beneficial Water Use from the DNRC and have a meter installed to measure total volume of water used. The meter is provided by DNRC, made possible with funding from the NPS. MBMG performs the lead role in monitoring, by inventorying wells and collecting the meter data.

All permit applications must include a statement of whether the proposed water use will be at a temperature equal to or greater than 60 °F. Applicants for uses of water less than 60 °F and 35 gallons per minute (gpm) or less and 10 acre-feet (AF) per year or less are generally subject to standard requirements in [§85-2-306](#), MCA for the exception for small groundwater uses. Applicants for uses of water less than 60 °F and greater than 35 gpm or 10 AF per year are subject to requirements of [§85-2-311](#), MCA for issuance of a provisional permit.

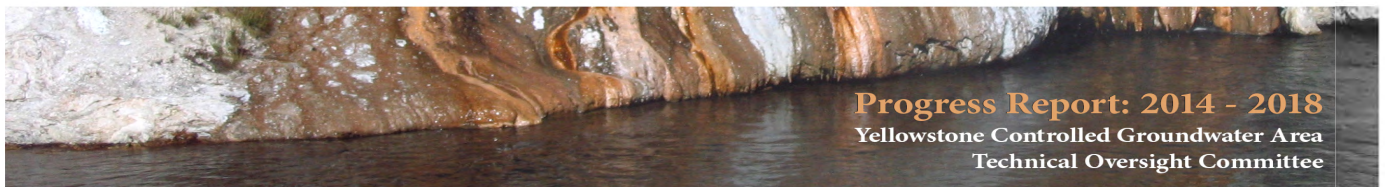
Appropriations of groundwater with a temperature of greater than 60 °F are subject to special provisions of Article IV, section G.2.c of the Compact and Administrative Rules of Montana ([ARM](#)) [36.12.12](#). Appropriations for groundwater between 60 °F and 85 °F must meet the following criteria:

- i. The wellhead water temperature is the result of the normal thermal gradient of the earth, plus the mean annual air temperature at the site, plus 14 °F,
- ii. The concentration of soluble chloride (Cl) is less than 10 parts per million (ppm),
- iii. The well does not contain a production zone completed within the Madison Group.

Appropriations of groundwater with a wellhead water temperature of 85 °F or more is presumed to be hydrothermal discharge water. DNRC will not process or grant an application for a permit unless the application contains credible information that the proposed appropriation does not include contribution by hydrothermal discharge water, is reviewed and approval recommended by the Technical Oversight Committee, and a contested-case hearing is held with the application approved by the hearings officer. If the application is denied, the well must be temporarily or permanently abandoned according to the Montana Board of Water Well Contractors Rules in [ARM 36.21.670](#).

Water Permitting Activities in YCGA

A total of 323 permits for the use of groundwater in the YCGA have been issued through the DNRC Office in Bozeman from the January 31, 1994, effective date of the compact through December 31, 2018 (Tables 2 and 3; Figure 2). There are 29 pending permits being processed by DNRC. There are 3 main areas of higher well permit density (Figure 3): Cooke City area (furthest east), Yellowstone River valley area (north central), and Hebgen Lake/West Yellowstone area (furthest west).



All but 6 of the 323 permits issued through December 2018 are for 10 AF or less. The 6 permits for over 10 AF account for 527 AF or 39 percent of the total 1,341.24 AF authorized. Two permits for one development issued in 1996 account for 279 AF or 21 percent of the total volume authorized.

There is one permit (provisional permit # [43B 30048372](#)), issued in 2010, that is for an appropriation with a water temperature of 60 °F or greater. Using the Compact criteria (see below for geothermal gradient criteria), well data were analyzed by MBMG staff and the TOC and found to meet criteria for use of water between 60 °F and 85 °F. Several permits have been issued in the Corwin Springs area for water above 55 °F. Monitoring of these warmer-water wells is described in the Summary of YCGA Monitoring, 2014 to 2018 Section.

The formula used to trigger special review of a proposed appropriation uses a representative geothermal gradient for the stable craton to compute the expected temperature and a representative mean air temperature for recharge and computes whether the temperature is higher than the expected threshold.

Formula: $\text{Geothermal Gradient} \times \text{Depth} + \text{Mean Air Temp} + 14 \text{ }^\circ\text{F}$
 $0.01646 \text{ }^\circ\text{F/feet (ft)} \times \text{Depth (ft)} + 45.3 \text{ }^\circ\text{F} + 14 \text{ }^\circ\text{F}$

The 14 °F is an adjustment factor to allow for error in the geothermal gradient and/or mean annual temperature so that the trigger temperature for action is reasonable, but protective. This equation is used to evaluate whether the ground-water temperature is substantially above the temperature expected at the bottom of a well without the influence of heat from the YNP geothermal system.

Table 2. Number of permits issued in YCGA by year received.

1995	51	2003	7	2011	12
1996	23	2004	14	2012	3
1997	35	2005	13	2013	5
1998	18	2006	16	2014	15
1999	15	2007	12	2015	4
2000	9	2008	11	2016	13
2001	5	2009	13	2017	5
2002	8	2010	6	2018	10
Total	323				

Table 3. Number of YCGA permits by hydrologic basin.

41F - Madison River	174
41H - Gallatin River	3
43B - Yellowstone River, Above and Including Bridger Creek	146
Total	323

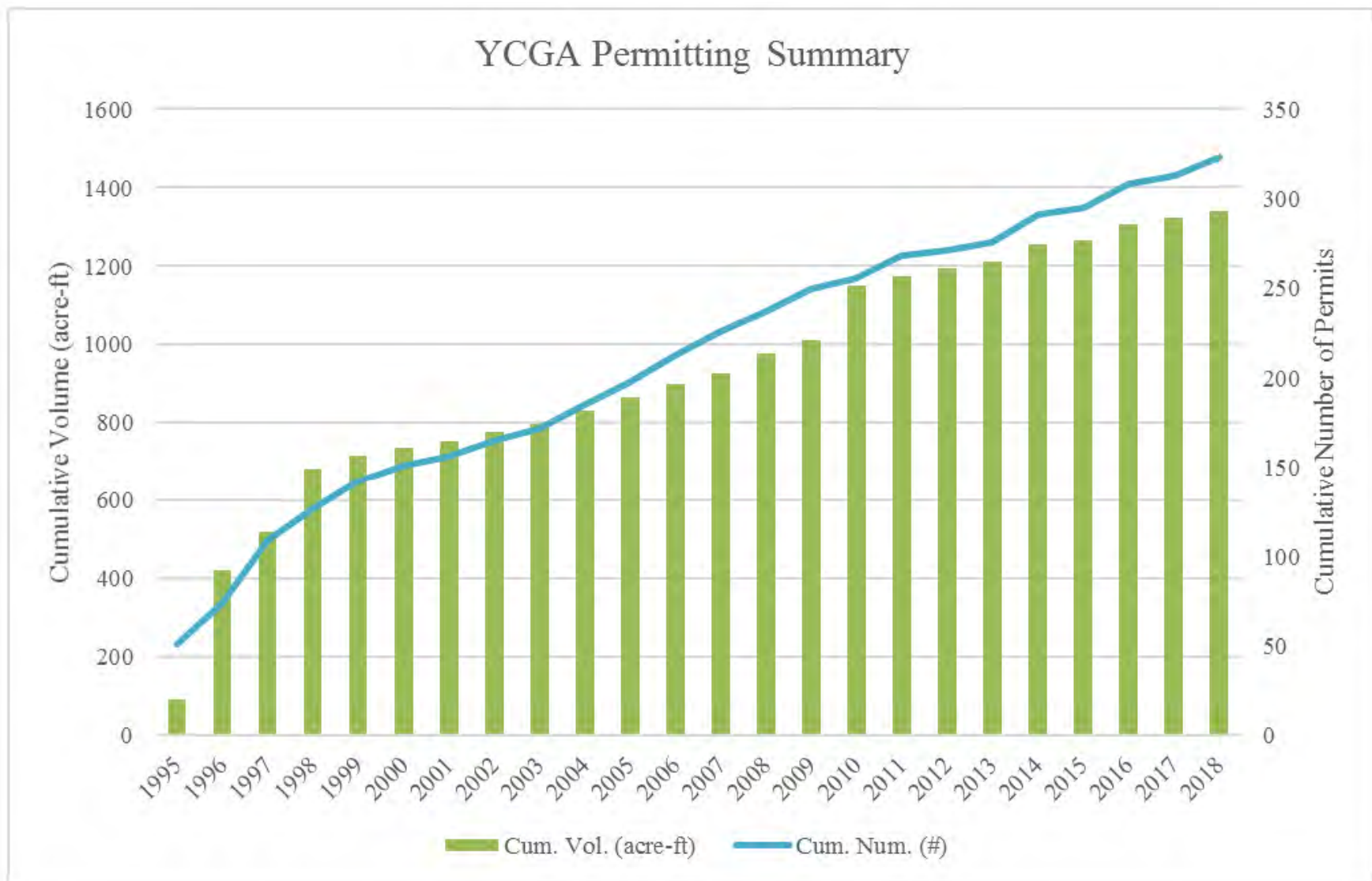


Figure 2. Number of YCGA permits and authorized volumes.

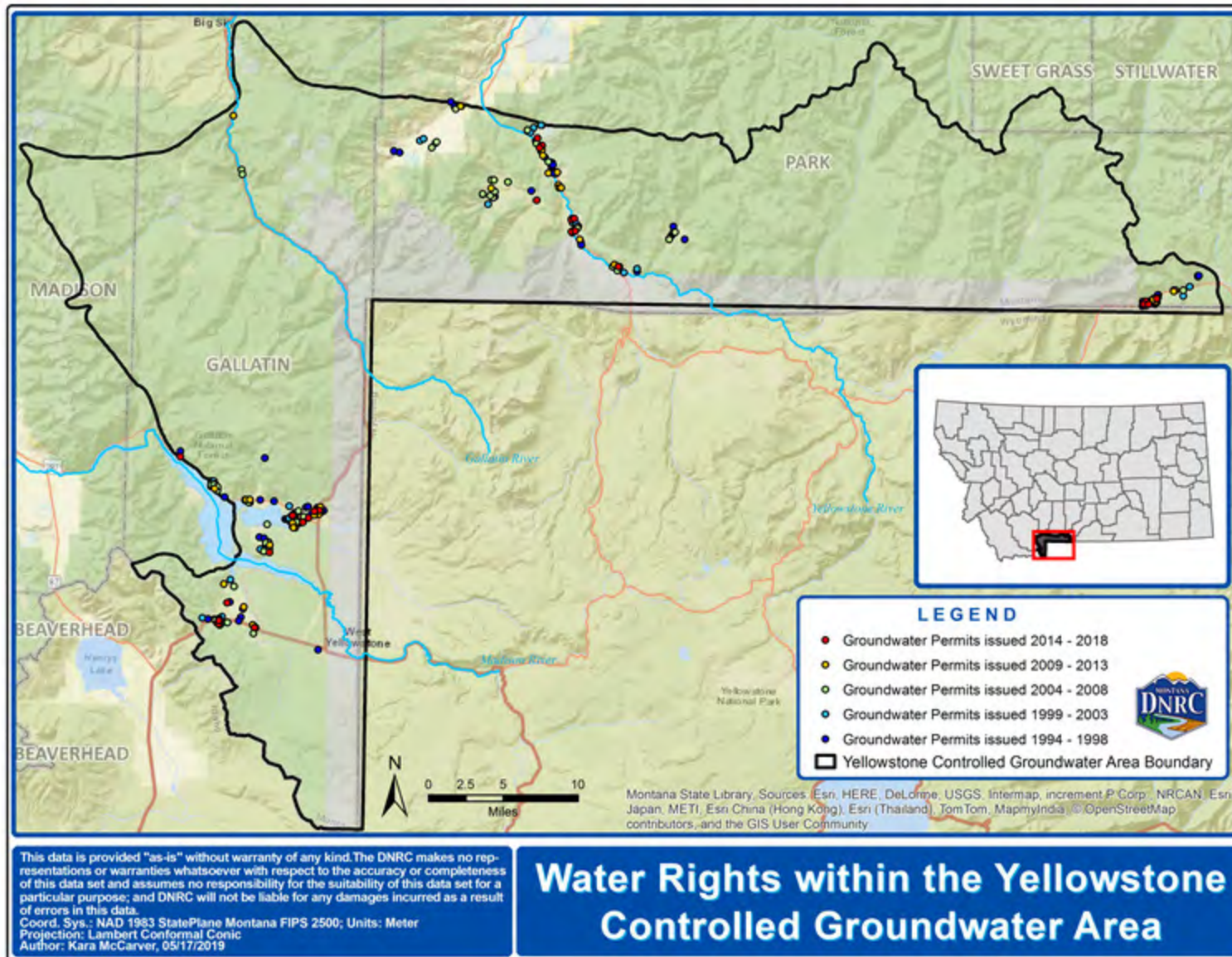
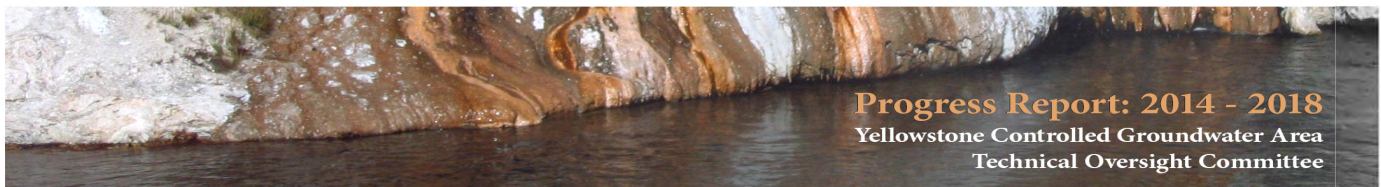


Figure 3. Map showing location of permitted YCGA wells.



Summary of YCGA Monitoring, 2014 to 2018

The MBMG has continued to monitor a mix of cold, warm, and hot water sites within the YCGA. Currently 34 sites are monitored. All sites are visited at least three times per year, typically in May, August, and November. Some monitoring sites are visited more often to maintain or repair monitoring equipment. The data collected include water level in wells as feet (ft) below ground surface (bgs), water temperature in wells and springs as degrees Celsius ($^{\circ}\text{C}$), flow from springs and flowing wells as gpm or cubic feet per second (CFS), water quality field parameters, and inorganic water quality samples. A summary of all the sites that MBMG has monitored since the Long-Term Monitoring Program was initiated, including sites that have been dropped over time for various reasons, is provided in Appendix. Monitoring site data is available to the public via the MBMG Ground Water Information Center (GWIC) website at <http://mbmggwic.mtech.edu>.

U.S. Forest Service (USFS) Special Use Permit, issued to MBMG in 2005 to allow monitoring activities on public lands managed by the USFS, expired in 2014. MBMG submitted an updated permit application in 2014 and a new permit was issued in 2017 allowing monitoring through the year 2036. Notable changes or updates to individual monitoring sites over the 5-year period from January 1, 2014 to December 31, 2018 are summarized below, following the same order as Appendix.

Soda Butte Creek Watershed-Cooke City and Silver Gate

Silver Gate Well ([106030](#)) Mean Temperature 5.1 $^{\circ}\text{C}$ Mean SWL 10.8 ft bgs

This well was originally drilled for water supply but never used. It has no pump and has been used by MBMG as a monitoring well since 1996. The well is 51 feet deep and completed in alluvium. It was monitored throughout the five-year period. A data logger is maintained in the well to collect hourly water-level and water-temperature data. A barologger is also maintained in the well to correct water-level data from data loggers in the area. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Lyman Well ([234520](#)) Mean Temperature 4.6 $^{\circ}\text{C}$ Mean SWL 2.1 ft bgs

This well was added to the monitoring network in August 2015 to replace the Kloster well (see below). The Kloster well was intended to monitor groundwater in bedrock within the Soda Butte Valley. The Lyman well is artesian and flows seasonally, usually from May through mid-July. The well is completed in bedrock but may also be in communication with the valley fill at the bedrock contact. A data logger is installed in the well to collect hourly water-temperature and water-level data. The well was sampled twice for major ions and trace elements and water isotopes (^2H , and ^{18}O) during the five-year period.

Kloster Well ([162539](#)) Mean Temperature 4.5 $^{\circ}\text{C}$ Mean SWL 48.0 ft bgs

This well failed in 2013 due to sedimentation inside the casing and was abandoned by the owner in September. The owner drilled a replacement well but denied MBMG access to monitor the new well. The well was monitored by MBMG from August 2007 to September 2013. A data logger was maintained in the well to obtain hourly water-level and water-temperature data. The well was sampled seven times for major ions and trace elements, and three times for water isotopes (^3H , ^2H , ^{18}O) before it was abandoned in 2013.

Yellowstone River Watershed-Gardiner and Corwin Springs Area

LaDuke Hot Spring ([171215](#)) ***Mean Temperature 63.8 °C*** ***Mean Flow 145 gpm***

LaDuke Hot Spring issues from USFS-managed public land. During the 5-year period, Western Shamballa, Inc., owner of a Statement of Claim for LaDuke Hot Spring, continued diverting their portion of the spring water northward, about 2 miles to Corwin Springs, to serve a restored footbath facility and then, in 2018, a new facility called Yellowstone Hot Springs. Issues with the pumping equipment occurred periodically during the five-year period, and when the pumps are not operating, the spring water overflows from the spring box and discharges to the Yellowstone River, as it did prior to installation of the pipe line. Western Shamballa, Inc., has provided measurements showing that the average rate diverted from LaDuke Hot Spring is 145 gpm while their Statement of Claim # 43B 194912 00 for LaDuke Hot Spring is for the unenhanced flow in the spring box up to 907 AF per annum (equivalent to a year-round constant pumping rate of 562 gpm). As discussed in the previous five-year report and noted at TOC meetings, an agreement between the USFS and Western Shamballa Inc on Western Shamballa's unenhanced use of the spring has continued operating successfully. The USFS owns an instream use Statement of Claim # 43B 59789-00 to the south seep portion of LaDuke Hot Springs.

The spring box is locked for security purposes and the owners (Western Shamballa Inc.) monitor water temperature and water level inside the spring box, and pumping rates from a separate pump vault. The owners provide their monitoring data to MBMG upon request, but the data must be compiled and summarized prior to entry into GWIC.

MBMG also maintains a separate water-temperature logger in the spring box and obtains periodic readings from a staff gauge mounted inside the spring box. The spring was sampled 5 times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

LaDuke Piezometer ([256421](#)) ***Mean Temperature 64 °C*** ***Mean SWL 5.5 ft bgs***

This piezometer is located about 10-feet west of the LaDuke spring box and was installed in 2010 by the owners while rehabilitating the spring box. MBMG obtained permission to use this piezometer in late 2013, and in cooperation with the landowner, properly abandoned two other piezometers near the spring box. MBMG installed a protective surface casing with a locking cap on the piezometer in 2014. In November 2018 a high-temperature logger was added to the piezometer to collect hourly water-temperature data. However, this logger failed and needs to be replaced. MBMG plans to add annual water sampling to this site in 2019.

USFS Hot Spring near LaDuke ([280402](#)) ***Mean Temperature 61.0 °C*** ***Mean Flow N/A***

This hot spring is located about 300 feet south-southeast of LaDuke Hot Spring and is on USFS land. The USFS gave permission for MBMG to begin monitoring this spring in the fall of 2014. Due to site conditions, measurement of discharge from this spring is not practical. Monitoring is focused on water temperature at the head of the spring and annual water chemistry sampling. In October 2014 a water-temperature logger was installed at the head of the spring to collect hourly water-temperature data. Hourly temperature data were collected from October 2014 through August 2018. When the site was visited in November 2018 the logger equipment was missing. MBMG plans to install a new temperature logger in 2019. This site was sampled 3 times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period.

The inorganic water chemistry at this site is generally the same as LaDuke Hot Spring. Both sites produce a calcium-sulfate type water at a temperature of about 64 °C, with a total dissolved



solids (TDS) concentration of about 2,100 milligrams per liter (mg/L). The monitoring data from this site is generally duplicative of the monitoring at LaDuke Hot Spring but provides an independent check on water temperature and water quality of the geothermal discharge in the LaDuke area. Since the site is within 300 feet of LaDuke Hot Spring a separate site visit is not required.

Bear Creek Warm Spring ([197921](#)) Mean Temperature 32.1 °C Mean Flow 32 gpm

This spring is located along Bear Creek, near the confluence with the Yellowstone River. A flume was installed in June 2012 to measure discharge. A data logger is installed in the spring pool to collect hourly water-level (stage) and water-temperature data. The stage measurements are correlated with manual readings of the flume stage during site visits to obtain hourly discharge measurements. To measure spring discharge, accurate readings of the pool stage are needed. MBMG has experimented with both vented and non-vented data loggers to try and obtain more accurate stage data. A more accurate vented logger was installed in 2017, but this logger failed in 2018. MBMG has purchased a replacement data logger and plans to install it in 2019. The new vented logger is designed so that a desiccant chamber does not need to be maintained on the vent line. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. The spring was also sampled for radon in 2014.

Powell Spring ([184260](#)) Mean Temperature 15.7 °C Mean Flow 7 gpm

This spring has been developed to provide water for several residents. A water-temperature logger is maintained at the head of the spring to collect hourly temperature data. An in-line flow meter with a totalizer is installed on the discharge line below the spring. Discharge is measured during site visits using the flow meter and a stop watch. The spring was sampled twice for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Sirr Spring ([171229](#)) Mean Temperature 13.1 °C Mean Flow 25 gpm

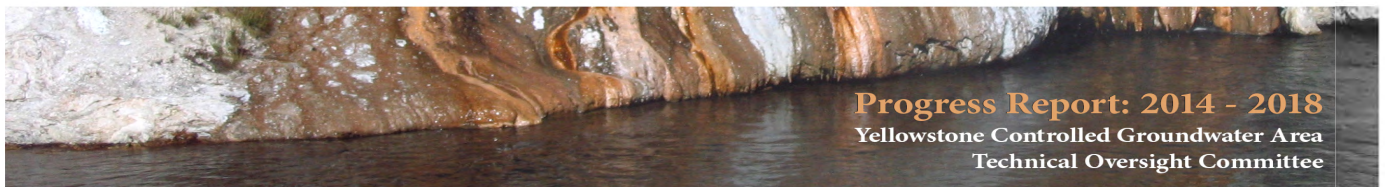
This spring is undeveloped. The spring discharge area consists of a small pool that discharges into a nearby irrigation ditch. A small flume is maintained on the outlet of the spring pool. The stage of the flume is manually read during site visits, and a datalogger is installed in the flume to collect hourly water-level (flume stage) and water-temperature data. Problems have been encountered with water from an irrigation ditch that floods out the flume in the spring. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Demaree Spring ([181620](#)) Mean Temperature 10.2 °C Mean Flow 2.0 gpm

This spring, also known as (aka) Cole Spring, has been developed to provide water for a single residence. A temperature logger is installed at the head of the spring to obtain hourly water-temperature data. An in-line flow meter with a totalizer is installed on the discharge line below the spring. Discharge is measured during site visits using the flow meter and a stop watch. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was sampled for radon in 2014.

Demaree Well ([138764](#)) Mean Temperature 20.1 °C Mean SWL 106.1 ft bgs

This well, aka Cole Irrigation Well, is used by the owner for landscape irrigation at the residence that is served by the Demaree Spring. It is 143 feet deep and is thought to be completed in Archean Bedrock adjacent to the Gardiner Reverse fault. A data logger is maintained in the well



to obtain hourly water-level and water-temperature data. In 2017 the data logger got stuck in the well when being retrieved. A drop tube was installed in the well to aid in retrieving the data logger and avoid getting it stuck in the well. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five years, and was sampled for radon in 2014.

Shooting Star Ranch Well ([252314](#)) Mean Temperature 21 °C Mean SWL -111.7 ft bgs

This well is 750 feet deep and is a flowing artesian well that is shut in. The well is completed in a thick sequence of Eocene Absaroka Group volcanic rocks. The warm water produced by the well is attributed to the natural geothermal gradient in the area. The well is used for fire protection and domestic purposes. Shut-in pressure is monitored each time the site is visited using a digital pressure gauge. Water temperature is measured each time the well is purged for sampling. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Strauss Well ([105959](#)) Mean Temperature 16.9 °C Mean SWL 66.9 ft bgs

This well is located about 140 feet northwest of the Yellowstone Basin Inn well (145529) and is also 100 feet deep. It is completed in alluvium. The well provides water to a residence at the Inn. A data logger is maintained in the well to obtain hourly water-level and water-temperature data. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. The well was also sampled for radon in 2014.

Galloway Well ([146967](#)) Mean Temperature 13.2 °C Mean SWL 120.0 ft bgs

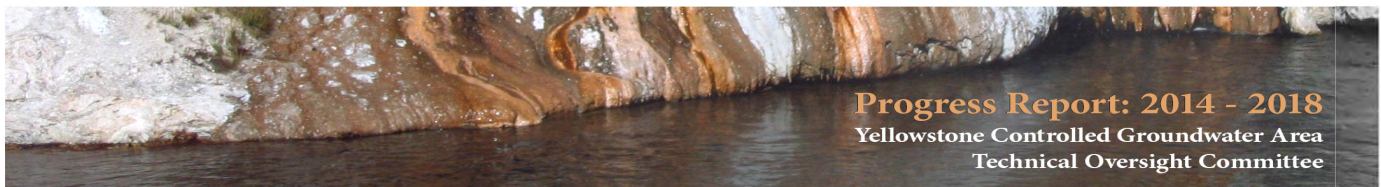
This well is used for domestic purposes and is 200 feet deep. The well is completed in an alluvial fan deposit. A data logger is maintained in the well to obtain hourly water-level and water-temperature data. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Gardiner Airport Well ([105980](#)) Mean Temperature 10.0 °C Mean SWL 107.0 ft bgs

This well is 263 feet deep and is located along the east side of the Yellowstone River. Power to the well pump was cut off in 2017 due to an oil spill at the airport. Since this time MBMG has not been able to collect water quality samples but has maintained a data logger in the well to collect hourly water-level and water-temperature data. The data logger failed in November 2018. MBMG plans to try and work with the well owner to reestablish power to the well pump and install a new data logger in 2019. This site was sampled 3 times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Miller Well ([152216](#)) Mean Temperature 23.2 °C Mean SWL 8.1 ft bgs

This well was drilled for domestic use, but it was never used due to poor water quality. The USGS used the well in the late 1980s for groundwater research. The well is 184 feet deep and is thought to be completed in an area where fresh groundwater is mixing with geothermal groundwater in glacio-fluvial valley fill deposits. A data logger is maintained in the well to obtain hourly water-level and water-temperature data. Water temperature is measured when the well is purged for sampling. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.



NPS CSCS-1 Well ([287868](#)) Mean Temperature 9.1 °C Mean SWL 46.9 ft bgs

This well is located in YNP and is owned by the NPS. It is located about 0.6 miles north-northeast of the Stevens Creek Buffalo Corrals and was drilled many years ago to serve a planned development that was never constructed. The well is 74 feet deep and completed in glacial outwash. The NPS gave MBMG permission to monitor the well in the fall of 2016.

A data logger was installed in the well in August 2016 to obtain hourly water-level and water-temperature data. The site is also equipped with a barologger for correcting water-level data from data loggers in the area. This well was sampled four times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period.

NPS Stevens Creek Well ([287867](#)) Mean Temperature N/A Mean SWL 47.4 ft bgs

This well is located in YNP and is owned by the NPS. It is located about ¼ mile south of the Stevens Creek Buffalo corrals and was drilled many years ago to provide water for a home used by the corral manager. This is an older well with no well log, and information on the well is limited. It is not used as a water supply, likely due to low yield and poor water quality. The NPS gave MBMG permission to monitor the well in the fall of 2016.

This well was inventoried by MBMG in the fall of 2016 and added to the monitoring network to monitor shallow groundwater. Based on a field inspection and collection of water quality samples, it is thought to be completed in Cretaceous bedrock that consists of marine shale and sandstone. However, it may also be completed in the glacial till, which is composed primarily of sediments derived from Cretaceous bedrock. The well was sampled in 2016 for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) using a portable pump. Well yield was less than 1 gpm, making it difficult to purge and sample. The well is only being monitored for water levels.

Yellowstone Basin Inn Well ([145529](#)) Mean Temperature 15.1 °C Mean SWL 68.3 ft bgs

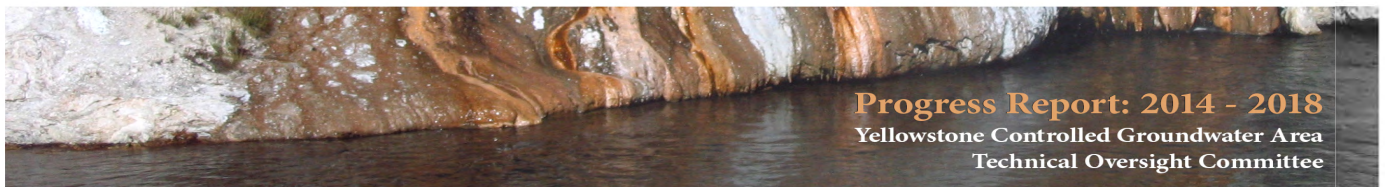
This well is 100 feet deep and serves as a public water supply for the Inn. The well was dropped from the monitoring network in August 2014 because it was considered redundant with Strauss well ([105959](#)), which is about 200 feet away (see below), and to avoid contamination of the public water supply. During the period of monitoring, this well was sampled nine times for major ions and trace elements, four times for stable water isotopes (^2H , ^{18}O), and once for tritium (^3H).

Gallatin River Watershed-Big Sky Area to Park Boundary

Anceny Spring ([258715](#)) Mean Temperature 17.4 °C Mean Flow 5 CFS

This is a large spring that discharges along the trace of the Spanish Peaks reverse fault. The fault places Archean crystalline basement rocks over Paleozoic limestone. The spring discharge forms a small pond, and discharge from the pond forms a spring creek. A temperature logger is maintained at the east edge of the pond, where the main spring discharge surfaces, to obtain hourly water-temperature data. In 2017 the temperature logger was moved from its previous location, about 20 to the west, to the east end of the pond to obtain more accurate data.

Spring discharge is measured below the spring in the spring creek, using a wading flow meter. The discharge site also has a staff gauge and a water-level logger to obtain hourly stage data. In 2018 a new vented logger was installed by the staff gage in an effort to obtain better stage data. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014. The spring property is listed for sale.



Snowflake Spring ([171216](#)) Mean Temperature 12.4 °C Mean Flow 11.3 CFS

Snowflake Spring is a large spring with multiple discharge points. The water surfaces on a slope along the west side of the Gallatin River valley. Similar to Anceny Spring, Snowflake Spring discharges along a large reverse fault. The fault places Madison Group limestone over Cretaceous formations. A temperature logger is maintained at the highest and most prominent discharge point to obtain hourly water-temperature data. Discharge from the spring area is measured by gauging the flow of a spring creek that forms at the base of the slope and drains to the Gallatin River. Water quality samples are collected at the same location as the temperature logger. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. The spring was also sampled for radon in 2014.

Altman Well ([215333](#)) Mean Temperature 5.5 °C Mean SWL 372.7 ft bgs

This is a domestic well that is 470 feet deep and completed in Paleozoic limestone. The well is located within 100 feet of the Gallatin River, but is clearly disconnected from the shallow aquifer along the river. A data logger was installed in the well in June 2014 to obtain hourly water-level and water-temperature data. In 2015-2016 the well owner constructed a house and began using the well. In 2017 MBMG worked with the owner to try and install a new type of continuous water-level monitor (Well Intel System) that the well owner could monitor. However, due to the extreme depth to the water in the well, the system was not successful. Instead, a drop tube was installed, and the existing data logger is being maintained. A barologger is also maintained in the well. The well was sampled three times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period.

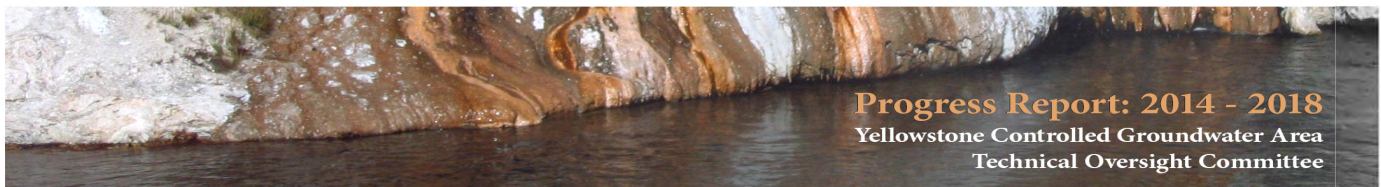
USFS Red Cliff Well ([259697](#)) Mean Temperature 4.3 °C Mean SWL 252.9 ft bgs

This well was added to the monitoring network in 2014 to monitor deep groundwater in the Madison Group limestone. The well is 693 feet deep and serves as the public water supply for the USFS Red Cliff Campground. Water flowing into the well through the perforated intervals (513-553 feet and 653-693 feet bgs) is cold (4.3°C) suggesting short flow path recharge. A data logger is maintained in the well to obtain hourly water-level and water-temperature data. MBMG has routinely had difficulty obtaining hand measurements and retrieving the data logger due to some type of obstacle in the well casing. Plans are to try and work with the USFS to install a drop tube in the well to make it easier to monitor. This will need to be completed when the campground is closed. The well was sampled four times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period.

Madison River Watershed-West Yellowstone-Hebgen Basin

Corey Spring ([182014](#)) Mean Temperature 7.8 °C Mean Flow 10.0 CFS

Corey Spring is a large, cold-water spring on private property that has been modified. The spring discharges from beneath road fill (Highway 287) and flows into a manmade pond, which in turn discharges to Hebgen Lake over a concrete wind wall. The spring is sourced from Madison Group limestone just north of the highway. A temperature logger is installed at the head of the spring to obtain hourly water-temperature data, and the discharge from the spring-pond is gauged each time the site is visited. Water samples are collected at the head of the spring. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.



Stinky Spring ([183268](#)) Mean Temperature 14.2 °C Mean Flow 34.2 gpm

Stinky Spring is a cool sulfur spring that discharges along the south edge of the Hebgen Basin, where an extensional fault may exist. The bedrock geology is covered by Yellowstone tuff and glacial deposits, but it is thought that the spring water originates from the Cretaceous Kootenai Formation under the tuff. The spring forms a small pond adjacent to, and on the upslope side of, a pack trail. Water from the pond is diverted under the trail through a culvert. During the five-year period, an old metal culvert became so corroded that it collapsed. MBMG replaced the metal culvert with a new plastic culvert in 2016.

A small flume is installed at the edge of the pond where it discharges into the culvert. Hand measurements are taken at the flume during site visits to measure discharge. The flume is also equipped with a non-vented water-level logger that collects hourly stage and water temperature data. The stage data is used to correlate pond level with the flume. In 2014 a separate water-temperature logger was installed in the center of the pond, where the spring water surfaces, to obtain better hourly water-temperature data. In 2017 a vented logger was added to the site to try and improve the accuracy of pond-stage vs. flume reading data. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. The spring was also sampled for radon in 2014 times.

Black Sand Spring ([183242](#)) Mean Temperature 9.3 °C Mean Flow 19.3 CFS

This is a large cold-water spring on USFS land that is undeveloped. The spring surfaces along the base of a small hill and forms a spring creek. A water-temperature logger is installed in the spring discharge area to collect hourly water-temperature data. The discharge is measured during site visits by gauging the spring creek just below the spring discharge area. Water samples are collected at the head of the spring. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

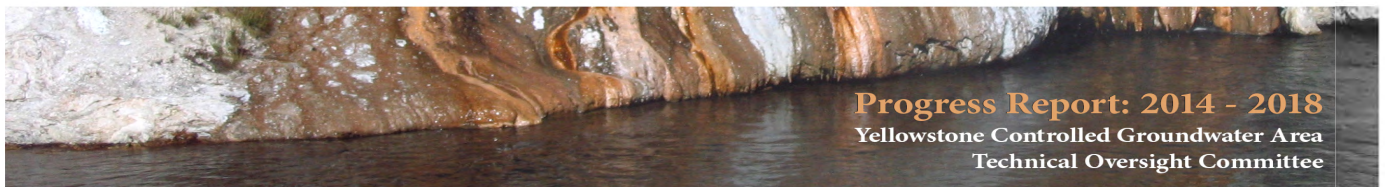
Ryberg Spring #4 ([8930](#)) and Ryberg Spring Creek ([277397](#))

Mean Temperature 10.8 °C Mean Flow 1.3 CFS

This spring is located along the west side of the Hebgen basin and is thought to be fault controlled. The spring (8930) surfaces through glacial till and forms a small sand boil. The spring discharge then flows eastward in a small channel (277397) where the discharge is measured. A temperature logger is installed in the sand boil to record hourly water-temperature data. The discharge from the spring is measured during site visits by gauging the spring channel. Water quality samples are collected at the sand boil. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Ryberg Well ([230654](#)) Mean Temperature 14.1 °C Mean SWL -15.6 ft bgs

The well is a flowing artesian well that is shut in. It is used as a domestic water supply for a summer home. The well is 119 feet deep and is reported to be completed in rhyolite under glacial outwash deposits. The shut-in pressure of the well is monitored during site visits using a digital pressure gage, and the water temperature is measured when the well is purged for sampling. The spring was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014. The radon sample results showed very high levels of radon ($\text{Rn}_{222}=35,069$ Picocuries per liter (pCi/L)).



Bakers Hole Campground S. Well ([106775](#)) Mean Temperature 22.1 °C Mean Flow 17 gpm

This well is a flowing artesian well that produces warm water. It was drilled by the USFS to provide water for the Bakers Hole Campground. The well is located at the south end of the campground, about 80 feet east of the Madison River. It is not used but, serves as a backup well for the campground. This well is old (circa 1948) and no driller's log has been found to verify total depth. However, it is reported to be less than 100 feet deep.

The well flows year-round, with the discharge routed to the river through a buried pipe. An in-line flow meter with a totalizer is installed on the discharge line. The flow meter was originally set up with a pulse logger to obtain hourly flow-meter data. However, the pulse logger routinely failed, and while the flow meter is still working, it has water in the dial making the totalizer hard to read. Discharge is measured during site visits using the flow meter and a stop watch. The well is also shut in during site visits to obtain a head measurement. MBMG has purchased replacement equipment and plans to install the equipment during the 2019 field season. A temperature logger is also maintained in the discharge line to obtain hourly water-temperature data. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Bakers Hole Campground N. Well ([8943](#)) Mean Temperature 18.0 °C Mean Flow 30 gpm

This well is also a flowing artesian well that produces warm water. It was drilled by the USFS to provide water for the Bakers Hole Campground and is serves as a public water supply for the campground. The well is located at the north end of the campground, about 110 feet east of the Madison River. It was drilled to 61.5 feet bgs but is only cased to 58 feet bgs.

Like the Bakers Hole Campground South well, this well flows year-round, and the discharge is routed to the river through a buried pipe. An in-line flow meter with a totalizer is installed on the discharge line. The flow meter was originally set up with a pulse logger to obtain hourly flow-meter data. However, the pulse logger routinely failed, and the flow meter failed in 2017. Discharge is measured during site visits, at the end of the discharge pipe, using a bucket and stop watch. The well can't be shut-in to measure head because it is in active use in the summer and the well head is locked inside a pump house. MBMG has also purchased replacement equipment for this well and plans to install the equipment during the 2019 field season. A temperature logger is also maintained in the discharge line to obtain hourly water-temperature data. The well was sampled three times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period.

Three Bears Lodge Well ([106842](#)) Mean Temperature 7.1 °C Mean SWL 38.2 ft bgs

The well is 140 feet deep and is used for irrigation at the lodge. The well is located in the town of West Yellowstone. A datalogger is installed in the well to collect hourly water-level and water-temperature data. A barologger is also maintained at this site to correct water-level loggers in the area. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

West Yellowstone KAO Backup Well ([165852](#)) Mean Temperature 5 °C Mean SWL 20 ft bgs

This well is 260 feet deep and serves as a backup well for the KOA campground. It is part of the KOA's public water supply system. A water-level logger is installed in the well to obtain hourly water-level and water-temperature data. The owners cooperate with MBMG and bring the well on line for flushing and sampling when requested. The well was sampled five times for major



ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period. It was also sampled for radon in 2014.

Hebgen Basin Fire Station #3 ([247335](#)) Mean Temperature 5.4 °C Mean SWL 58.6 ft bgs

This well is located on the west side of Hebgen Basin, south of Hebgen Lake. The well is used as a domestic water supply for the fire station. MBMG has been collecting periodic measurements from this well since 2010. In 2014 the well was inventoried and added to the monitoring network. A data logger was installed in the well in May 2018 to obtain hourly water-level and water-temperature data. The well was sampled five times for major ions, trace elements, and stable water isotopes (^2H , ^{18}O) during the five-year period.

Keland Well ([106778](#)) Mean Temperature 12.3 °C Mean flow 1.5 gpm

This well is located about 500 feet north of the Bakers Hole North Campground (see above). It is also a shallow flowing well that produces warm water. It was dropped from the network in 2014 because it was considered redundant with the flowing wells in the campground.

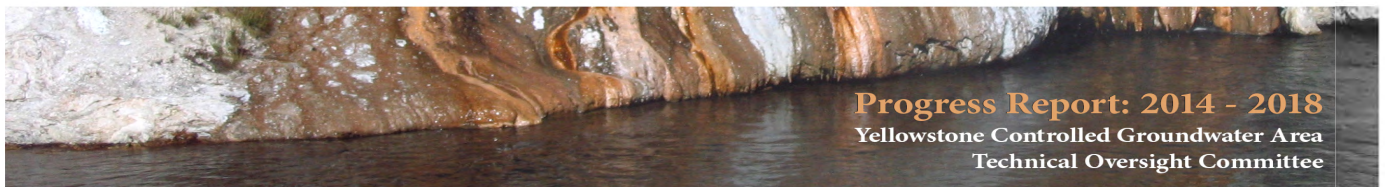
Overview of Monitoring Trends

Soda Butte Creek Watershed-Cooke City and Silver Gate

Surface water and groundwater flow into YNP from the upper Soda Butte Creek Basin, entering YNP at the Northeast Entrance, near Silver Gate, Montana. The bedrock geology consists of gently dipping Paleozoic sedimentary formations overlying Archean metamorphic basement rocks, intruded by Tertiary igneous bodies and covered by a thick sequence of andesitic volcanoclastic deposits. Glacial till covers the bedrock along the valley sidewalls and alluvium and glacial outwash deposits cover the valley floor. A hydrogeologic assessment of the area (Metesh et al., 1999) found no evidence of geothermal resources in the area, and all surface water and groundwater sites that have been visited by MBMG produce cold water. The closest known geothermal feature is Soda Butte, located 12 miles southwest of the Northeast Entrance. There are currently three wells monitored in this basin. Three wells are monitored in the Upper Soda Butte watershed. Of these, the Silver Gate well ([106030](#)) has the longest record, and while it does not show any significant changes, the data do suggest a slight increase in groundwater level and temperature over the period of monitoring.

Yellowstone River Watershed-Gardiner and Corwin Springs Area

Surface water and groundwater flow into the Gardiner Basin from YNP at the North Entrance. Additional groundwater and surface water flow into the Gardiner Basin from the mountains surrounding the basin inside and outside YNP. The geology of the Gardiner Basin is complex, with bedrock that includes Archean metamorphic basement, Paleozoic sedimentary rocks, Mesozoic sedimentary rocks, Tertiary volcanic rocks, Tertiary intrusive rocks, Quaternary volcanic rocks, and Quaternary travertine deposits. Surficial geology units include Quaternary glacial moraine, glacial outwash, landslide deposits and alluvium. The long-term monitoring sites include sites in most of these geologic units. Currently 15 sites are monitored in the Gardiner Basin, which include a mix of cold and geothermal springs and wells, which reflect the complex geology of the area. Overall, none of the geothermal monitoring sites show any significant trend towards decreasing or increasing discharge other than annual variations that are likely attributed to snowpack and precipitation trends.



Gallatin River Watershed-Big Sky Area to Park Boundary

Monitoring in the Upper Gallatin River watershed is focused along the Upper Gallatin River after it flows out of YNP. The monitoring sites are focused on Paleozoic carbonate bedrock aquifers (Cambrian and Mississippian). Two wells and three large discharge springs are currently being monitored. All the monitored sites produce cold water and no geothermal resources have been identified in the monitored watershed area. The two monitored wells are completed in the Cambrian Pilgrim formation ([215333](#)) and the Mississippian Madison Group ([259697](#)). Both wells show annual water-level fluctuations of about 5 to 30 feet, and groundwater levels in both wells have increased since the spring of 2017. Two of the monitored springs, Slow Vehicle ([255289](#)) and Anceny ([258715](#)), discharge along a major reverse fault, where Archean basement rock has been faulted over the Madison Limestone. Snowflake Spring ([171216](#)) discharges along a thrust fault where the Madison Limestone is thrust over Cretaceous sedimentary bedrock. All the springs have large seasonal fluctuations in discharge that are most likely associated with annual changes in snowpack and precipitation as rain. For example, the measured discharge of Anceny Spring ranges from 1,719 to 2,767 gpm). Both Anceny and Snowflake Springs show a general increase in discharge since 2016-2017.

Madison River Watershed-West Yellowstone-Hebgen Basin

Surface water and groundwater flows into the Hebgen Basin from YNP at the West Entrance, and also from the Mountains that bound the basin on the south and east. There are warm-water springs and wells in the area which may be due to some geothermal activity in the area. A confined aquifer underlies the basin between West Yellowstone and Hebgen Lake. MBMG currently monitors 11 sites in the Hebgen Basin that include three flowing-artesian wells, three cold water springs, and a warm water spring that produces hydrogen sulfide gas. Most of the monitored wells and springs appear to show seasonal and annual fluctuations that generally follow snowpack and precipitation patterns. However, one flowing artesian well ([230654](#)) does not follow annual precipitation patterns and may reflect longer-term changes in groundwater recharge. Two large-discharge cold water springs Corey Spring ([182014](#)), and Black Sand Spring ([183242](#)) show a pattern similar to Snowflake Spring ([171216](#)), with decreasing flow from 2012 until the spring of 2017, and increasing flow since the spring of 2017.

Miscellaneous MBMG Activities

Lucky Minerals Drilling Proposal-Emigrant Gulch

In June 2015, Lucky Minerals, Inc. submitted a Mineral Exploration Plan to Montana Department of Environmental Quality (DEQ) to complete exploration drilling in the Emigrant Creek watershed for base and precious metals deposits. The proposed exploration area is in Park County and is located about 7 mi SE of Emigrant, Montana and 19 miles due north of the YNP boundary. The Mineral Exploration Plan originally called for exploratory drilling on public land managed by USFS and private land. In December 2015, Lucky Minerals withdrew its application for drilling on public land managed by USFS.

The TOC discussed the proposed drilling project and concluded that the project was outside the YCGA, and it would be premature to evaluate the potential impacts of the project on YNP. However, the proposed drilling project caused significant public concern. To help address the public concerns the USFS provided funding to MBMG to complete an investigation to characterize the water quality in the Emigrant Creek and East Fork of Emigrant Creek drainages.



Field work was completed in the Fall of 2015 and a report was published (LaFave, 2016). This report describes the baseline water-quality and stable isotope data collected during the investigation. The report evaluated potential impacts that the drilling may have on nearby geothermal features (e.g. Chico Hot Springs). Based on the geologic, hydrologic, and geochemical data, LaFave (2016) concluded that it is unlikely that water from the Emigrant Creek watershed is connected to the geothermal system that feeds Chico Hot Springs. It is also considered unlikely that the project could impact groundwater resources within the YCGA or YNP.

Crevice Mountain Mining Exploration Proposal

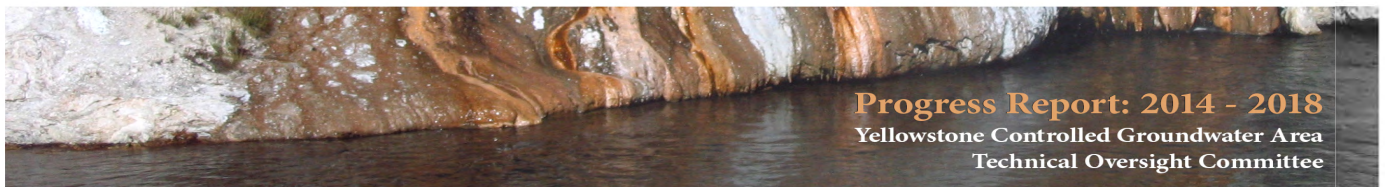
Crevice Mining Group LLC (CMG) applied for an Exploration License from the DEQ in October 2015 that included exploratory drilling, extensive underground development, and surface disturbances. The proposed project site is on Crevice Mountain, about 3 miles southeast of Jardine, Montana in the NE $\frac{1}{4}$ of Section 22, T. 9 S., R. 9 E. The project is located within the YCGA and is about 1 mile north of the YNP boundary. DEQ reviewed the application and requested extensive additional information (Wayne Jepson, DEQ, per. communication). DEQ did not receive responses from Crevice and the permit is on hold.

In 2018, CMG filed a Small Miners Exclusion Statement (SMES), which exempts the project from DEQ permitting requirements, provided the project disturbs less than 5 acres, doesn't involve any discharges of water, and does not cause air pollution. While DEQ has no ability to deny the SMES, it could take enforcement action if there is a discharge or if they exceed their acreage limit (Wayne Jepson, DEQ, per. communication). The status of the Crevice project or any work done by CMG under their SMES is unknown. DNRC has a pending application # 43B 30072675 for the purpose of dust suppression from a proposed well that has not been drilled. Due to the proximity of the project to YNP, NPS, with assistance from MBMG, collected baseline water quality samples during the 2019 field season in the area and are expected to publish a report in 2020.

Reported 70 °F Groundwater near West Yellowstone

In August 2015, Potts Drilling (Bozeman, Montana) notified DNRC and MBMG that they measured a groundwater temperature of 70 °F in a well being drilled in the Hebgen Basin. The driller was at a depth of 320 feet bgs and had not completed the well. The well is located about five miles west of West Yellowstone, along the southwest margin of the Hebgen Basin. Glacial till and Quaternary volcanic tuffs are exposed in the well area and cover Paleozoic and Mesozoic bedrock. The Kootenai Formation is exposed just west of the well site. Glacial till at the drill site covers tuff, which in turn covers folded and faulted Paleozoic and Mesozoic sedimentary bedrock.

MBMG staff visited the drilling site on August 11, 2015, and the driller had extended the well to 340 feet bgs. Examination of the cuttings suggested the well may have reached the Kootenai Formation, and the driller reported that the water temperature previously reported may have been elevated due to warm water being pumped into the borehole while drilling, possibly heated by warm air temperatures and heat from the air compressor. MBMG revisited the well on August 12, 2015 after the driller had completed the well at a depth of 358 feet bgs, but there was no way to accurately measure the water temperature. However, the driller did report that after completing the well, the water did not seem warm. MBMG revisited the well on October 21, 2015 and collected a water sample using a portable pump.



After purging, the water temperature was measured at 6.9 °C (44.4 °F) by MBMG. The water temperature measured after the well was completed confirmed the well did not intercept geothermal water, and the earlier reported temperature was attributed to the warm water in the drill tender tank (68 °F) and warm air blown into the well by the air compressor. The well water had a rotten-egg odor while being purged and the laboratory results for the sample show the groundwater is a sodium-bicarbonate type water with a high pH (8.9), a low dissolved oxygen concentration (0.03 mg/L), and is very reducing, with a field measured oxidation reduction potential (ORP) of -301 mV. It is probable that the well is completed in sandstones of the Kootenai Formation in an area where the groundwater is isolated from the atmosphere and the oxidation of sulfides (pyrite) in the formation is consuming any available oxygen.

Stephens Creek

The National Park Service (NPS) expressed interest in obtaining a new water source to aid with dust control at the Stephens Creek Buffalo Corrals, located 3 miles west-northwest of Gardiner, Montana. The existing water supply for the facility is a spring ([181616](#)), which does not produce enough water for the planned uses. The NPS hoped to drill a new water supply well within the existing disturbed area at the corrals. At the request of the NPS, MBMG investigated to determine the feasibility of successfully completing a well at the corrals. MBMG reviewed published geologic maps of the area, conducted a field investigation to verify the mapped geology, and sampled known water sources in the area.

The geologic review indicated that the local geology consisted of a layer of glacial moraine and possibly some glacial outwash deposits, which cover folded and faulted Cretaceous shale and sandstone. The spring serving the corrals was inspected and sampled. It appears to surface at the contact between volcanic deposits and underlying Cretaceous shale and sandstone. Two wells owned by the NPS were also inspected, inventoried and sampled ([287867](#) and [287868](#)). Well [287867](#) is located at the Corral residence and was originally drilled to supply water for the residence. Historical information on this well was limited, but sampling showed that the well yield was very low and water quality was poor. The well is thought to be completed in Cretaceous shale and sandstone. Well [287868](#) is located about 0.5 miles north of the Corrals along the dirt road running along the southwest side of the Yellowstone River. This well was originally drilled to provide water for a planned facility at the well site that was never constructed. This well is completed in glacial outwash deposits and was found to have good water quality and a suitable yield. Both wells were added to the Long-Term Monitoring Network and instrumented with data loggers.

MBMG recommended the best location would be in the outwash deposits to the north and west, but this area is outside of the existing corrals and would require extensive site assessment work prior to drilling. For drilling at the corrals, MBMG recommended drilling into the till to look for water bearing layers, but not continuing into the underlying shale bedrock if water was not found. A consultant was hired to drill the well, but no water producing zones were found in the till or shallow bedrock under the till.

Xanterra Public Water Supply Well

In June 2017, Xanterra Parks and Resorts (Xanterra) constructed employee housing and drilled a 281 foot deep public water supply well ([292700](#)) in the Gardiner Basin, about 4.5 miles northwest of Gardiner, Montana. The well location, approximately one mile southeast of LaDuke Hot Springs, is of special interest due to being in the Corwin Springs Known Geothermal



Resource Area (Taylor and Hinds, 1976). The driller’s log reports unusual conditions at the bottom of the borehole indicating the well is completed near the top of a geothermal groundwater reservoir, including the following notes on lithology from 273-281 feet bgs: “sand/gravel/gray shale/H2O stinks-heaving/279 feet clay/shale/oil-gray/H2O shut off”.

Other geothermal wells are located near the Xanterra well. The Miller geothermal well ([152216](#)) is located approximately 0.4 miles to the northwest. A well drilled in 2012 ([266377](#), also known as 98° well in the previous 5-year report) intercepted geothermal groundwater approximately 0.3 miles to the northwest on the same terrace. The driller reported hitting groundwater with a temperature of 37 °C (98 °F) at a depth of 282 feet bgs and reported the following unusual drilling conditions: “stopped under ream drilling @ 282 feet due to hot water and heaving sands came back up casing to 201 feet.” The TOC discussed this well in 2013, no actions were taken, and has not been properly abandoned. MBMG evaluated rehabilitating the well as a geothermal monitoring well but determined the risks of trying to remove the heaving sands to recover the well were too great. Overall, the drillers logs for both the Xanterra PWS well and the 98° well indicate that geothermal resources are present under the area at a depth of 270 and 290 feet bgs.

Summary of Yellowstone National Park Monitoring, 2014 to 2018

Introduction

This brief discussion presents a summary of YNP’s hydrothermal monitoring efforts from 2014 to 2018. Topics discussed include the use of Cl flux, fixed-wing and helicopter airborne thermal infrared (TIR) condition assessments, temperature monitoring of hydrothermal features and additional efforts for protecting hydrothermal systems.

Terms used to describe hydrothermal systems are defined by Jaworowski (2010):

A hydrothermal area is a contiguous geologic unit generally including one or more hydrothermal features, bounded by the maximum aerial extent of hydrothermally altered ground, thermal deposits, geothermal gas emissions, or heated ground. A thermal group is a subdivision of a thermal area that contains one or more hydrothermal features and can be isolated from other groups based on physiographic, hydrologic, or geochemical parameters. A thermal feature is a vent, or small cluster of related vents, emitting gases and/or hot water. A thermal drainage is a physiographic/hydrologic drainage to which heated waters are contributed by adjacent thermal areas. For example, Wall Pool and Black Opal Pool are thermal features in the Biscuit Basin thermal group, which is part of the Upper Geyser Basin thermal area; and these features contribute thermal waters to the Firehole River thermal drainage.

Reasons to monitor hydrothermal systems are presented in Table 4.

Table 4. Reasons to monitor hydrothermal systems (from Heasler et al., 2009).

Reasons to monitor vital signs of hydrothermal systems	Explanation
Human health and safety	<ul style="list-style-type: none"> • Hot systems can cause thermal burns (and death) • Some systems may cause chemical burns (acid waters, vapors or rocks) • Some systems concentrate toxic chemicals (mercury, arsenic, etc.) • Some systems produce toxic gases (hydrogen sulfide, carbon dioxide)



Reasons to monitor vital signs of hydrothermal systems	Explanation
	<ul style="list-style-type: none"> • Some systems may have the potential for hydrothermal explosions
Baseline data	<ul style="list-style-type: none"> • Without baseline data, natural variation in heat, water and chemistry cannot be assessed, and potential impacts from human activities, seasonal variation, climate change, etc., cannot be determined. Without baseline data, it is difficult to determine what normal changes are and what significant changes are that might portend broader geologic events. Short-term (daily, weekly, seasonal, annual) variation needs to be distinguished from long-term trends (are systems getting larger or smaller; hotter or cooler?). • Baseline data are also critical for scientific researchers to be able to test hypotheses about hydrothermal systems and their components. • Baseline data may be useful to researchers in other fields (e.g., seismicity, geomicrobiology) • Baseline data may help clarify the interaction of thermal water with local cold groundwater.
Environmental impacts	<ul style="list-style-type: none"> • Hydrothermal systems may be having an impact on wildlife (Chaffee et al., 2007; Varley and Schullery, 1998) or on water quantity and/or quality of adjacent streams • Gases may produce indoor air pollution where there are buildings (Durand, 2006)
Development of local or neighboring resources	<ul style="list-style-type: none"> • Water (even local cold), geothermal, oil, gas, or mineral production may influence underground water flow path characteristics and therefore ultimately the resulting surface hydrothermal feature; springs may dry up, or change from hot spring to fumaroles as water table drops (Allis, 1983; USGS, 2003; Barrick, 2007) • Monitoring can also help document recovery of hydrothermal features from anthropogenic impacts • Monitoring elevation data can detect subsidence from nearby fluid production
Planning, development or construction activities	<ul style="list-style-type: none"> • Geothermal features may be impacted by development or construction, or the thermal features may impact managerial decisions (e.g., road construction in thermal areas)
Research and education activities	<ul style="list-style-type: none"> • Research and education activities can be a source of data for monitoring efforts (see discussions of vital signs later in this chapter), but if conducted improperly, research and education may have a detrimental impact on geothermal features.
Vandalism	<ul style="list-style-type: none"> • Vandalism cannot be documented without baseline information about what existed before damage
Interpretation activities	<ul style="list-style-type: none"> • Monitoring data can provide data for local interpretation activities
Volcano monitoring	<ul style="list-style-type: none"> • Chemical changes may indicate impending hydrothermal explosion (Fournier et al., 1991) • Changes in physical appearance of spring may mean other hazards exist, such as landslides (springs reportedly became cloudy prior to a landslide in a Guatemala thermal area)



Reasons to monitor vital signs of hydrothermal systems	Explanation
	<ul style="list-style-type: none"> Changes may be indicator of magmatic activity (see discussion of fumarole gasses in volcano chapter)

Use of Chloride (Cl) Flux for Hydrothermal Monitoring

Since the early 1980s, researchers and the NPS have used Cl flux of major rivers exiting YNP to estimate hydrothermal activity (see Friedman and Norton, 1990 and associated references). Through 2010, approximately twenty water samples were collected annually at each monitoring site on the Yellowstone, Madison, Snake, Falls, and Henry’s Fork rivers. Large tributaries with substantial thermal inflows were also sampled in the Yellowstone and Madison river basins to examine hydrothermal trends at a finer resolution including the Firehole, Gibbon, and Gardner rivers. Although periodic water sampling can yield an estimate of annual hydrothermal trends, including associations between Cl concentration and specific conductivity (SC) in major rivers, data acquisition is constrained by the number of site visits and analytical costs.

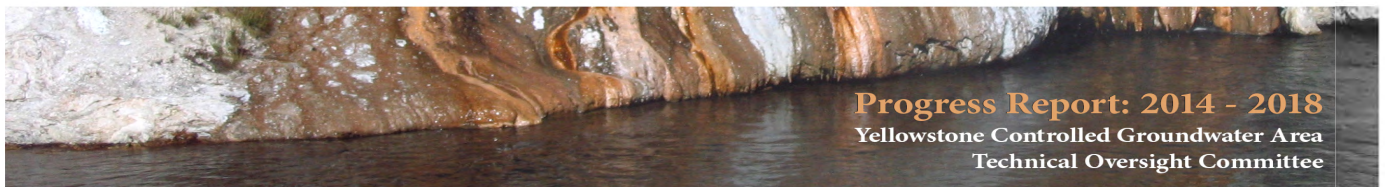
Beginning in 2010, SC, which is relatively easy to measure and can be automated, has been used as a proxy for Cl. The NPS Geology program and USGS researchers have installed In-Situ Aqua TROLL® 100 continuous recording probes which records water temperature and SC at 15-minute intervals at nine Cl flux monitoring sites (Clor et al., 2012). This higher resolution data yields a wealth of hydrologic information compared to the 28 samples per year for each river under the sample plan used prior to 2010 (Norton and Friedman, 1985; Friedman and Norton, 2007; McCleskey et al., 2017). On an annual basis, the NPS Geology program and USGS researchers collect 2-3 samples per site to verify and improve the SC-solute correlations.

The use of SC probes at the various monitoring sites enables a more consistent estimation of Cl flux and can be used to identify changes in river chemistry as a result of geyser eruptions, rain events, or changes in thermal inputs as a result of earthquakes or other natural events. The use of SC as a proxy for Cl requires quantification of the relationship between SC, Cl, and other geothermal solutes (SO₄, F, HCO₃, SiO₂, K, Li, B, and As). At each monitoring site, numerous water samples were collected over a wide range of hydrological conditions and analyzed for Cl concentration-SC relationships which are used to determine short- and long-term Cl flux (McCleskey et al., 2012; McCleskey et al., 2016).

Thermal Infrared (TIR) Imagery Acquisition of Hydrothermal Areas

Fixed-wing Airborne TIR Monitoring

Beginning in 2005, the YNP Geology Program funded researchers from Montana State University, University of Montana, and Utah State University to collect and manage thermal imagery. These initial collaborations resulted in the monitoring of hydrothermal areas both park-wide (satellite) and for specific areas (fixed-wing). Acquisition of fixed-wing thermal imagery continued under an agreement with Utah State University until September 2015. The current YNP Geology Program staff is actively seeking funding to reinstate the fixed-wing thermal infrared acquisition program. Geology Program staff seek to continue collaborative efforts with USGS Astrogeology Program staff to acquire and analyze thermal infrared imagery that can be assessed against earlier imagery for temporal variations in heat output in the thermal basins.



YNP Geology Program staff have also processed imagery acquired since 2005 with structure for motion (SfM) techniques to render 3-dimensional models of 2-dimensional image sequences. These analyses more effectively indicate temporal variations between geo-rectified image datasets.

Helicopter TIR Condition Assessments

Helicopter reconnaissance is a rapid method to perform visual and photographic condition assessments of YNP’s numerous hydrothermal areas. Image acquisition targets are chosen based on ground observations or based on unusual characteristics noticed while in flight.

Using YNP contract helicopters, YNP Geology Program members acquire oblique angle visual and thermal infrared imagery from 50 meters (m) to 300 m. (150 to 1,000 ft.) above ground level over thermal areas. Two Garmin Etrex Vista GPS units document the flight path and altitude every 100 m., within a ± 4 m. error. Day-time thermal infrared images were acquired using a FLIR SC640 640 by 480 pixel, 8 to 12 microns from 2009 to 2011. Between 2012 and 2016, a FLIR SC660, 8 to 12-micron camera was used. For all flights, a 38 mm lens acquired both visible and thermal imagery.

Approximately 3,700 paired images (visible and TIR) have been acquired over multiple targets in the period 2014-2018 (Table 5). An example of a visible and TIR image taken over the Lower Geyser Basin is shown in Figure 4.

Table 5: Helicopter TIR Flights over YNP, 2014-2018.

Date	Number of TIR images	Areas Imaged
3/25/2014	90	Lower Geyser Basin, Norris, Old Faithful, Red Spouter
9/25/2014	196	Isa Lake, Norris Road Construction, Old Faithful
3/27/2015	143	Mammoth to West Thumb, Norris, Old Faithful, Fountain Paint Pots
9/12/2015	214	Mammoth, Old Faithful, Rhodes, Obsidian Pool
9/20/2016	276	Mammoth to Norris
9/25/2016	115	Mirror Plateau
9/26/2016	218	Mammoth, Solfatara, Juniper
9/27/2016	216	Washburn, Bog Creek, Hayden Valley
9/28/2016	242	Lower, Midway, Upper, Shoshone, and Heart Geyser Basins
9/30/2016	155	Hot Spring Basin, Sulfur Hills, and Crater Hills

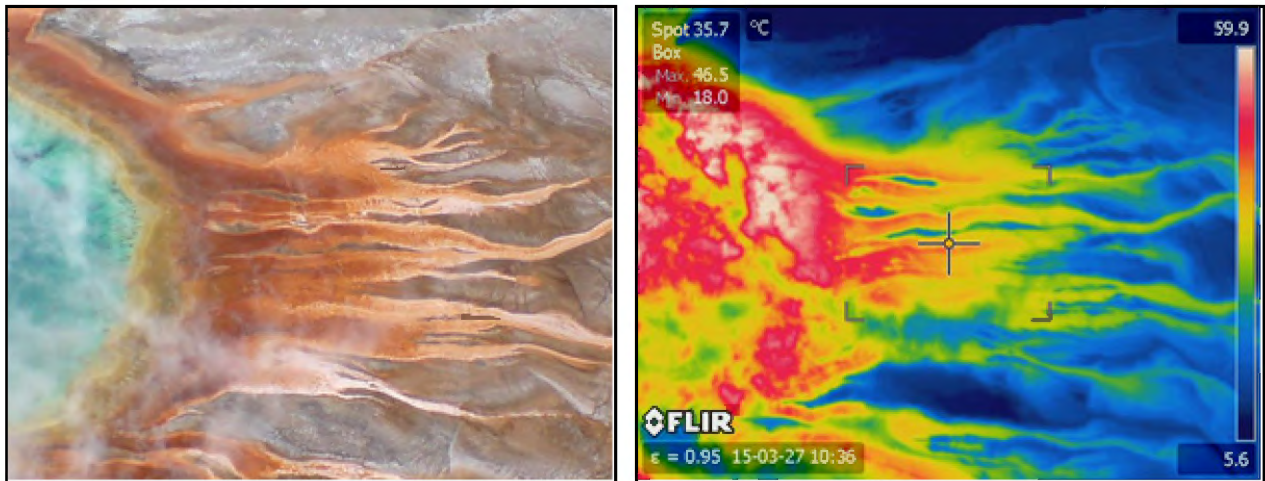


Figure 4. Visible and TIR photo pair taken from a helicopter on March 27, 2015 of Grand Prismatic, Midway Geysers Basin.

Ground-based Thermal Feature Temperature Monitoring

The YNP Geology Program and its research partners, which include the USGS, monitor select hydrothermal features in YNP with temperature loggers. Temperature loggers comprise a thermistor and a data logger and are located in a thermal pool or, in the runoff channel of a hydrothermal feature. In 2018, there are more than 80 temperature loggers deployed in hydrothermal features in YNP. The temperature loggers are not calibrated, and, therefore, the data collected with these loggers are treated as binary information; the system is either erupting/overflowing or not. Monitored features are chosen based on their significance to the hydrothermal system, cultural significance, safety of visitors and/or potential anthropogenic impacts to the hydrothermal feature. For example, temperature loggers exist on 14 thermal features in the Norris Geysers Basin, 30 features in the Lower and Upper Geysers Basins (Figure 5), 3 features in West Thumb and Dragon's Mouth in Mud Volcano.

Onset[®] Computer Corporation temperature loggers were used to measure kinetic surface temperatures. Onset[®] loggers are paired with thermistors of cable lengths that vary from 2 m. to 17 m. in length, and temperatures readings were usually collected on a 1-minute interval. (About 536,000 data values per site per year).

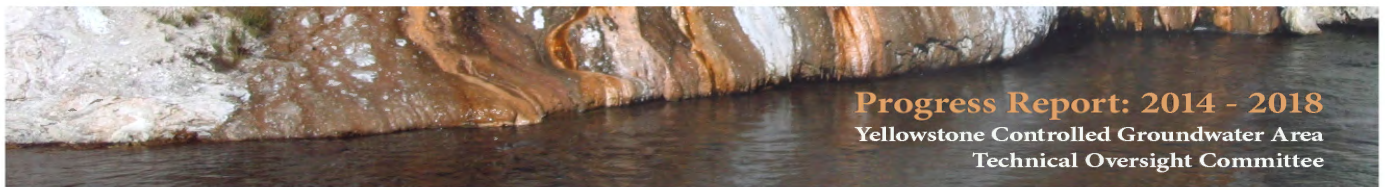


Figure 5. Temperature logger locations in the Upper and Lower Geyser Basins.

Future Protection Efforts

Federal Highways – Yellowstone River Bridge Reconstruction (2019)

Federal Highways conducted a preliminary drilling program in June and July of 2019 to assess bridge alignment options of a new structure and the proximity to the shallow hydrothermal system near the existing Yellowstone River Bridge as part of a road reconstruction project scheduled to begin in 2021. Temperatures were measured in the borings as well as pH and SC of the water. Geothermal gas concentrations also were measured in the borings. On-site descriptions of cuttings and core were used to assess the hydrothermal fluid flow regime. Temperature values and gas concentrations were used to quantify locations where thermal road designs should be used.

Yellowstone Volcano Observatory Hydrothermal Systems Monitoring Plan Meeting (2019)

The YNP Geology Program and scientists from the USGS brought together a panel of leading experts to meet on the Montana State University campus to review current hydrothermal monitoring practices and to create a new hydrothermal system monitoring plan for years 2020 to 2030. The new hydrothermal system monitoring plan will be a part of the new YVO Yellowstone Volcano Monitoring Plan for 2020 to 2030. This publication will be a USGS Special Investigations Report.

Water Use Data and Analysis

Returns of meter cards from owners of permitted wells has always been low (20-25%). During the 5-year period MBMG has attempted to improve the turnout rate by including a letter along with the meter cards when they are mailed, and by allowing well owners to simply email or text a photo of the meter dial to MBMG. While these efforts seem to have helped some, more effort is needed if the return rate is to be improved.



YCGA Statue specifies that the meter cards should be mailed to well owners in January each year. However, since many homes are either vacation cabins or summer homes, many owners are at the permitted address in the winter. MBMG is considering doing a second mailing in the late spring or early summer and visiting some of the permitted well sites during the field season to explain the requirement and provide any help the well owners may need.

Re-evaluation of YCGA Boundary

The Compact was established to protect the geothermal resources of YNP. Long-term monitoring of wells and springs necessary to assess impacts of future development on YNP's geothermal system is the most important means to meet this goal. The TOC will continue to proactively encourage data collection, analysis and review to protect the hydrothermal flow system of YNP. Discussion by the TOC on boundary modifications has occurred, but no action has been taken as there is no evidence for changing the boundaries at this time.

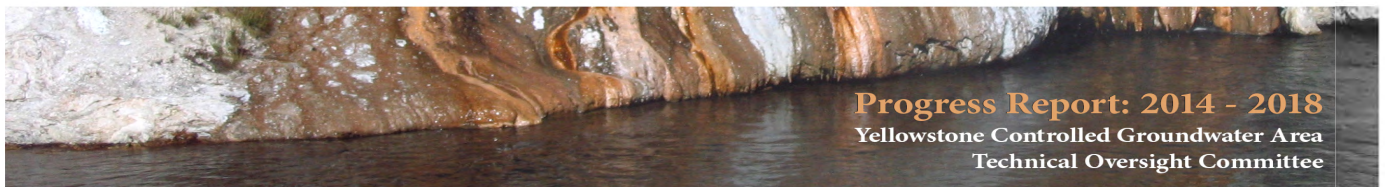
Education and Public Outreach

The following are highlights from the education and public outreach related to the YCGA.

- The DNRC has worked with the Board of Water Well Contractors (BWWC) to provide information to their members of the YCGA drilling and measurement requirements through a newsletter (BWWC, 2015).
- The DNRC has also published an informational flyer to help applicants navigate the YCGA application process (DNRC, 2018).
- Since 2014, MBMG has included a letter to permitted well owners along with the annual meter reading cards that explains the purpose of the meter reading requirements and offers assistance to well owners with meters.
- In May 2014, MBMG presented a poster on the YCGA Long-Term Monitoring Program at the 2014 annual meeting of the Rocky Mountain Section of the Geological Society of America, held in Bozeman.
- In October 2014, MBMG presented an overview of the YCGA and the Long-Term Monitoring Program at the annual meeting of the Montana Section of the American Water Resources Association, held in Kalispell.
- Graduate student Joe Schmechel defended his thesis (Schmechel, 2005) on the hydrogeology of the West Yellowstone area in April 2015. MBMG employed Joe Schmechel to assist with monitoring in the YCGA, served on his thesis committee, and assisted with his field work.
- In August 2015, MBMG assisted with a field trip to YNP for faculty and students from Sun Yat-Sen University in China. An overview of the YCGA and the Long-Term Monitoring Program was provided.
- In March 2017, MBMG gave a presentation at Montana Tech on research sampling completed by MBMG in the YCGA.
- In September 2018, MBMG gave a presentation on the Long-Term Monitoring Program at a Montana Tech Geochemistry Seminar lecture.
- In October 2018, MBMG presented an overview of the YCGA and the Long-Term Monitoring Program on a field trip during the 2018 annual meeting of the Montana Section of the American Water Resources Association, held in West Yellowstone.

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Appendix

Yellowstone Controlled Groundwater Area Active and Discontinued Long-Term Monitoring Program Sites (as of 1/1/2019)

GWIC SITE ID	SITE NAME	SITE TYPE*	MONITORING STATUS	WATER TEMP**	PERIOD OF RECORD	DATA LOGGER TYPE***
SODA BUTTE CREEK WATERSHED-COOKE CITY-SILVER GATE AREA						
106030	SILVER GATE	Monitor Well	Active	Cold	Sept 2006→	WL/T,BARO
234520	LYMAN	Domestic Well	Active	Cold	August 2015→	WL/T
162539	KLOSTER	Domestic Well	Well Abandoned by Owner	Cold	Aug 2007→Nov 2013	
YELLOWSTONE RIVER WATERSHED-GARDINER-CORWIN SPRINGS AREA						
171215	LADUKE HOT SPRING	Spring	Active	Hot	Oct 2005→	HIGH TEMP)
256421	LADUKE HOT SPRING LD 1	Piezometer	Water Level Only	Hot	Nov 2013→	Manual WL
280402	USFS SPRING NEAR LADUKE HOT SPRING	Spring	Active	Hot	October 2014→	TEMP
197921	BEAR CREEK WARM SPRING	Spring	Active	Hot	July 2009→	WL/T (vented)
184260	POWELL SPRING	Spring	Active	Warm	Oct 2008→	TEMP
171229	SIRR SPRING	Spring	Active	Cold	April 2009→	WL/T, TEMP
181620	DEMAREE SPRING (AKA, COLE SPRING)	Spring	Active	Cold	May 2007→	TEMP
138764	DEMAREE WELL (AKA, COLE WELL)	Irrigation Well	Active	Warm	Oct 2006→	WL/T
252314	SHOOTING STAR RANCH	Domestic Well	Active	Warm	Nov 2009→	Manual Pressure
105959	STRAUSS	Domestic Well	Active	Warm	May 2007→	WL/T
146967	GALLOWAY	Domestic Well	Active	Cold	Aug 2005→	WL/T
105980	GARDINER AIRPORT	Domestic Well	Active	Cold	Sept 2006→	WL/T
152216	MILLER	Monitor Well	Active	Warm	March 2006→	WL/T, BARO
287868	NPS CSCS-1	Monitor Well	Active	Cold	June 2016→	WL/T
287867	NPS-STEVENS CREEK CORRAL RESIDENCE	Unused Domestic	Active	Cold	June 2016→	WL/T
145529	YELLOWSTONE BASIN INN	PWS Well	Discontinued/Redundant	Warm	May 2007→August 2014	
182012	MCPHERSON	Spring	Discontinued/Owner Request	Cold	April 2009→Dec 2010	
140974	SPHINX MOUNTAIN MOBILE HOME PARK #2	PWS Well	Discontinued/Owner Request	Cold	May 2009→May 2011	
181621	SPERANO	Spring	Discontinued/Owner Request	Cold	June 2008→May 2010	

*[PWS=Public Water Supply]

**[Sites are classified as cold (<15°C), warm (15° to 25°C), or hot (>25°C).]

*** WL/T = Water level and temperature logger, TEMP = Water-temperature logger, BARO = Barometric Pressure Logger, Manual WL = Hand measurements only

***Yellowstone Controlled Groundwater Area
Active and Discontinued Long-Term Monitoring Program Sites (as of 1/1/2019)***

GWIC SITE ID	SITE NAME	SITE TYPE*	MONITORING STATUS	WATER TEMP**	PERIOD OF RECORD	DATA LOGGER TYPE***
GALLATIN RIVER WATERSHED-BIG SKY AREA						
258715	ANCENY SPRING	Spring, Stream	Active	Warm	Oct 2010→	WL/T (vented) TEMP (spring)
171216	SNOWFLAKE SPRING	Spring, Stream	Active	Cold	April 2010→	TEMP
255289	SLOW VEHICLES SPRING	Spring	Active	Cold	April 2010→	TEMP
215333	ALTMAN	Well	Active	Cold	July 2007→	WL/T, BARO
259697	USFS RED CLIFF CAMPGROUND	PWS Well	Active	Cold	August 2014→	WL/T
183236	SHEEP CAMP SPRING	Spring	Discontinued/Ephemeral	Cold	July 2007→Nov 2011	
MADISON RIVER WATERSHED-WEST YELLOWSTONE-HEBGAN BASIN AREA						
182014	COREY SPRING	Spring	Active	Cold	July 201→	TEMP
183268	STINKY SPRING	Spring	Active	Warm	Oct 2005→	WL/T (vented), TEMP
183242	BLACK SAND SPRING	Spring	Active	Cold	May 2010→	TEMP
8930	RYBERG SPRING #4	Spring	Active	Cold	Aug 2010→	TEMP
277397	RYBERG SPRING CREEK	Stream	Active	Cold	Aug 2011→	WL/T
230654	RYBERG	Flowing Well	Active	Warm	Nov 2011→	Manual Pressure
106775	BAKER'S HOLE CAMP-SOUTH WELL	Flowing Well	Active	Warm	May 2007→	TEMP, Head
8943	BAKER'S HOLE CAMP-NORTH WELL	Flowing Well	Active	Warm	May 2007→	TEMP
106842	3 BEARS LODGE	Irrigation Well	Active	Cold	March 2006→	WL/T, BARO
165852	WEST YELLOWSTONE KOA-BACKUP WELL	PWS Well	Active	Cold	May 2010→	W/T
247335	HEBGEN BASIN FIRE STATION 3	Domestic Well	Active	Cold	July 2010→	Manual WL, BARO
8935	WEST YELLOWSTONE KOA MAIN WELL	PWS Well	Discontinued/Redundant	Cold	March 2006→August 2010	
106778	KELAND	Flowing Well	Discontinued/Redundant	Cold	Nov 2006→August 2014	
181626	LIONSHEAD SPRING	Spring	Discontinued	Cold	May 2007→August 2008	
164216	LONESOMEHURST WUA	Spring	Discontinued	Cold	Aug 2008→May 2012	
181930	BEAVER CREEK	Spring	Discontinued/Ephemeral	Cold	May 2007→Nov 2011	

*[PWS=Public Water Supply]

**[Sites are classified as cold (<15°C), warm (15° to 25°C), or hot (>25°C).]

*** WL/T = Water level and temperature logger, TEMP = Water-temperature logger, BARO = Barometric Pressure Logger, Manual WL = Hand measurements only



**Yellowstone Controlled Groundwater Area
Technical Oversight Committee Members**

Dr. Stephan Custer, Chair

Stephan Custer

Marvin Miller, Montana University System

Marvin Miller

John Kilpatrick, USGS

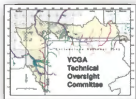
John M. Kilpatrick

David Susong, NPS

David Susong

Attila Felnagy, DNRC

Attila Felnagy



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