SPRING INVENTORY AND BASELINE SAMPLING OF THE YELLOWSTONE CONTROLLED GROUND WATER AREA, MONTANA

MBMG Open-File Report 510

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Montana Tech of
The University of Montana

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Abstract

The Water Rights Compact between the State of Montana and the United States National Park Service (NPS) became effective on January 31, 1994 (DNRC, 1999). The Yellowstone Controlled Ground Water Area (YCGWA) was established to implement controls on the development of ground water near Yellowstone National Park (Park) in order to preserve its natural geothermal features. Funded through the National Park Service, the Montana Bureau of Mines and Geology has conducted an inventory and collected baseline data on wells (previous report) and springs (this report). About 330 spring sites were visited and documented; site location and chemistry data from this study and from previous investigations were compiled and are listed in the MBMG Ground Water Information Center database. In a related study, the MBMG has mapped and compiled data on bedrock and surficial deposits within the controlled ground water area; these data, in map form, are published separately. Chemistry from springs and wells throughout the study area reflect a complex system of ground-water recharge, deep circulation near the Yellowstone caldera, and geothermal discharge through a wide variety of rock types. Mixing of geothermal waters with shallow colder water is evident in the chemistry and isotope analytical results. Hydrogeologic and geochemical changes in the geothermal system of Yellowstone National Park and the greater Yellowstone area are inevitable. Distinctions between man-induced changes and natural processes cannot be made without comprehensive surface-water and ground-water monitoring both inside and outside the Park.

Introduction

The Yellowstone Controlled Ground Water Area (YCGWA)

The Water Rights Compact between the State of Montana and the United States of America National Park Service (NPS) became effective on January 31, 1994 (Montana Department of Natural Resources and Conservation, 1999). The Yellowstone Controlled Ground Water Area (YCGWA) was established to implement controls on the development of ground water near Yellowstone National Park (Park) in order to preserve its natural geothermal features. The Montana Bureau of Mines and Geology (MBMG) was required by the Compact to initiate, within 3 years after receipt of Federal funding, an inventory of all ground-water appropriations in the YCGWA with a priority date before January 31, 1994, that could be located and accessed with reasonable diligence.

The YCGWA is approximately 875,000 acres and includes1,367 sections in 53 townships (table 1) in Madison, Gallatin, and Park Counties, Montana. The largest watersheds within the area are the upper Madison River, the South Fork Madison River, and the upper Yellowstone River, which flow out of the Park; and Bear Creek, Hellroaring Creek, Slough Creek, and Soda Butte Creek which flow into the Park (figure 1). The principal population centers include West Yellowstone near the west entrance of the Park, Gardiner near the north entrance, and Silver Gate and Cooke City near the northeast entrance.

Well Inventory

The MBMG, in a cooperative agreement with the NPS, completed the well inventory of the Controlled Ground Water Area and produced a summary report in 2000 (Metesh and Kougioulis, 2000). These data for about 600 wells included location, water temperature, and field chemistry. In addition to the inventory, samples were collected from a representative number of wells based on well depth, aquifer type, water temperature, chloride concentration, and geographic distribution. Laboratory analyses conducted by the MBMG Analytical Division included major cations, major anions, trace metals, and ^{222}radon. Isotopes, including oxygen-18 (^{18}O), tritium (^{3}H), deuterium (^{2}H), and helium (^{3}He), were analyzed by other laboratories. All of the information gathered during the well inventory and baseline sampling is available through the MBMG Ground Water Information Center (GWIC) as hard copy or via the Internet at: http://mbmggwic.mtech.edu.

Table 1. Yellowstone Controlled Ground Water Area (January 31, 1994)

Township	Range	Sections
06S	04E	33, 34
07S	04E	2, 3, 4, 9, 10, 11, 12, 13, 14, 15, 16, 21, 22, 23, 24, 25, 26, 27, 28, 32, 33, 34, 35, 36
07S	05E	19, 20, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36
07S	06E	26, 27, 28, 28, 30, 31, 32, 33, 34, 35, 36
07S	07E	31, 32, 33, 34, 35
07S	10E	23, 24, 25, 26, 27, 28, 31, 32, 33, 34, 35, 36
07S	11E	3, 4, 5, 8, 9, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36
07S	12E	25, 30, 31, 32, 33, 36
07S	13E	19, 20, 21, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36
08S	02E	13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36
08S	03E	1, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36
08S	04E	All
08S	05E	All
08S	06E	All
08S	07E	All
08S	08E	All
08S	09E	All
08S	10E	All
08S	11E	All
08S	12E	1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36
08S	13E	All
08S	14E	7, 18, 19, 20, 29, 30, 31, 32
09S	02E	1, 2, 3, 4, 5, 9, 10, 11, 12, 13, 14, 15, 16, 22, 23, 24, 25, 26, 33, 34, 35, 36
09S	03E	All
09S	04E	All

Table 1 (continued). Yellowstone Controlled Groundwater Area (January 31, 1994)

Township	Range	Sections
09S	05E	1, 2, 5, 6, 7, 8, 12, 17, 18, 19, 20, 21, 27, 28, 29, 30, 31, 32, 33, 34
09S	06E	1, 2, 3, 5, 6, 12, 13
09S	07E	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23
09S	08E	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 22, 23, 24
09S	09E	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24
09S	10E	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24
09S	11E	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24
09S	12E	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24
09S	13E	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24
09S	14E	5, 6, 7, 8, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 33, 34, 35, 36
09S	15E	18, 19, 20, 29, 30, 31, 32
10S	02E	1, 2, 3, 11, 12, 13
10S	03E	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 32, 33, 34, 35, 36 (All, except 31)
10S	04E	All
10S	05E	3, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 22, 27, 28, 29, 30, 31, 32, 33, 34
11S	03E	1, 2, 3, 4, 10, 11, 12, 13, 14, 15, 23, 24, 25
11S	04E	All
11S	05E	3, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 22, 27, 28, 29, 30, 31, 32, 33, 34
12S	03E	33, 34, 35, 36
12S	04E	1, 2, 3, 4, 5, 9, 10, 12, 13, 14, 15, 22, 23, 24, 25, 26, 27, 34, 35, 36
12S	05E	3, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 22, 27, 28, 29, 30, 31, 32, 33, 34
13S	03E	1, 2, 3, 4, 11, 12, 13
13S	04E	All
13S	05E	3, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 22, 27, 28, 29, 30, 31, 32, 33, 34
14S	04E	1, 2, 3, 4, 5, 10, 11, 12, 13, 14, 15, 16, 22, 23, 24, 25, 25, 26, 27, 34, 35, 36
14S	05E	3, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 22, 27, 28, 29, 30, 31, 32, 33, 34
15S	04E	1
15S	05E	3, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 20, 21, 22, 27, 28, 33, 34

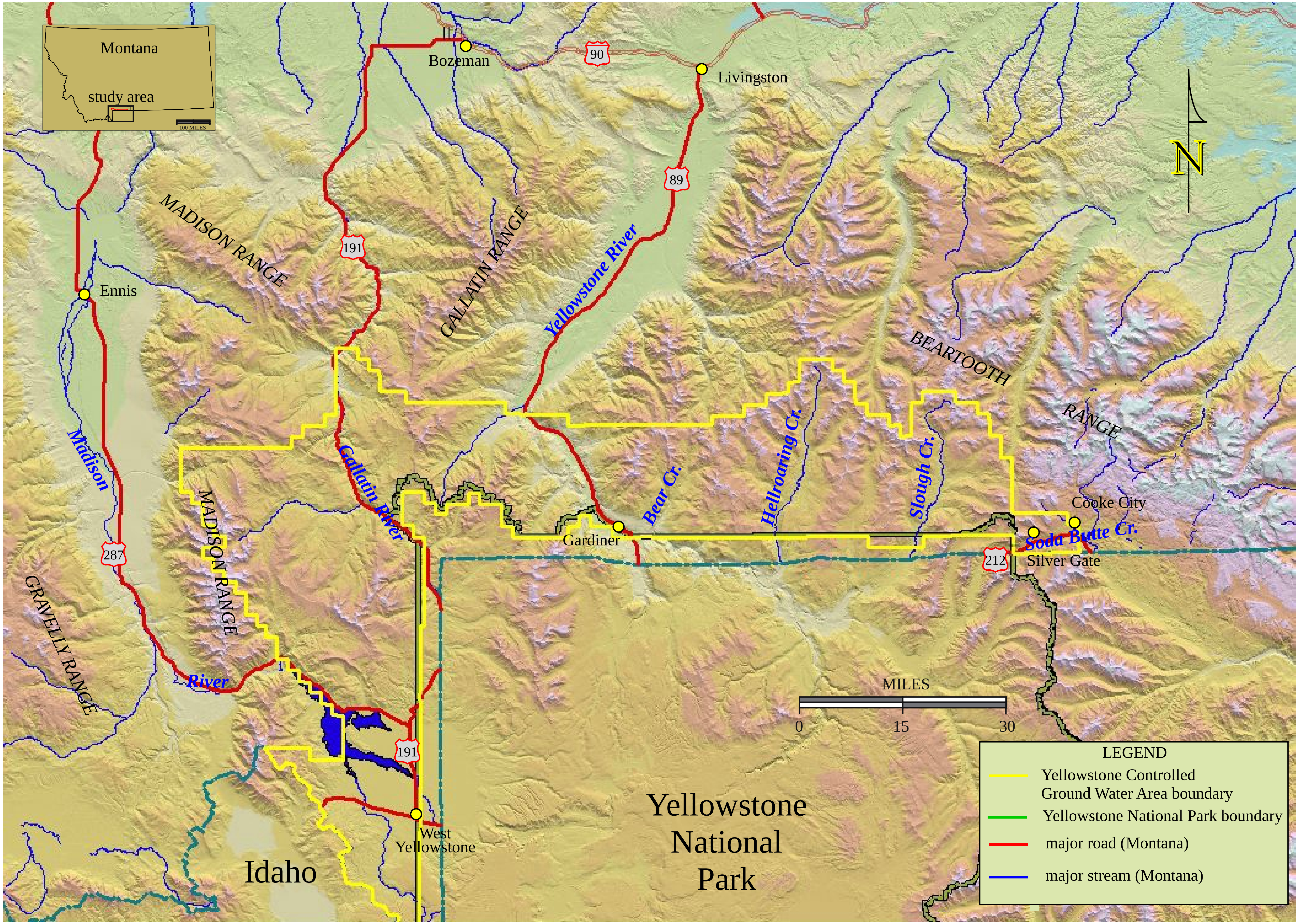


Figure 1. The Yellowstone Controlled Ground Water Area in Montana was established in 1994. The area includes West Yellowstone, Gardiner, Silver Gate, and Cooke City. Major watersheds are Soda Butte Creek, Slough Creek, Hellroaring Creek, the Yellowstone River, the Gallatin River, and the Madison River.

Spring Inventory

In an unpublished report by an advisory group to the U.S. Department of Interior concerning ground-water control areas near Yellowstone National Park, a spring inventory was recommended. In a manner similar to the well inventory, each spring was to be visited and sampled for field parameters. The intent was to locate and sample geothermal springs, springs for which a water right exists, and springs that contribute significant and sustained flow to streams. Field measurements included discharge (Q), specific conductivity (SC), temperature (T), pH, and chloride concentration. In a preliminary investigation based on 1:125,000-scale maps of the area, approximately 120 mappable springs were identified within the YCGWA.

Visual evidence of thermal activity (algae, mineral deposits, etc.), a temperature greater than 15^{O}C, a specific conductivity value greater than 1000 μmhos/cm, or a chloride concentration greater than 50 milligram per liter (mg/L) were used as indicators of geothermal activity in this inventory. Spring sites meeting these criteria were sampled. Additional spring sites were sampled to assure a geological and geographical distribution. Sample location and elevation were measured using a Global Positioning System (GPS) or estimated from a 1:24,000 topographic map and altimeter data. Sample collection for standard analysis was conducted under the MBMG Standard Operating Procedures used for the well inventory. Field quality control (QC) sampling consisted of duplicate samples, field blanks, and equipment rinseate samples. Sample collection procedures for isotopes conformed to the procedures required by the receiving laboratory. All point, line, and arc data compiled for the inventory are suitable for GIS applications at a 1:100,000 scale or larger. Attributes such as water chemistry and spring discharge were assigned to each inventoried site. All of the information gathered during the spring inventory and baseline sampling is available through the MBMG Ground Water Information Center (GWIC) as hard copy or via the Internet at: http://mbmggwic.mtech.edu.

Streamflow

Streamflow data were compiled for the eight major watersheds (figure 1) of the controlled ground water area. Four of these discharge into Yellowstone Park, and four discharge out of Yellowstone Park. Additional springs contributing significant, sustained flow were inventoried and sampled and at least one seepage-run was conducted on the main stream of each watershed during the late fall - early winter to quantify stream-losses/gains and to give an estimate of ground-water base flow.

Geologic Mapping

Surficial deposits and bedrock were mapped throughout the area outside the Yellowstone Park boundary to enhance the hydrologic evaluations. Mapping at 1:24,000-scale of Quaternary and Tertiary units (with emphasis on geomorphic features) was conducted; the author also took advantage of bedrock geologic mapping conducted under the MBMG-USGS STATEMAP program. A geologic map with detailed descriptions of the surficial deposits in the area will be published by Lonn and others.

Report Objectives

Data collected during the inventory of springs are summarized here to provide a description of baseline water chemistry within the controlled ground-water area near Yellowstone National Park. Some data from a well inventory presented in a previous report are also included.

Spring Inventory

Scope

The general approach to the spring inventory was to obtain records of all surface-water water rights from the Montana DNRC for the controlled ground-water area. Sites whose sources of water were clearly identified as stream diversions, and therefore not springs, were eliminated. The list of sites whose sources could not be identified or were identified as springs was used as the basis for the field inventory. In the field, the sites for which a water-right owner was recorded were inventoried; springs in the area that were deemed capable of sustained flow, regardless of water rights, were also included. Table 2 presents a summary of the spring inventory for each of the three sub-areas: Cooke City area, which includes all sites in the Soda Butte Creek drainage; the Gardiner area, which includes sites in the Yellowstone River and Bear Creek drainages; and the West Yellowstone area, which includes the Madison and Gallatin River drainages.

Table 2. Spring inventory results

Sub-area	Inventoried sites	Attempted	Multiple water rights
Cooke City	42	2	14
Gardiner	72	59	16
West Yellowstone	117	37	26
TOTAL	231	99	56

Inventoried Sites

Inventoried sites includes all sites whose location was verified (figure 2). Field measurements (pH, SC, Eh, and flow) and samples for chloride analyses were collected at each of these sites. Latitude, longitude, and elevation was verified on 1:24,000-scale maps or by GPS. In addition to those identified as having a water right, 53 undeveloped springs were inventoried. Not included in the total count, but included in the project database, are multiple water-right

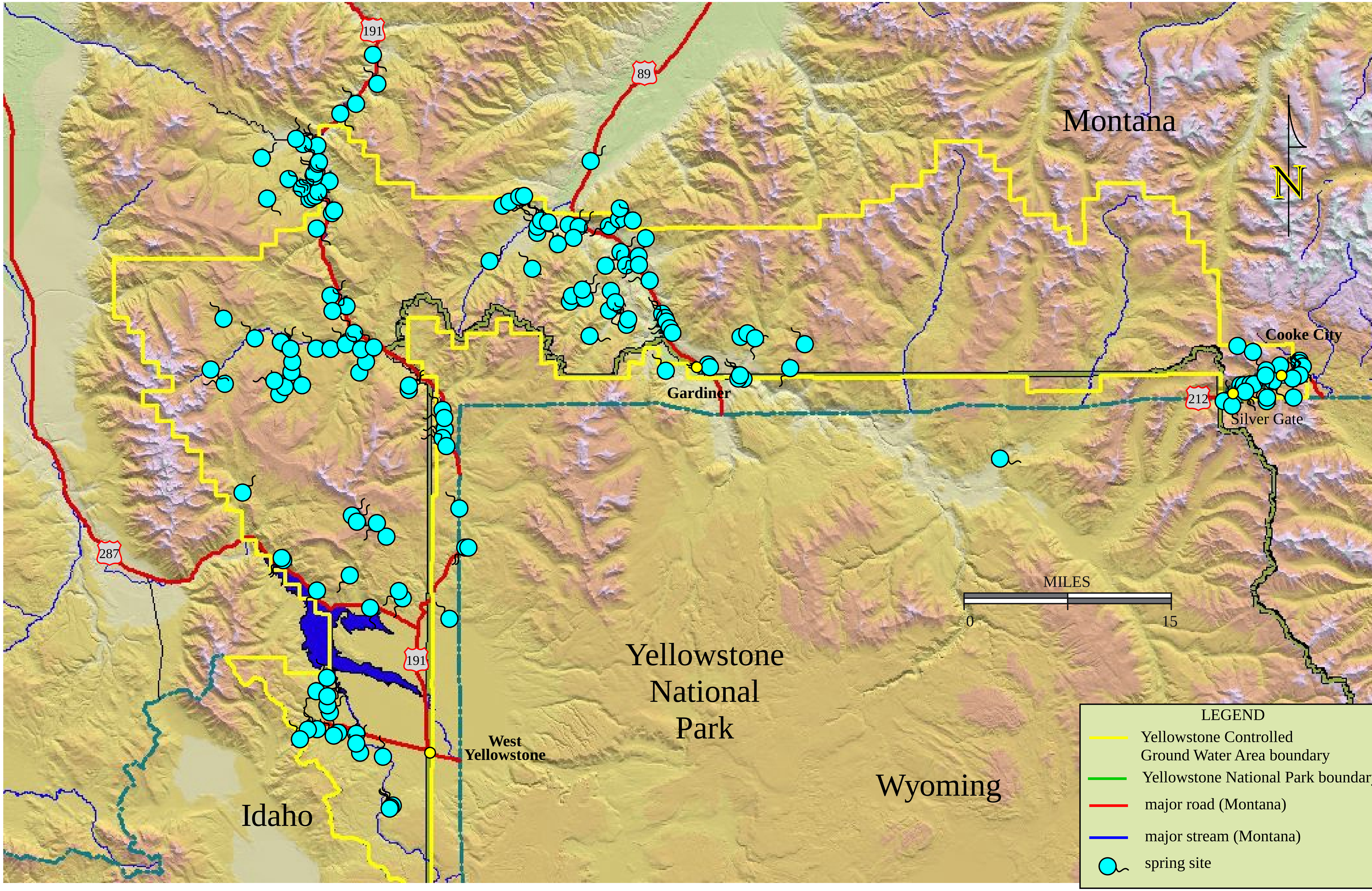


Figure 2. The spring inventory verified the location of 231 spring sites, including 53 previously unrecorded sites. Additional sites closely outside the boundary are also shown.

owners, spring sites and adit discharges identified during an abandoned-inactive mines inventory (Hargrave and others, 2000) of that portion of the Gallatin National Forest within the controlled ground-water area.

Recorded Sites - attempted visits

An inventory of each site for which a water-right was recorded was attempted. Sites visited, but not designated as inventoried (table 2), are those sites whose recorded location was visited, but no single, identifiable spring was found (figure 3). In most of these cases, although surface water was present, no single spring or sustainable flowing water was found in the area nor any man-made structures to indicate a diversion. Attempts were also made to find the water-right owner of record, or property owners in the area. In a few cases, access to the area of the spring was not possible; the general location was verified, but only some field data was collected. The records for several sites indicated multiple water-right owners.

Multiple Water Rights

Fifty-six of the sites inventoried had more than one recorded water-right; that is, a single spring was used by two or more individuals. Each of these sites was counted as one site in the inventory, but each is listed under the separate water-right owners in the database.

Summary of Field Data

Water temperatures of the inventoried springs ranged from just above freezing in the Cooke City area to about 65^{O}C at LaDuke spring in the Gardiner area. The great majority of springs had temperatures lower than 10^{O}C; 48 of the 231 sites had water temperatures higher than 10^{O}C (figure 4). Specific conductivity, which may be used as a rough indication of total dissolved constituents, ranged from less than 50 µmhos/cm at several sites to nearly 2700 µmhos/cm at LaDuke spring; the range of SC values is distributed almost evenly between 50 and 600 µmhos/cm (figure 5). The pH of the inventoried springs was near neutral (6 to 10) for all but three sites (figure 6); most sites are within the 7 to 9 pH range (figure 7). Three sites exhibiting low pH were inventoried in the Cooke City area; all three were identified as discharges associated with mine waste or mineralized rock.

The chloride concentrations for the inventoried springs ranged from less than the detection limit (0.1 mg/L for most samples) to about 45 mg/L at the LaDuke spring. The largest group of samples is that whose chloride values were below the detection limit (figure 8). Figure 9 presents the distribution of chloride concentrations within the range of 1mg/L to the maximum value.

Norton and Friedman (1985) demonstrate the relationship between geothermal heat flux and the chloride concentration related to discharge from Yellowstone National Park. In their work, there was a correlation between heat flux and chloride concentration in surface waters exiting the Park. As noted, nearly all of the springs inventoried in this investigation were considered “cold” springs. The chloride concentrations and water temperature show little correlation in the controlled ground-water area (figure 10). Similarly, there was little correlation found between specific conductance (SC) and temperature nor was there correlation between SC and chloride concentrations.

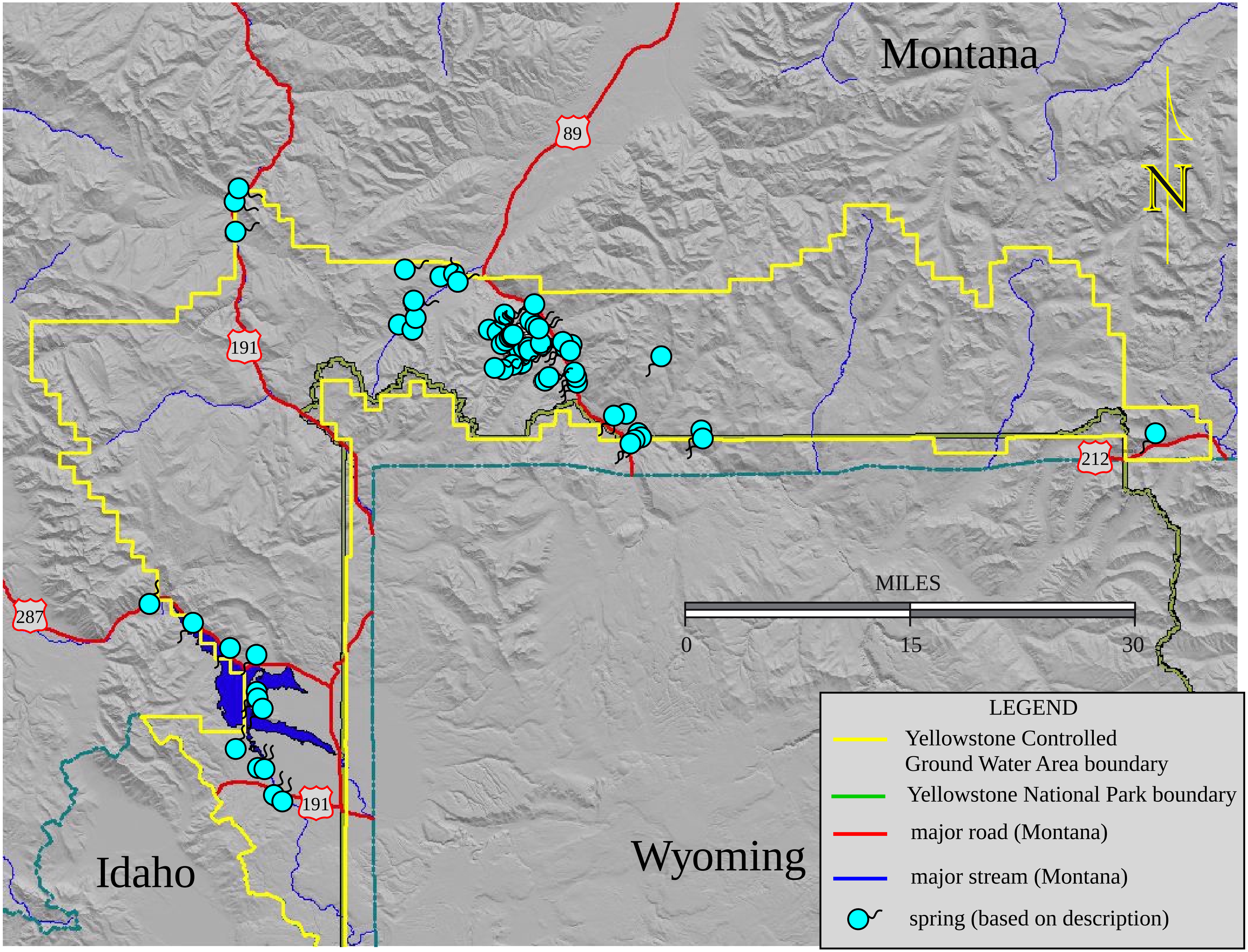


Figure 3. There was no evidence of any diversion or use at 99 of the visited sites listed as having a water right. The locations and flow directions shown are based on descriptions provided in the water-right decrees or the best evidence in the field.

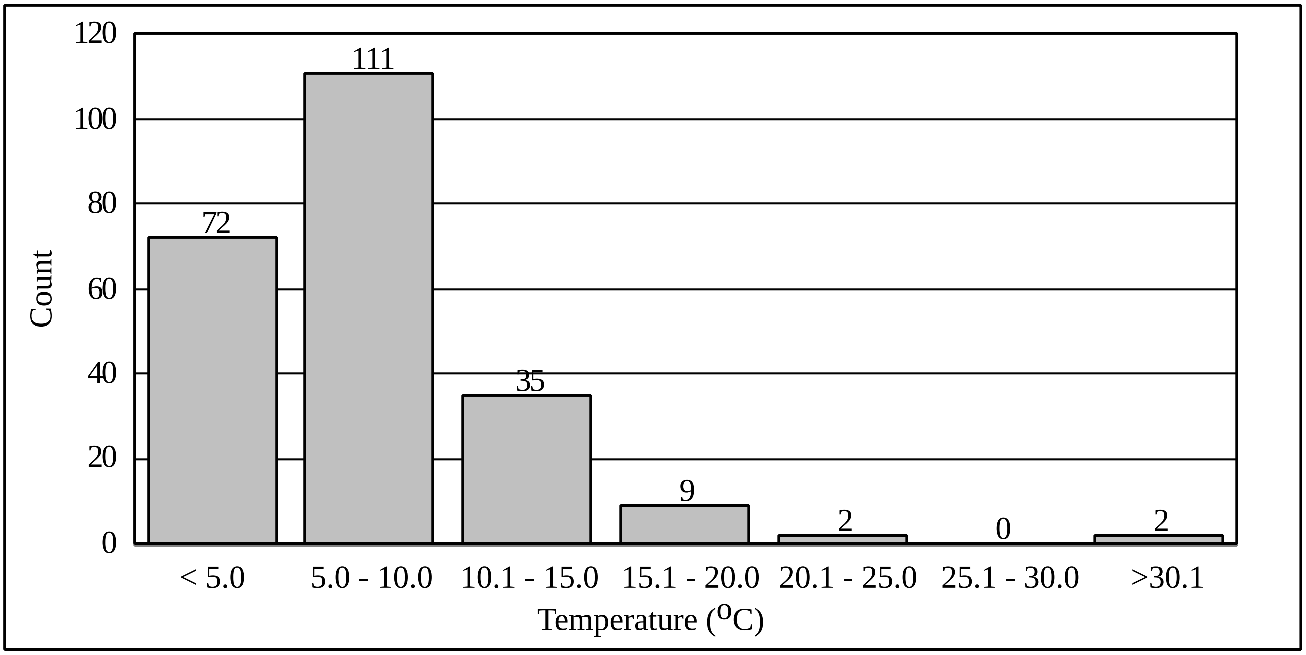


Figure 4. The temperatures of the great majority of inventoried springs were 10°C or less.

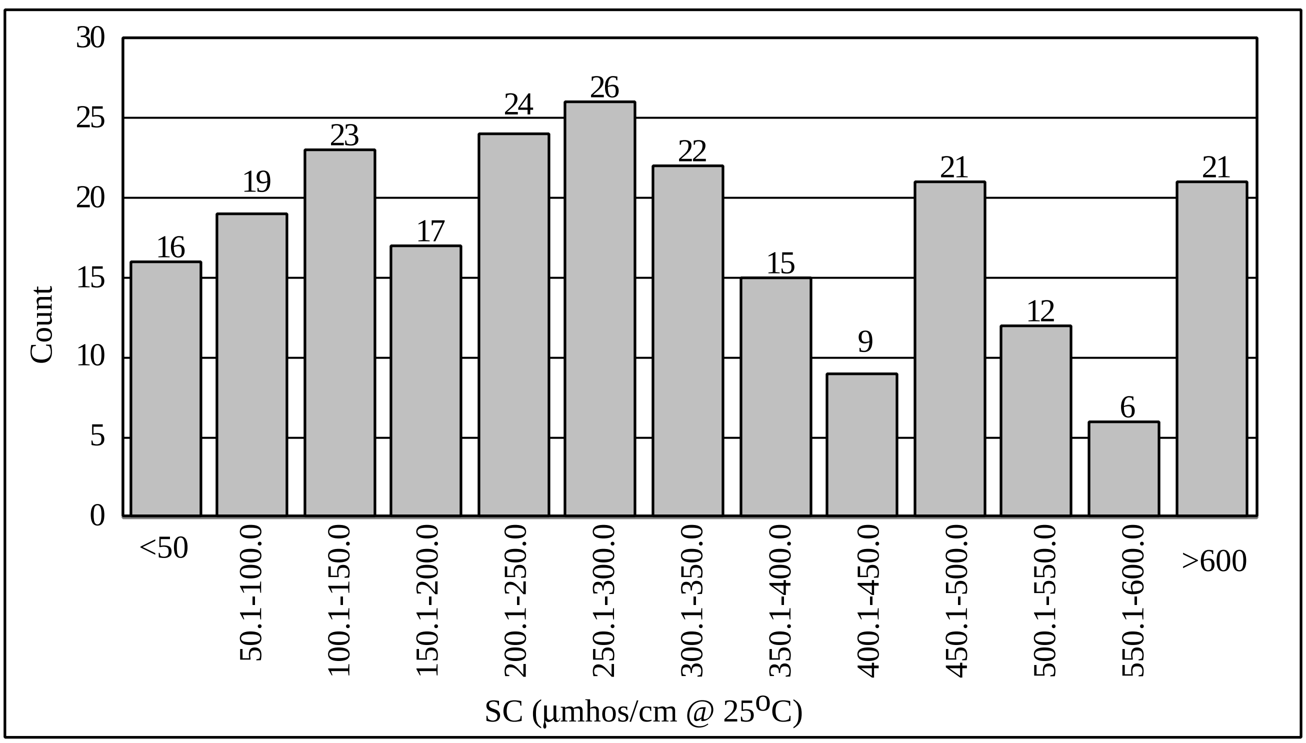


Figure 5. Specific conductance (SC) values are distributed uniformly throughout the range of observed values.

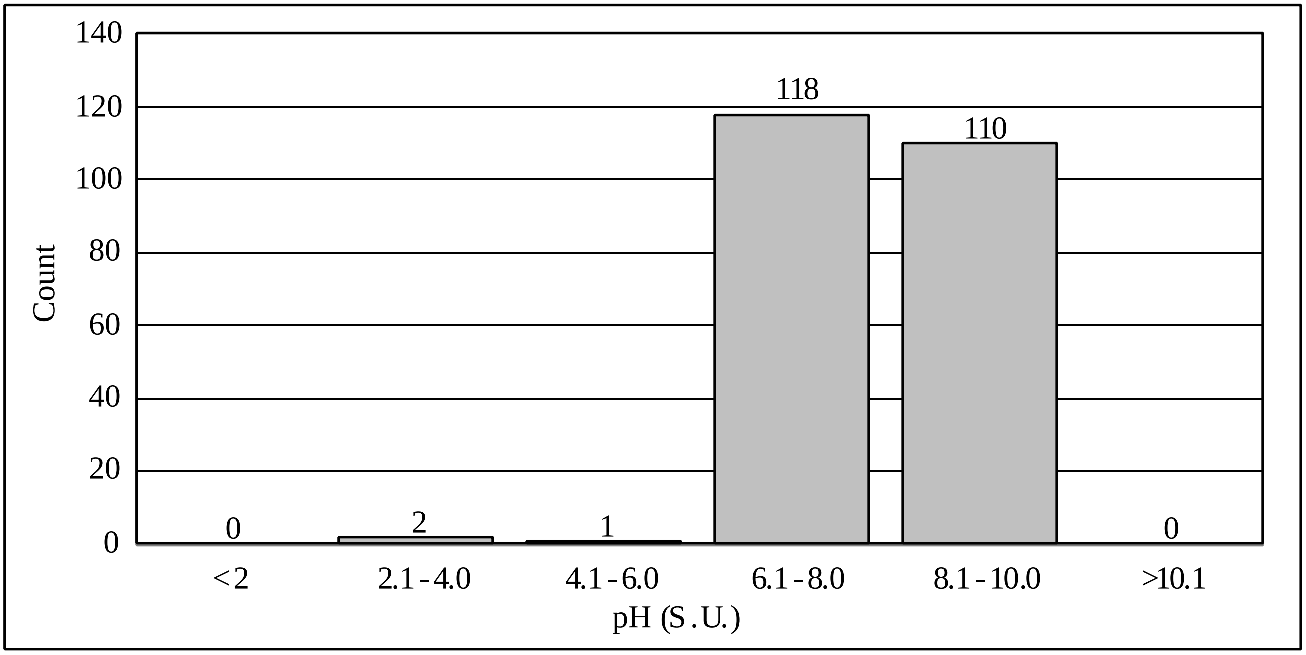


Figure 6. The pH of most spring waters was between 6 and 10.

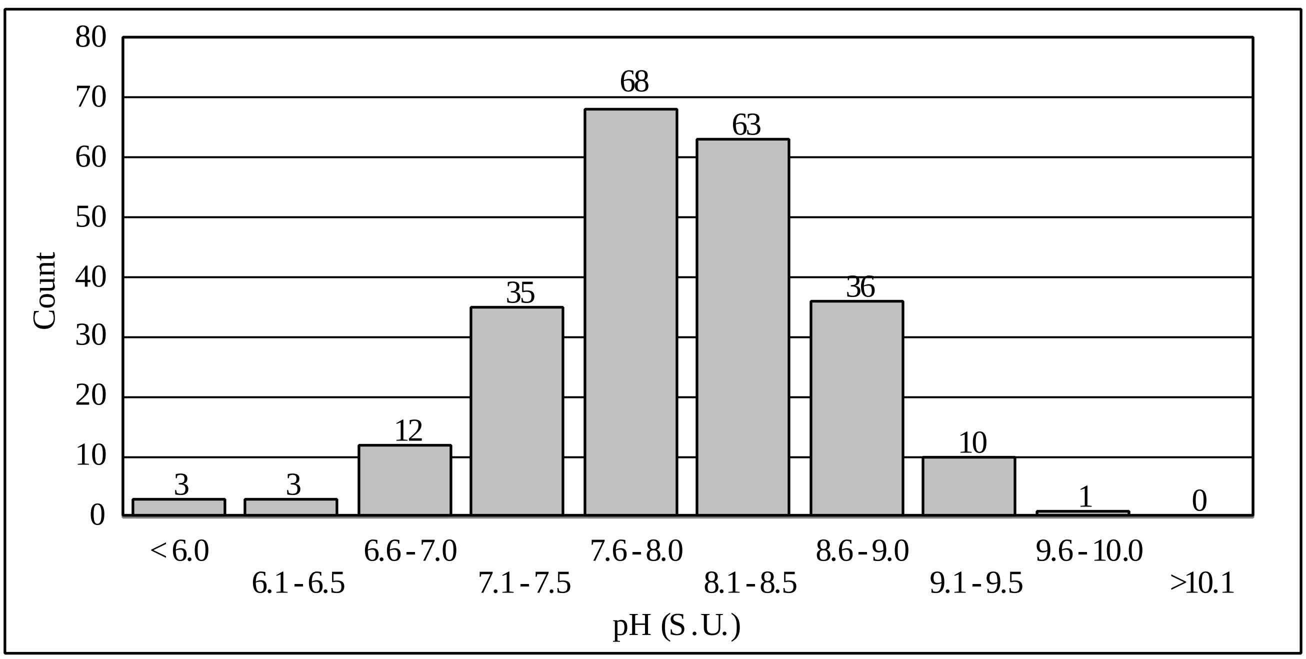


Figure 7. The distribution of pH was nearly normal between 6 and 10.

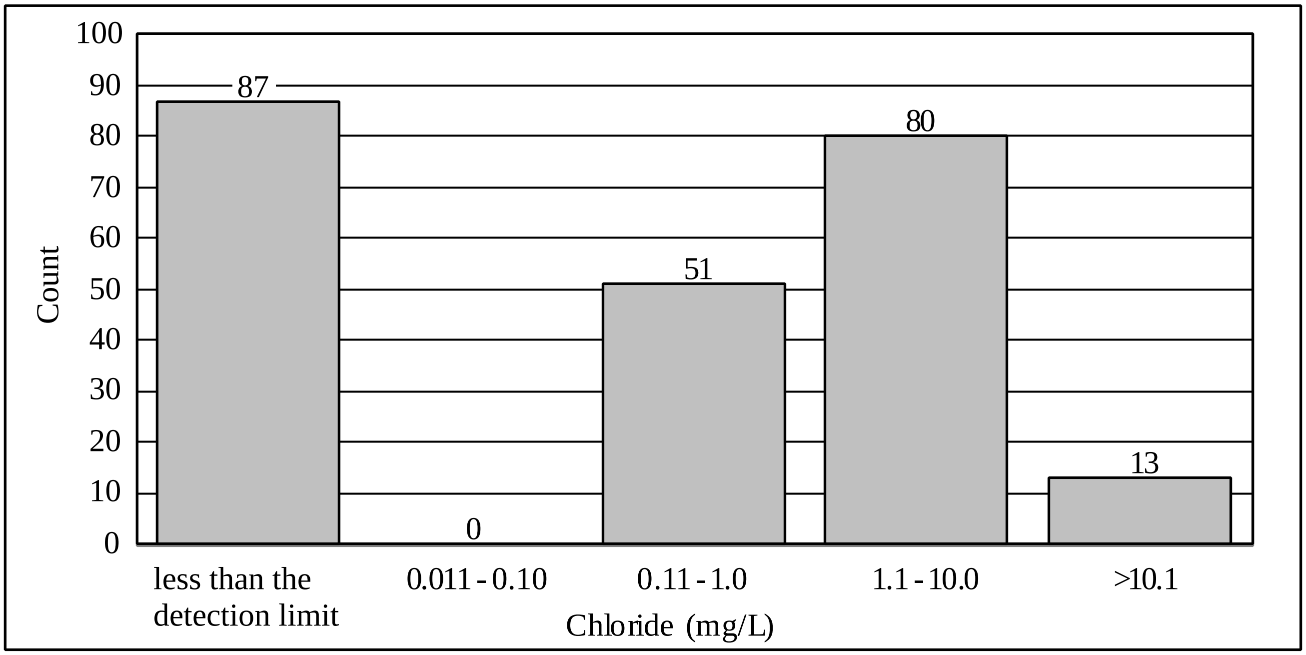


Figure 8. Chloride concentrations ranged from less than the detection limit to about 45 milligrams per liter.

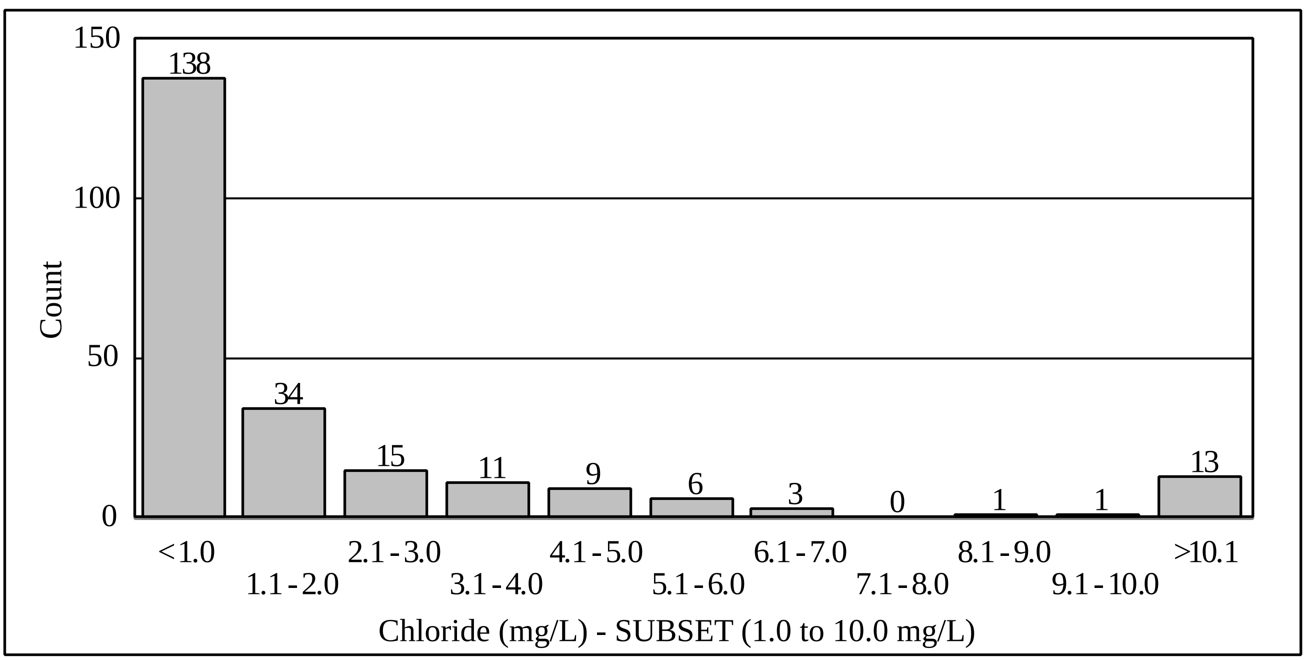
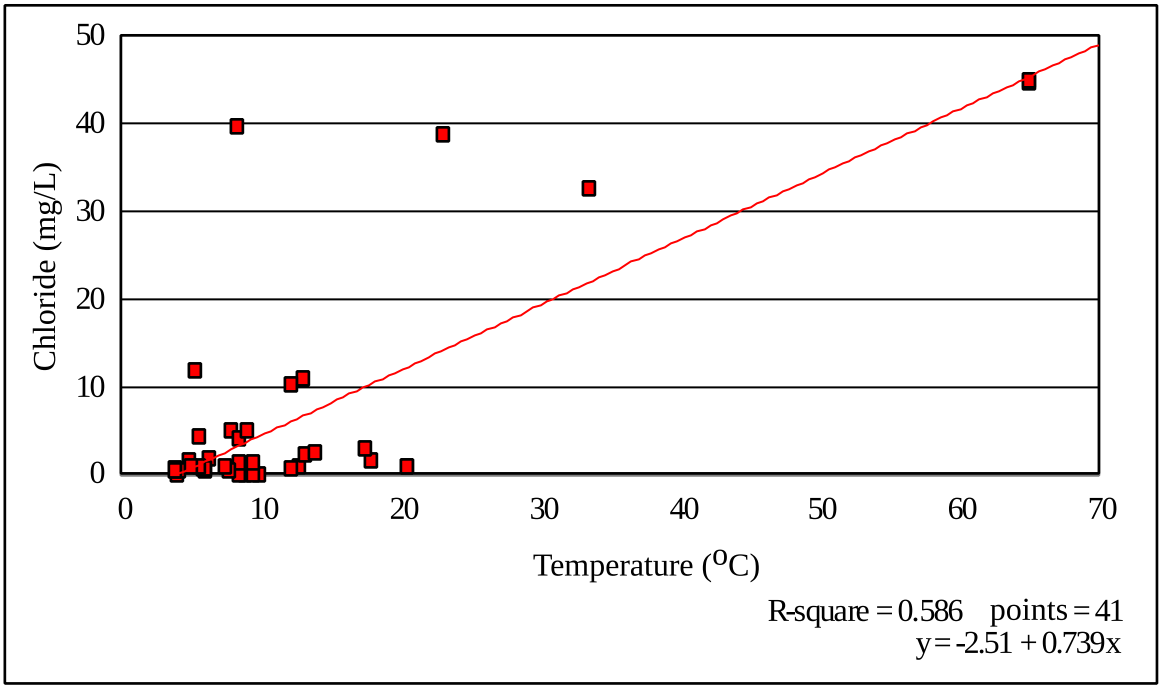


Figure 9. Chloride concentrations less than 1 milligram per liter were by far the most common.



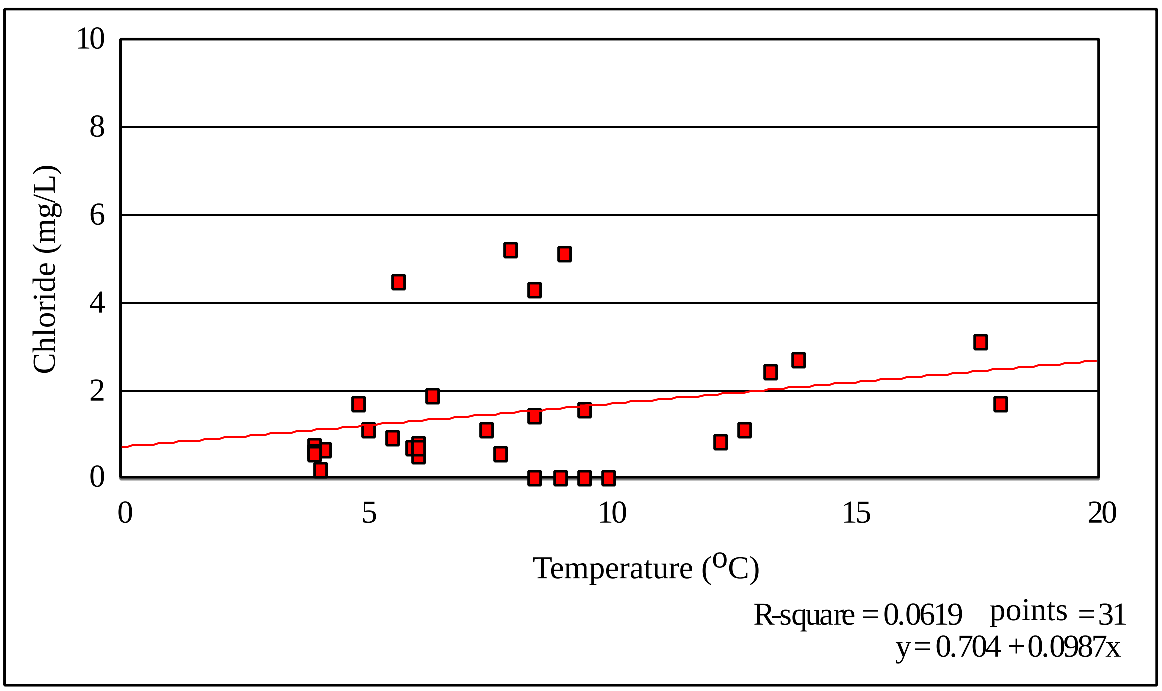


Figure 10. Chloride concentrations show little correlation to temperature for springs in the study area. The top graph shows data for the entire range of concentration and temperatures, the bottom graph limits the analysis to lower concentrations and lower temperatures.

Table 3 presents averages for each of the field values grouped by the three sub-areas within the controlled ground water area. Although the West Yellowstone sub-area is the largest and has the greatest number of springs, the Gardiner area has the greatest number of warm springs, the highest average temperature for all springs, the highest average chloride concentration, and the highest average SC values.

Table 3. Average values for temperature, SC, pH, and chloride for each of the three sub-areas.

Sub-area	Temperature (^{O}C)	Chloride (mg/L)	pH (S.U.)	Specific Conductivity (µmhos/cm @ 25^{O}C)
Cooke City	5.10	0.13	7.69	272
Gardiner	11.28	9.53	7.74	470
West Yellowstone	6.88	2.58	7.92	312

Evaluation of Baseline Data

Spring Water Chemistry

To augment the body of data related to the YCGWA, data from other investigations were compiled and included in the database. These data include well and spring chemistry collected by Rautio and Sonderegger (1980) and Sonderegger and others (1981). The MBMG and U.S. Forest Service collected surface-water data for an abandoned mine inventory of the Gallatin National Forest (Hargrave and others, 2000). Metesh and others (1999) conducted a surface-water / ground-water interaction study within the Soda Butte Creek drainage for the National Park Service. Unpublished studies that produced chemistry data for a variety of surface-water sites (mine adits, seeps, springs, and streams) were also compiled and included in the database.

In this investigation, samples were collected from all springs having water temperatures greater than 15^{O}C, field-chloride concentrations greater than 50 mg/L, or specific conductance values greater than 1000 µmhos/cm. Additional sites were selected based on discharge, multiple users, or geologic source. Still others, particularly those in the Soda Butte Creek drainage, were selected to help establish a baseline chemistry throughout the area. Several of the warm-water springs, including LaDuke spring near Gardiner and Stinky spring near West Yellowstone, had been sampled in the past by other workers, but the opportunity was taken to re-sample them to provide information on temporal changes in chemistry.

A total of 31 spring samples (and 7 QA/QC samples) were collected for this investigation (table 2 and figure 11); an additional 71 samples collected and analyzed for other investigations were compiled for the project database. A partial listing of analytical results is presented in the appendix. Complete results of the chemical analysis, along with all field-data collected for the site, are available through the MBMG Ground-Water Information Database (GWIC) database.

Table 4. List of spring sites sampled for the spring inventory

Source	MBMG ID	TWN	RNG	SEC	Tract	Date
Lower Wapiti spring	179653	09S	04E	19	BBDD	10/05/2000
Micklewright	184263	11S	03E	25	AACA	10/11/2000
USFS	183268	13S	04E	22	DCDB	10/11/2000
Diamond P ranch	184430	13S	04E	22	CDDA	10/11/2000
USFS Black Sands Spring	183242	13S	05E	31	ACDA	10/12/2000
Cole / Dupert	184262	09S	08E	5	ABAB	10/17/2000
Yellowstone River spring	184260	08S	08E	32	DCCC	10/17/2000
Canyon Creek Ranch	184258	07S	06E	35	AAAC	10/24/2000
Cinnabar Creek spring	180879	08S	07E	26	BBBB	10/25/2000
Bear Creek Warm Springs	197921	09S	09E	19	DCBC	10/25/2000
Miller Mountain Mine Adit	184259	09S	14E	26	BDBD	10/26/2000
Cooke Ranger Station spring	167710	09S	15E	29	BABA	10/26/2000
Sharp #16	169046	09S	14E	27	CACD	10/26/2000
Smith	169391	09S	14E	34	BDCC	10/26/2000
LaDuke Spring	171215	09S	08E	32	CACC	10/19/2000
USFS/CUT	171227	08S	07E	13	BBDB	10/03/2000
YNPW-03	179632	10S	05E	2	BDAD	10/05/2000
YNPW-06	179635	10S	05E	19	DBAD	10/05/2000
McCuaig	179644	07S	04E	4	CCCB	10/06/2000
YNPW-07	179655	11S	06E	19	BCDA	10/04/2000
Cinnamon Spring	182010	08S	04E	28	ADBD	10/12/2000
Cedar Creek	182012	08S	07E	12	DBCC	10/19/2000
Corey Springs #1	182014	12S	05E	7	BCCC	10/11/2000
Sheep Camp	183236	09S	03E	10	ABDB	10/05/2000
YNPG spring	183239	07S	04E	20	CDCB	10/05/2000
West Gallatin River spring	183576	07S	04E	20	ADBB	10/05/2000
Basin Cabin	8929	13S	04E	9	DDDD	10/12/2000
Snowflake spring	171216	09S	04E	12	DCAD	7/1/1999
Cooke City spring	163261	09S	15E	30	ABDA	9/24/1997
Silver Gate spring	163259	09S	14E	33	AABD	9/24/1997
Sloan spring	169047	09S	14E	33	DAAD	10/31/1998

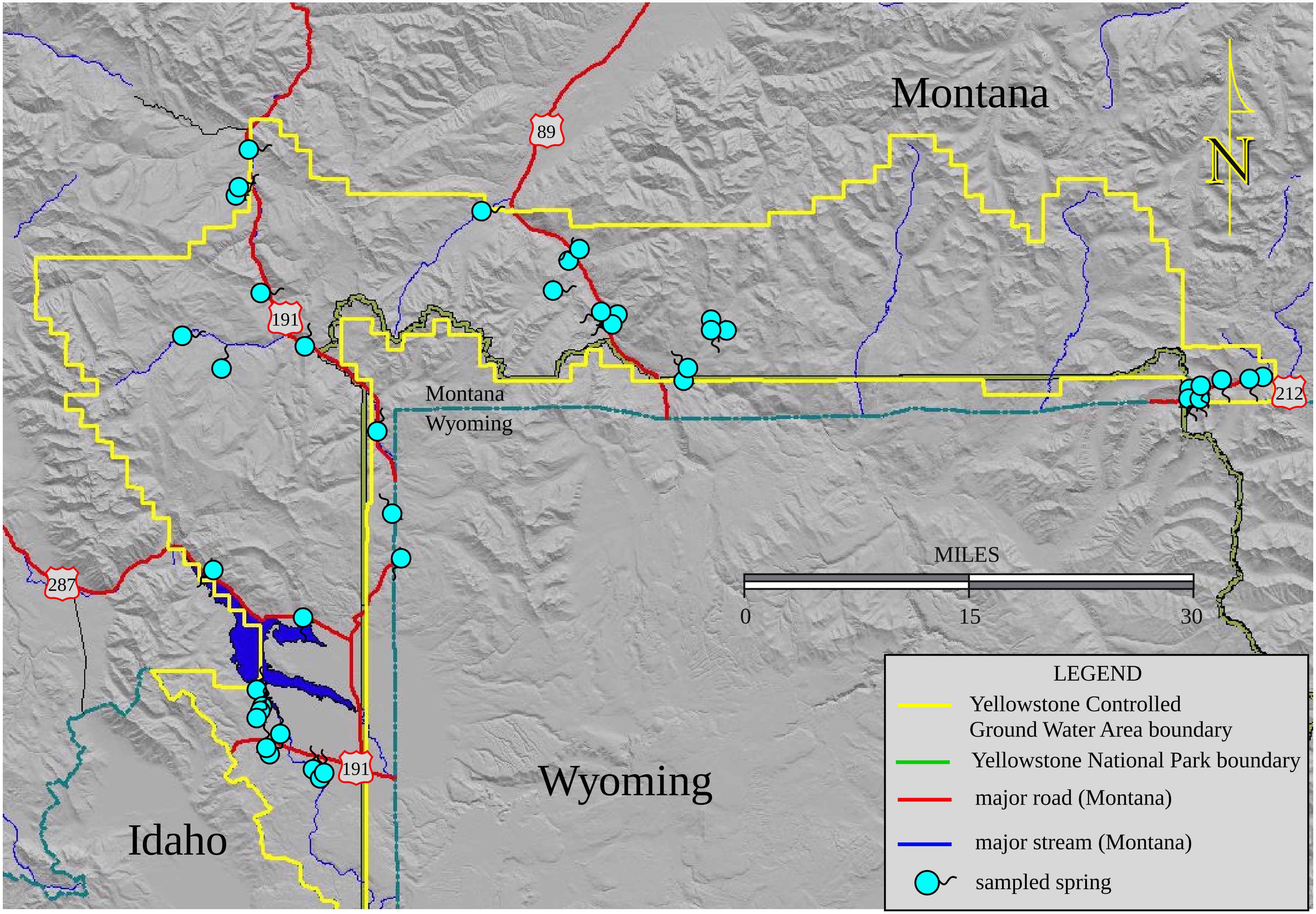


Figure 11. Baseline chemistry data were collected from 31 springs. Results from other sampling, including some sites that lie outside the YCGWA boundary, were incorporated in the evaluation and are also shown. Several sites were sampled twice over a 2- or 3-year period.

The water chemistry of the springs sampled is as varied as the geologic sources. Springs in the Cooke City area are hosted by Archean granite and Paleozoic sedimentary rocks which include limestones and shales. The Gardiner area springs are hosted by Archean granitic rocks, Paleozoic sedimentary rocks, and Tertiary/Quaternary volcanic intrusive and extrusive rocks. In all areas, and particularly in the West Yellowstone area, most springs emerge from unconsolidated Quaternary material such as glacial till or outwash deposits.

Water chemistry also varies within the group of warm springs. Most springs in the Gardiner area, including the CUT spring and Bear Creek spring, are sodium-, calcium-, or magnesium-bicarbonate type water (figure 12). The LaDuke Spring which is in the controlled ground-water area and the Chico Spring which is just north of boundary are calcium-sulfate dominant. The CUT well across the Yellowstone River from LaDuke shows a very similar chemistry; the two springs and the well are calcium-sulfate dominant. Sodium or calcium is the dominant cation in most warm springs and wells (>15^{O}C) in the West Yellowstone area; sulfate is the dominant anion (figure 12).

A Piper plot of warm wells (>15^{O}C) and springs produces a similarly wide scatter of water types. Selected warm wells and springs are presented in figure 13. Sites with the highest total dissolved solids (largest circles), owing particularly to high sulfate concentrations, are the Bear Creek spring, the LaDuke spring, and the CUT well.

Reservoir Temperatures

Several methods to estimate the reservoir temperature have been proposed over the years by several authors; the most widely used are those using dissolved concentrations of silica (as SiO_2), Na-K-Ca, and Na-K-Ca with a correction for Mg; Fournier (1981) presents a good summary of methods and applications. These methods represent semi-empirical equilibrium equations for which the water temperature at the reservoir is calculated. As noted by the authors of the methods, these calculations should be interpreted in consideration of the geologic and hydrogeologic setting. Table 5 presents the results of calculations based on several methods for selected warm wells and springs within the YCGWA and one spring (Chico spring) about 15 miles north of the YCGWA. Sodium, potassium, and calcium concentrations are used to

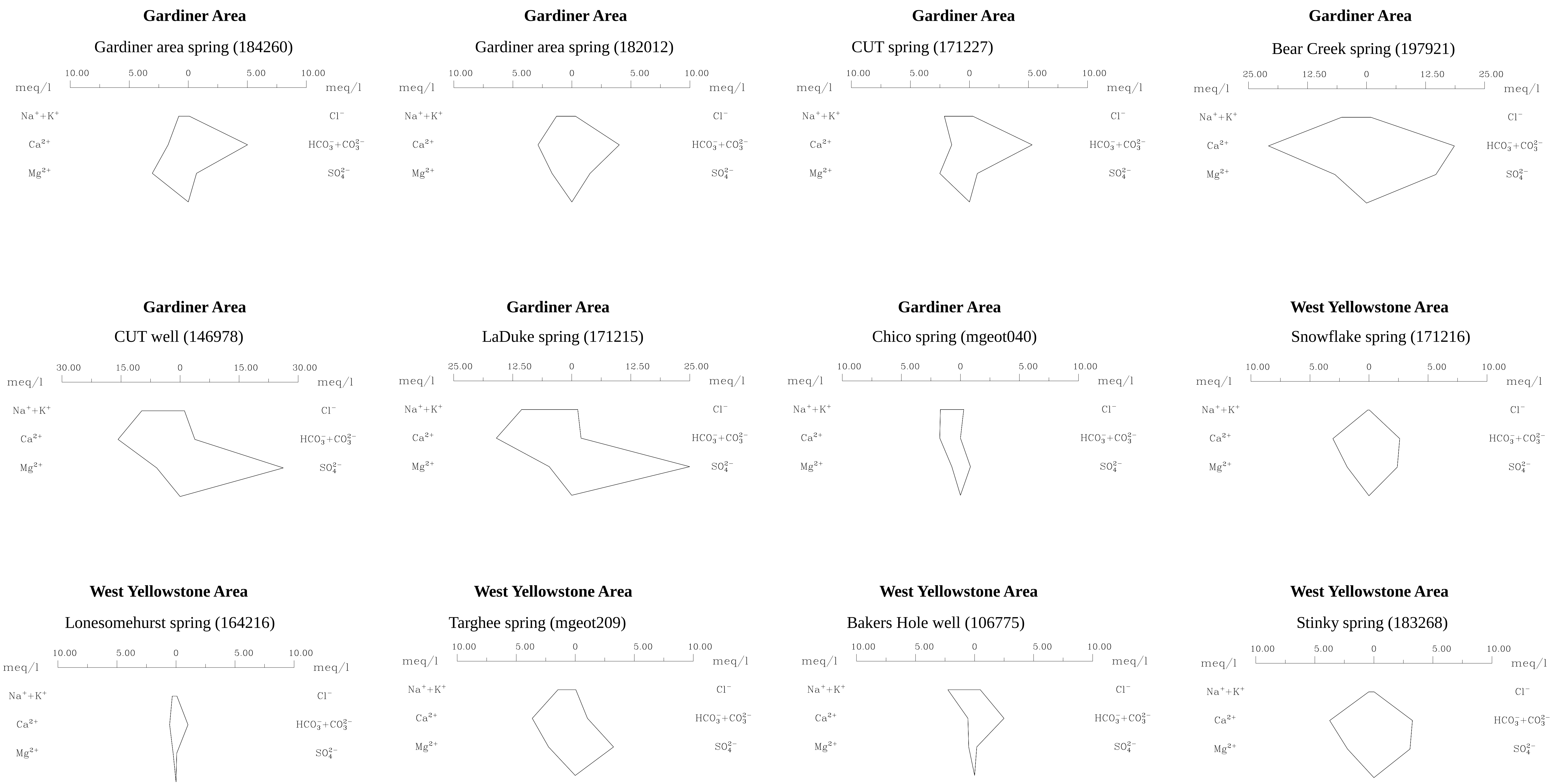


Figure 12. Stiff plots for selected warm water springs and wells show a wide variety of water types.

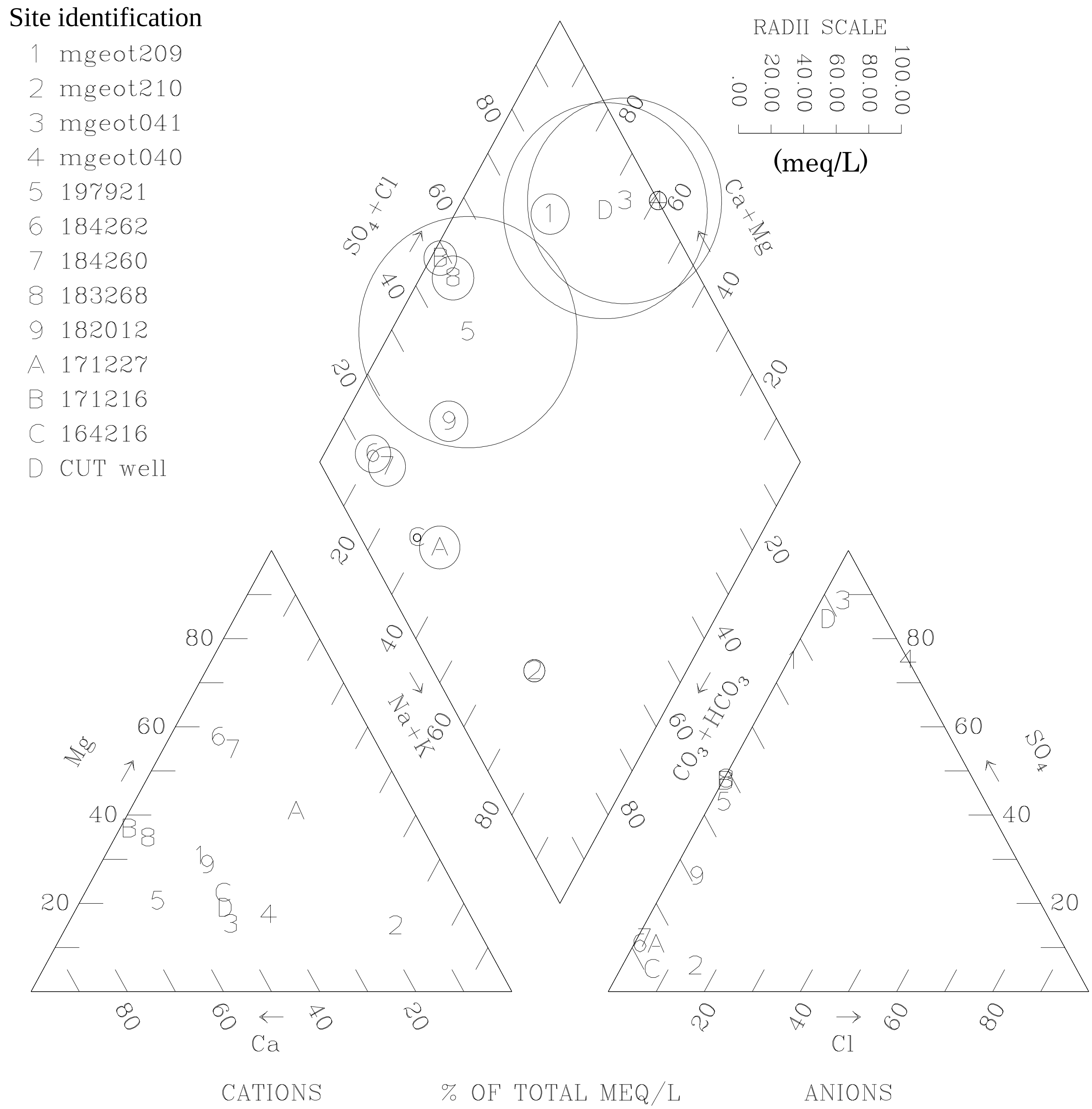


Figure 13. A Piper plot of major cations and anions shows the range of water types in warm-water wells and springs in and near the Yellowstone Controlled Ground Water Area. The radii of the circles in the central area of the diagram are determined by the sum of the cations and anions.

calculate an adjusted reservoir temperature based on the Ca:Na ratio (column 1). These results can be further adjusted for a low-temperature system with a correction based on the magnesium concentration (column 2). Silica concentrations (as SiO_2) are likely controlled by the solubility of chalcedony in geothermal systems having temperatures below about $180^{O}C$ (column 3).

Most models of the Yellowstone Park geothermal system suggest a large, single heat source below the caldera in the central area of the Park. Taken at face value, the large range and standard deviation of the calculated reservoir temperatures in table 5 suggest either several heat sources or a significant amount of mixing between cold and hot ground-water along the flow paths. The wide variation in water chemistry discussed earlier favors a complex mixing model of multiple ground-water flow paths. Regardless of the source of recharge to geothermal system, spring waters discharging from the area north of the Park are at least partially equilibrated with a variety of rock types including Archean granitic rocks, Paleozoic sedimentary rocks, and Tertiary/Quaternary volcanic rocks. Thus, the spring-water chemistry reflects the influence of reservoir temperature, host-rock lithology, travel path, and probable mixing of cold and hot ground water makes the system far too complex to evaluate using a simple model.

Table 5. Calculated reservoir temperatures for selected springs and wells in the YCGWA based on water chemistry. Temperatures are ^{O}C.

Site ID	Site name	Surface Temp (^{O}C)	(1) Na-K-Ca Corrected (^{O}C)	(2) Na-K-Ca Uncorrected (^{O}C)	(3) chalcedony (^{O}C)
8940	Targhee [a]	18.0	25.1	213.9	19.1
106775	Bakers Hole well [a]	16.0	43.7	183.4	97.1
106775	Bakers Hole well (1998) [b]	22.9	33.3	183.3	103.2
171215	La Duke spring [a]	65.0	74.5	161.7	70.9
171215	La Duke spring (2002)	65.0	72.7	161.0	66.4
	Chico Hot Springs [a]	42.0	63.0	183.0	53.6
197921	Bear Creek spring	33.6	76.5	220.7	46.1
184262	Gardiner Area Spring	13.3	29.5	178.9	16.5
184260	Gardiner Area Spring	17.6	34.4	165.6	14.1
183268	Stinky Spring	20.6	27.3	219.7	12.7
182012	McPherson spring	13.1	52.3	193.5	22.0
171227	USFS/CUT	12.2	26.1	181.9	60.1
171216	Snowflake Springs	12.3		209.0	
164216	Lonesomehurst	13.9	48.0	230.4	34.4
	Standard Deviation	17.89	18.69	22.23	31.04

a) data from Sonderegger and others (1981)
b) Metesh and Kougioulis, 2000

Isotope Analyses

Isotope samples were collected from springs that exhibited warm water temperatures, moderate to high SC, moderate to high chloride concentrations (>5 mg/L), and whose geologic sources were unambiguous. All sampling was done in the fall months, several weeks after any precipitation events to avoid contamination by atmospheric or surface water.

$\delta^{18}O$ and $\delta^{2}H$ isotopes

Rye and Trusedell (1992) reported $\delta^{18}O$ values ranging from -18 to -20 parts per mil (‰) and $\delta^{2}H$ values ranging from -125 to -150 ‰ for surface waters and springs in the Yellowstone Park area. Oxygen-18 values from springs in this inventory ranged from -7.48 to -19.15 ‰ (table 6) and $\delta^{2}H$ ranged from -138.0 to -151.7 ‰. Kendall and Coplen (2001) reported $\delta^{18}O$

values of -8 to -24 per mil (‰) and δ^2H values of -100 to -160 ‰ for surface waters in Montana. The slope of these data (5.04) is notably less than that of the global "meteoric water line" (MWL) (8.17) and the values tend to be heavier with respect to $\delta^{18}O$ (figure 13). Similarly, values for springs collected in this investigation are slightly heavier with respect to $\delta^{18}O$ and tend to plot slightly below the MWL (figure 14). One sample (M:183576), from the Gallatin River drainage, exhibits a $\delta^{18}O$ value much heavier than both the other samples and the MWL. In addition to the heavy $\delta^{18}O$ value, the water from this spring exhibits a hardness of 185 mg/L (as $CaCO_3$) and is a calcium-bicarbonate water type (Ca = 2.16 meq/L, HCO_3 = 3.62 meq/L) typical of water in contact with limestone. Cation exchange with $CaCO_3$ is typically thought to cause enrichment of $\delta^{18}O$ but does not affect δ^2H (Drever, 1997); however, waters of similar chemistry in other sites in the study area do not show the marked enrichment.

The addition of results from well samples collected in 1998 (table 7) shows ground water has similar δ^2H and slightly heavier $\delta^{18}O$ values (figure 15). Most of the wells sampled had water temperatures above $10^{O}C$; rock-water interaction with geothermal waters is often thought to cause enrichment of $\delta^{18}O$. In general, the δ^2H results from wells and springs agree well with those found in the northern area of the Park by Rye and Trusedell (1992); values are at or near -150 ‰. Results for $\delta^{18}O$, however, are generally heavier than those reported by Rye and Truesdell and plot off the meteoric water line. Enriched values in surface water samples is usually explained as the result of evaporation. Given that many of these samples are from wells, evaporation is not likely. Alternatively, rock-water interaction in geothermal systems tend to enrich $\delta^{18}O$ while δ^2H is unaffected (Drever, 1997). Minerals within rocks contain abundant oxygen, but very little hydrogen. In process of mineral dissolution, $\delta^{18}O$ in the rock is exchanged for $\delta^{16}O$ in the water; the rock becomes depleted and the water becomes enriched with respect to $\delta^{18}O$. Cooling of the water as it flows out of the geothermal system has little effect on either $\delta^{18}O$ or δ^2H and thus, the signature is preserved.

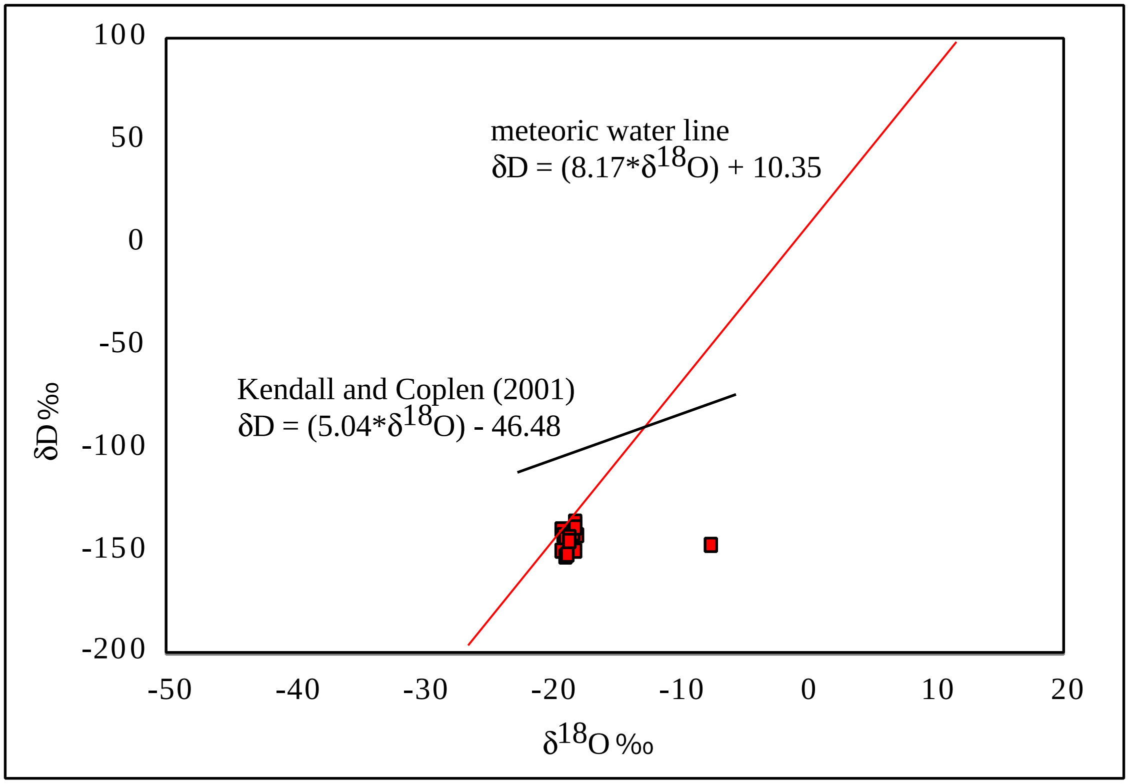


Figure 14. Deuterium - ^{18}Oxygen isotope results from springs cluster near the meteoric water line. A single sample from the Gallatin River drainage indicates much heavier oxygen. This typically is due to interaction with calcium carbonate.

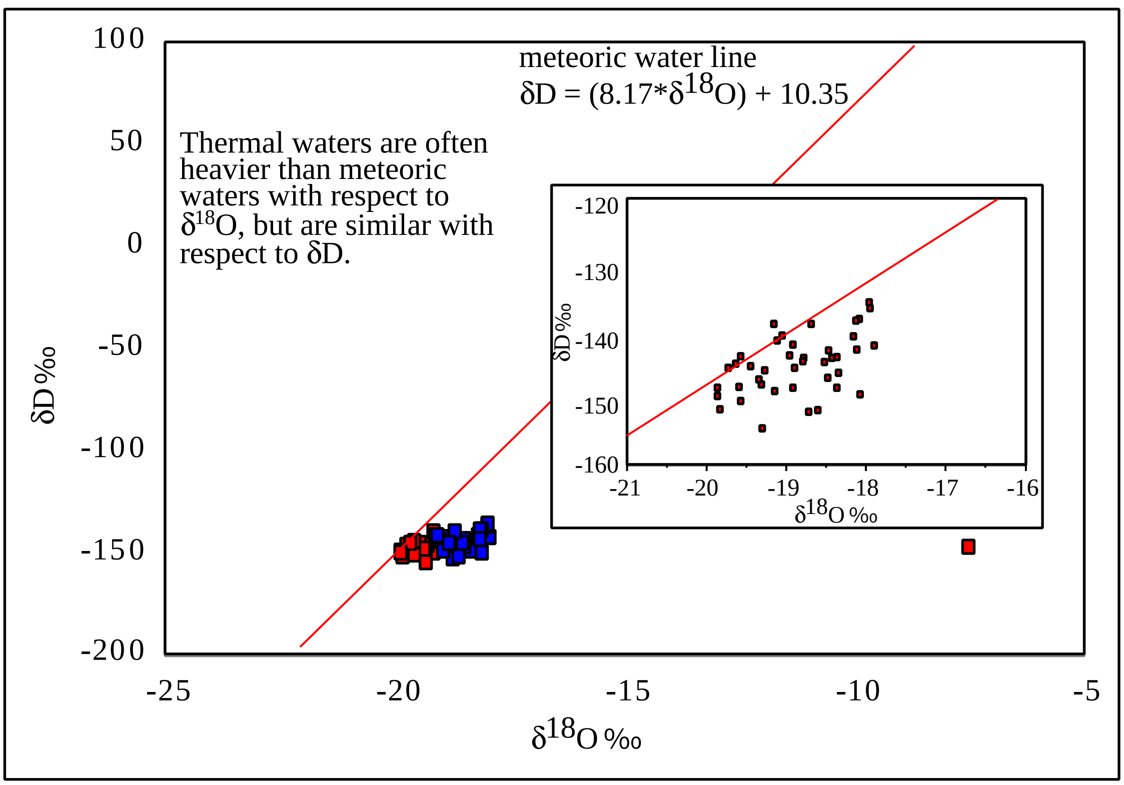


Figure 15. A comparison of Deuterium - ^{18}Oxygen isotope results from springs and wells indicates a tendency for enrichment of oxygen in wells. Deuterium values in wells are similar to those in springs and are near the meteoric water values. The inset shows the data at an expanded scale.

Tritium isotopes

Tritium (^3H) is a radioactive isotope of hydrogen and has a half-life of 12.45 years in the atmosphere. Nearly all of the tritium in the atmosphere and water on the planet is a result of above-ground nuclear-weapons testing that began in the 1950's. Background, “pre-bomb”, atmospheric tritium levels measured in rain water have been estimated to be 5 to 10 tritium units (TU, [3.23 picocuries/Liter]). The level increased to more than 1,000 TU in the United States during the peak of testing in 1963 and has since declined to a range of 20 to 100 TU depending on geographic location (Drever, 1997). In general, tritium values less than 0.5 TU indicate pre-1952 age and values greater than 10 TU indicate post-1952 age. Tritium values between 0.5 and 10 TU are likely to be a mixture of pre- and post-1952 waters (Drever, 1997) or a result of mixing. In many ground-water flow systems there is the potential for mixing; the tritium values in these cases are of limited use without a defined flow path.

Tritium values for springs in this study ranged from less than detection (6.0 TU for standard tritium analysis) to 14.0 TU, with a precision of 8 TU. Several sites were re-sampled and other sites sampled one time only as part of another study; these samples were analyzed using the enriched-tritium method that provides lower detection limits (table 6) as well as better precision. Table 7 presents tritium values for wells sampled in 1998. These values range from less than detection (6.0 TU) to 39 TU; samples from wells in the same area as springs generally showed slightly higher tritium values.

Ten of the 27 springs sampled and 13 of the 18 wells sampled have tritium values greater than 10 TU. Although the warmest waters show little or no tritium, several warm springs show tritium values greater than background. These findings suggest an apparent age of less than 50 years which conflicts with the widely accepted model of deep, very old recharge waters being the source for hot springs in the Yellowstone area. As suggested by the chemistry, however, there remains the possibility of these older waters mixing with younger, tritiated water along the discharge flow path.

Table 6. Isotope data from springs in the YCGWA (maps of sample locations are in the appendix).

Site ID	**Site name**	**Temp** (^{O}C)	**Sample Date**	**^{18}O(‰)** SMOW	**^{2}H** (‰)	repeat	**^{3}H** (T.U)	precision	repeat
8929	USFS	7.3	10/12/2000	-17.90	-142.0	-141.6	<6	+/- 8	
167710	Cooke Ranger Station	5.8	10/26/2000	-19.15	-138.7	-137.7	7	+/- 8	
171215	Laduke Hot Springs	65.0	10/19/2000	-18.37	-143.8	-142.3	<6	+/- 8	
	Enriched ^{3}H	61.6	09/25/2002				<0.8	+/-0.6	
179632	YNP * Spring	6.1	10/05/2000	-18.43	-143.9	-142.4	<6	+/- 8	
179635	YNP * Spring	4.2	10/05/2000	-17.95	-136.4	-136.9	18	+/- 8	
179653	USFS * Wapiti Spring	5.7	10/05/2000	-18.34	-146.1	-146.2	25	+/- 8	16 +/- 8
179655	YNP * Spring	5.4	10/04/2000	-17.96	-135.5	-136.0	12	+/- 8	
182012	Spring	13.1	05/28/2000	-18.36	-148.3	-148.2	<6	+/- 8	
	Enriched ^{3}H	12.0	09/25/2002				1.3	+/-0.6	1.96 +/-0.6
182014	Spring	7.6	10/11/2000	-18.92	-141.9	-141.7	<6	+/- 8	
183236	Sheep Camp	6.1	07/19/2000	-18.78	-143.9	-143.7	<6	+/- 8	
	Enriched ^{3}H	4.5	09/23/2002				11.6	+/-1.0	
183239	Spring	6.1	10/05/2000	-19.14	-148.9	-149.1	22	+/- 8	19 +/- 8
183242	Black Sand Spring	9.1	05/29/2000	-18.16	-140.6	-140.3	20	+/- 8	
183268	Stinky Spring	16.6	10/11/2000	-18.08	-138.0	-139.0	<6	+/- 8	
	Enriched ^{3}H	17.0	09/24/2002				<0.8	+/-0.6	
183576	Spring	6.4	10/05/2000	-7.48	-146.4	-148.2	9	+/- 8	
184258	Spring	8.5	10/24/2000	-18.48	-146.9	-147.0	<6	+/- 8	
184259	USFS * Miller Mtn	4.1	10/26/2000	-18.47	-142.8	-144.7	13	+/- 8	18 +/- 8
184260	Spring	15.1	10/17/2000	-18.72	-152.0	-150.8	<6	+/- 8	
	Enriched ^{3}H	15.0	09/25/2002				4.4	+/-0.7	
184261	Bear Creek Spring	23.1	10/25/2000	-18.07	-149.4	-149.0	7	+/- 8	
184262	Spring	13.3	10/17/2000	-18.60	-151.7	-149.7	<6	+/- 8	
184263	Spring		10/11/2000	-18.52	-144.5	-143.5	13	+/- 8	
181930	Beaver Cr **Enriched ^{3}H**	5.1	09/23/2002				9.3	+/-0.9	
182679	Spring **Enriched ^{3}H**	9.9	09/27/2002				9.3	+/-0.9	
197957	Spring **Enriched ^{3}H**	4.2	09/24/2002				14.0	+/-1.2	11.8 +/-1.1
181621	Spring **Enriched ^{3}H**	14.8	09/25/2002				3.9	+/-0.7	4.7 +/-0.7
164216	Spring **Enriched ^{3}H**	8.8	09/24/2002				10.2	+/-1.0	
197921	Bear Cr **Enriched ^{3}H**	33.6	09/26/2002				6.4	+/-0.8	
171228	Spring **Enriched ^{3}H**	9.8	09/25/2002				1.2	+/-0.5	

Table 7. Isotope data from wells in the YCGWA (after Metesh and Kougioulis, 2000; maps of sample locations are in the appendix).

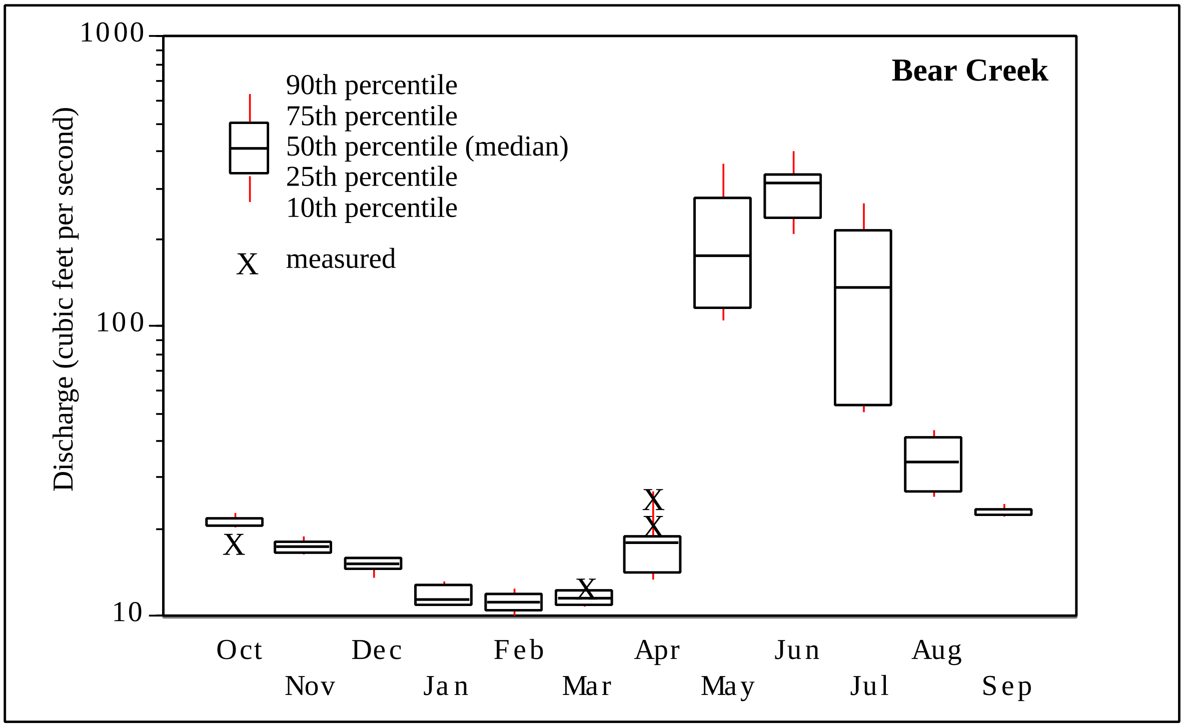
Site ID	**Site name**	**Temp** (^{O}C)	**Sample Date**	**^{18}O**(‰) SMOW	**^{2}H** (‰)	**^{3}H** (T.U)		precision
105980	Gardiner Airport	11.1	05/28/1998	-18.96	-143.5	33	+/-	8
106598	Well	6.5	06/10/1998	-19.27	-145.7	39	+/-	8
106726	Well	12.9	06/12/1998	-19.31	-154.4	13	+/-	8
106737	USFS	9.4	06/10/1998	-18.89	-145.4	16	+/-	8
106775	Baker Hole Camp	23.1	06/09/1998		-148.4			
		22.9	06/09/1998	-19.59	-148.2	<6	+/-	8
106853	Wwell	9.6	06/17/1998	-19.11	-141.2	23	+/-	8
134029	CUT	12.4	06/10/1998			<6	+/-	8
		12.1	06/10/1998	-18.92	-148.4	<6	+/-	8
137132	Well	3.9	09/28/1998	-18.69	-138.8	27	+/-	8
140290	Well		09/18/1998	-18.79	-144.4	12	+/-	8
144533	Well	5.4	08/27/1998	-19.45	-145.1	8	+/-	8
146964	Well B	7.6	06/04/1998	-19.85				
		7.7	06/04/1998	-19.83	-151.6	15	+/-	8
152503	Well	5.1	07/08/1998	-19.73	-145.3	24	+/-	8
157970	Well	9.5	06/10/1998	-19.31	-147.9	7	+/-	8
158049	Well	11.8	06/16/1998	-19.05	-140.5	10	+/-	8
158183	Well	7.5	06/17/1998	-18.13	-138.3	20	+/-	8
163260	Well	4.4	09/28/1998	-19.34	-147.1	8	+/-	8
8925	Well	13.2	06/18/1998	-19.57	-150.4	9	+/-	8
157967	Well	11.4	06/18/1998	-19.86	-148.4	15	+/-	8
		11.4	06/18/1998		-148.9			
999999a	Well			-19.57	-143.6	8	+/-	8
				-19.63	-144.7			
133389	Well	11.4	06/17/1998	-19.86	-149.6	12	+/-	8
			06/17/1998		-151.6		+/-	8
74340	Well	11.7	07/08/1998	-18.12	-142.6	<6		

Stream Low-Flow Investigation

The largest watersheds within the area include the upper Madison River, the South Fork Madison River, and the upper Yellowstone River, which flow out of the Park; and Bear Creek, Hellroaring Creek, Slough Creek, and Soda Butte Creek which flow into the Park (figure 1). To provide information on the relative water contribution of watersheds in the YCGWA, a limited low-flow study was conducted. Stream low-flow occurs when the water flowing into a stream is comprised only of discharge from ground water; neither surface runoff nor precipitation contributes to the flow in the stream. In high-elevation, snow-dominated watersheds such as those of the greater Yellowstone area, low flow usually occurs in the early spring just prior to the spring snow melt.

Metesh and others (1999) provide a detailed discussion of surface-water / ground-water interaction and the timing of low flow in the Soda Butte Creek drainage. In that investigation, domestic wells and several surface water stations were selected, surveyed, and monitored over a 2-year period to quantify ground-water and surface-water discharges. Such data do not exist for the other watersheds in the controlled ground water area. Thus, stream low-flow data were used to estimate of ground-water discharge for each watershed.

Streamflow in Soda Butte Creek at the Northeast Entrance to the Park and Bear Creek near its confluence with the Yellowstone River has been monitored for the past 3 years (1999 - 2002) by the U.S. Geological Survey. Additional measurements of flow in these streams, coincident with measurements in Hellroaring and Slough Creeks, were made for this investigation. Figure 16 presents box plots of percentile ($Y_{(P)}$) or probability of non-exceedance where, for example, the 90^{th} percentile is equivalent to 10 percent probability of exceedence. The 90^{th}, 75^{th}, 25^{th}, and 10^{th} percentiles were calculated from daily streamflow measurements at USGS gage stations nearest the Yellowstone Park boundary.



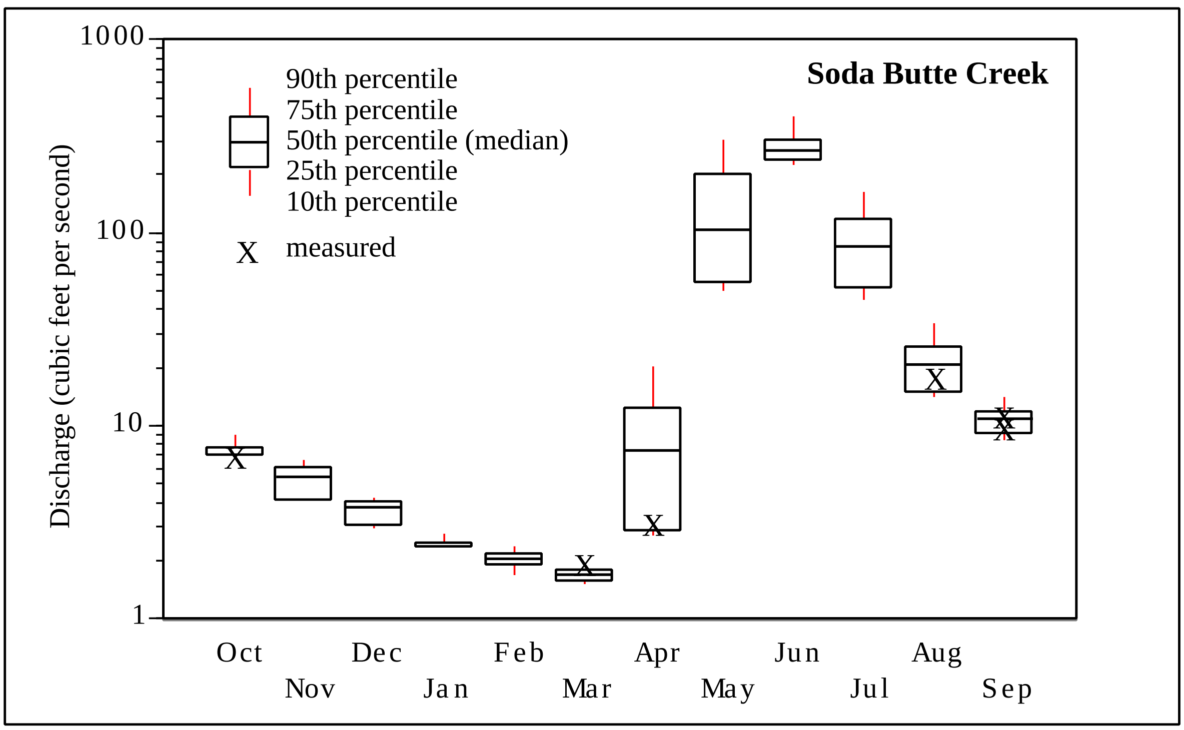


Figure 16. Box plots of monthly discharge for Bear Creek at its confluence with the Yellowstone River (top) based on 3 years of records; and Soda Butte Creek at the Northeast Entrance (bottom) based on 3 years of records.

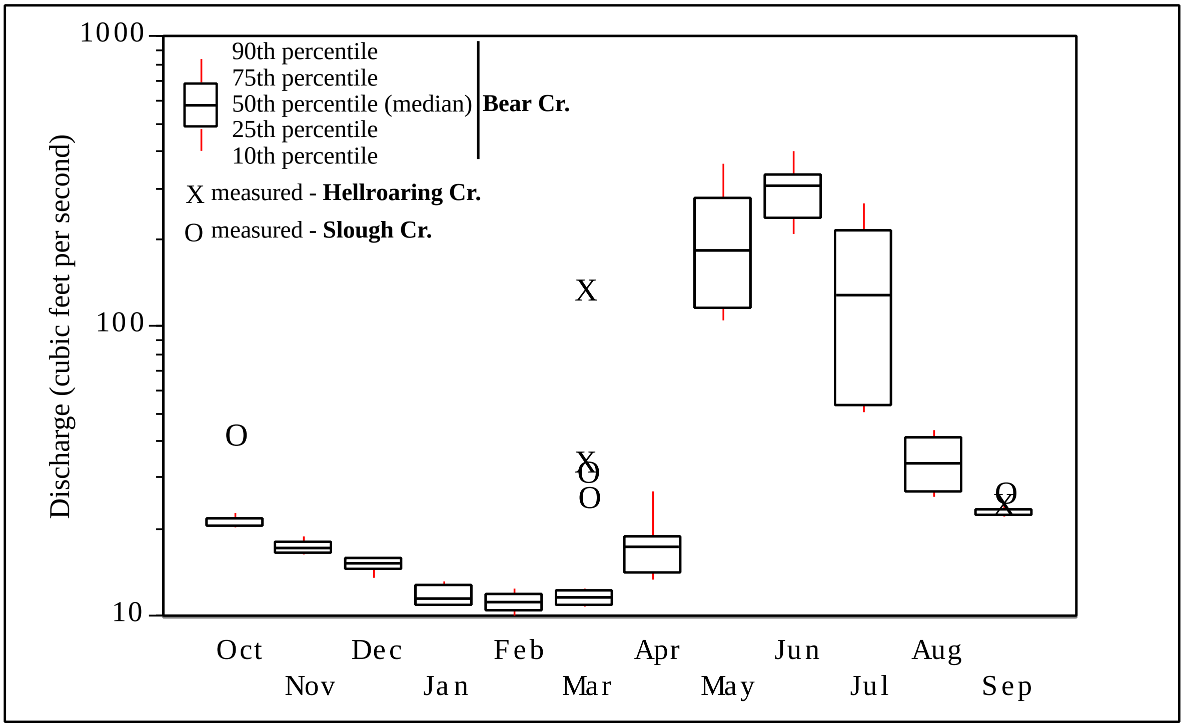
Secondary measurements (X) agree well with data from both watersheds. The poorest correlation coincides with the April measurements when snow melt varies considerably from day to day. In both watersheds, low flow occurs in late February to early March.

Measuring low flow during March in Slough and Hellroaring Creeks was particularly difficult due to access. It generally required a full day ski or snowshoe trip into the drainage; if the trip was made too early, the stream was buried under snow; if too late, the stream discharge reflected snow melt. The trip into these drainages was timed with the first exposure of streamflow in Soda Butte Creek near Silver Gate. Figure 17 compares streamflow in Hellroaring Creek and Slough Creek, measured in 1999 and 2000, to the box plots of Bear and Soda Butte Creeks. The March 2000 measurement for Hellroaring Creek was made after runoff had begun in that drainage; Slough Creek and Soda Butte Creek were still at or near low-flow conditions. Not reflected on the graphs are attempts to measure streamflow in late February and early March; the streams were not exposed during these attempts. Similarly, measurements in April were not made due to dangerously high streamflow in both years. These limited results suggest a low flow of about 20 cfs for Slough Creek and about 30 cfs for Hellroaring Creek.

Figure 18 presents the results of the same method applied to data from the Madison River near West Yellowstone, the Gallatin River at Gallatin Gateway, and the Yellowstone River near Gardiner. Low flow for these rivers is not well defined owing to their large drainage area and recharge by geothermal waters within the Park and YCGWA. Table 8 presents a summary of low-flow discharge for each of the major drainages.

Table 8. Summary of estimated low flow values for the major drainages of the controlled ground water area.

Drainage	Area (square miles)	Estimated low flow (cfs)
Soda Butte Cr. above NE entrance to YNP	28	2
Slough Cr. above state boundary	158	20
Hellroaring Cr. above state boundary	157	30
Bear Cr. above Yellowstone R.	84	11
Yellowstone R. above state boundary	2,594	840
Gallatin R. above Gallatin Gateway	825	305
Madison R. above West Yellowstone	420	400



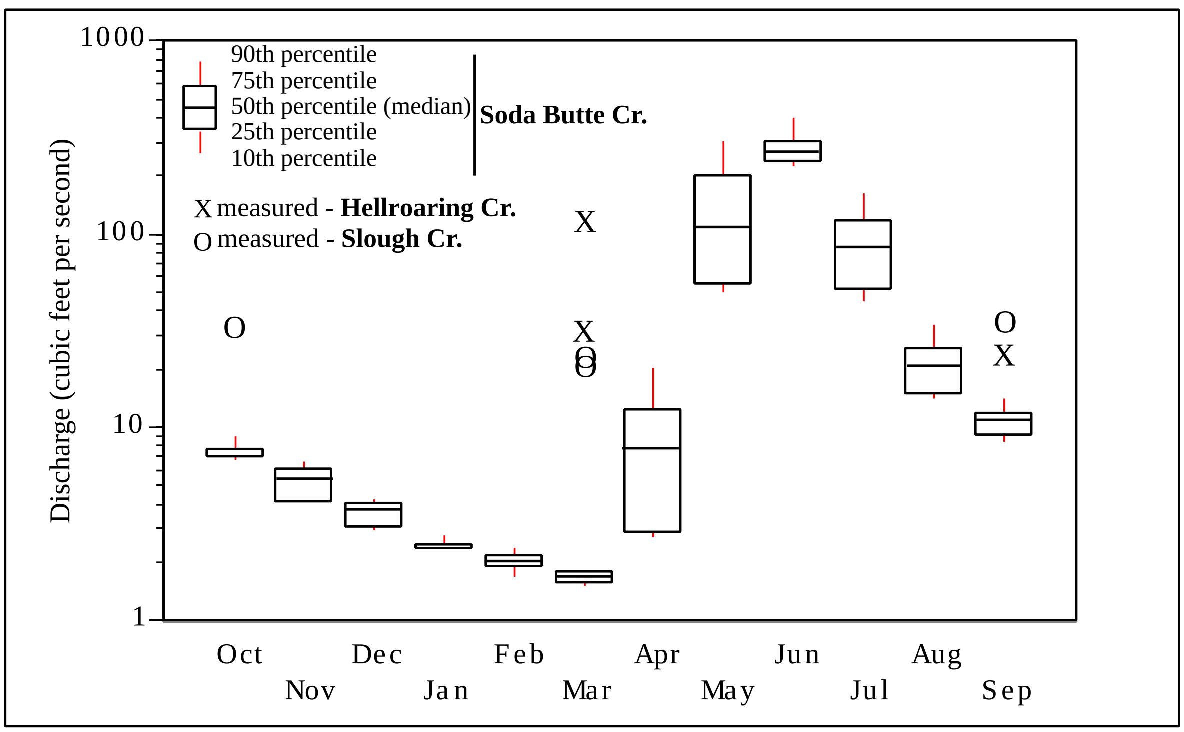
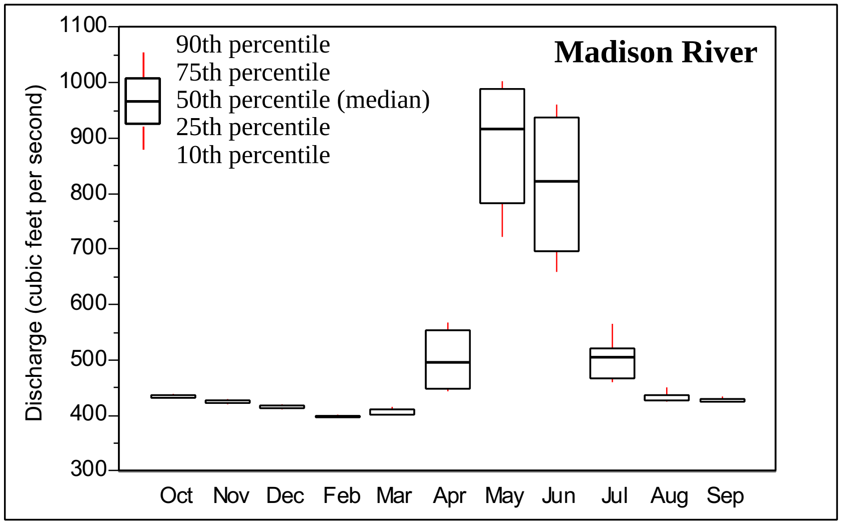
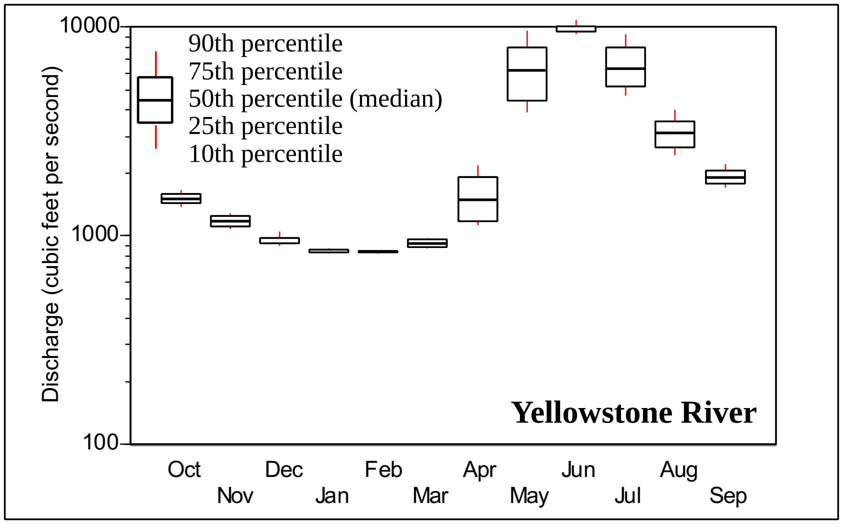


Figure 17. Box plots of monthly discharge for Bear Creek (top) and Soda Butte Creek (bottom) with data from Hellroaring Creek (X) and Slough Creek (O) for comparison.





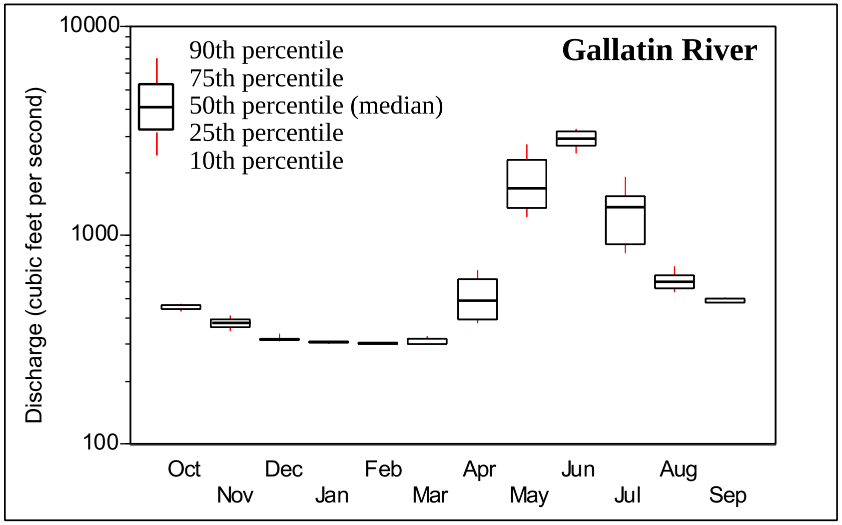


Figure 18. Box plots of monthly discharge for the Madison River near West Yellowstone (top) based on 78 years of records, the Gallatin River at Gallatin Gateway (bottom) based on 75 years of records, and the Yellowstone River near Gardiner (right) based on 98 years of records.

Long-term Monitoring of Springs and Wells

Mandate

The inventory of wells in the YCGWA identified about 600 sites; the present inventory of springs identified about 230 sites (figure 19). Section H.2.a of Article IV of the Water Rights Compact between the State of Montana and the National Park Service (Compact) provides for a monitoring program by the Montana Bureau of Mines and Geology (MBMG) in consultation with the Technical Oversight Committee (TOC). This section further states that the Working Group Report (Custer and others, 1993) will be used as a guide for selection of sampling sites and frequency until superseded by recommendations of the TOC. The Working Group observed in 1993 (p. 20) that "If no funds are allocated for characterization, flow line, or long-term reference data collection, one would have to question the commitment to protect the hydrothermal system in the Park." A detailed monitoring program has been submitted to the National Park Service and is summarized here.

Recommendations

The Working Group emphasized the need for long-term monitoring of wells and springs both inside and outside the park boundaries. The TOC identified the critical issues to be addressed through monitoring:

1) Evaluation of the relationships between warm and cold wells and springs.
2) Monitoring encourages discovery, inventory, and assessment of unregistered new wells.
3) Identification and evaluation of changes in wells and springs through time.
4) Identification and evaluation of spatial relationships of wells and springs through time.

All wells with water temperatures greater than or equal to 15^{O}C (59^{O}F) should be monitored and the data collected should include water levels, alkalinity, specific conductance (SC), chloride, pH, oxidation-reduction potential (ORP), and water temperature. At present, there are 10 known wells in the YCGWA with water temperatures greater than 15^{O}C (59^{O}F). In addition to warm water wells, the TOC recommended monitoring an additional five wells with water temperatures less than 15^{O}C (59^{O}F). The cold water sites will provide baseline response to climatic and anthropogenic changes and provide insight into changes due to climate or development that might influence warm springs.

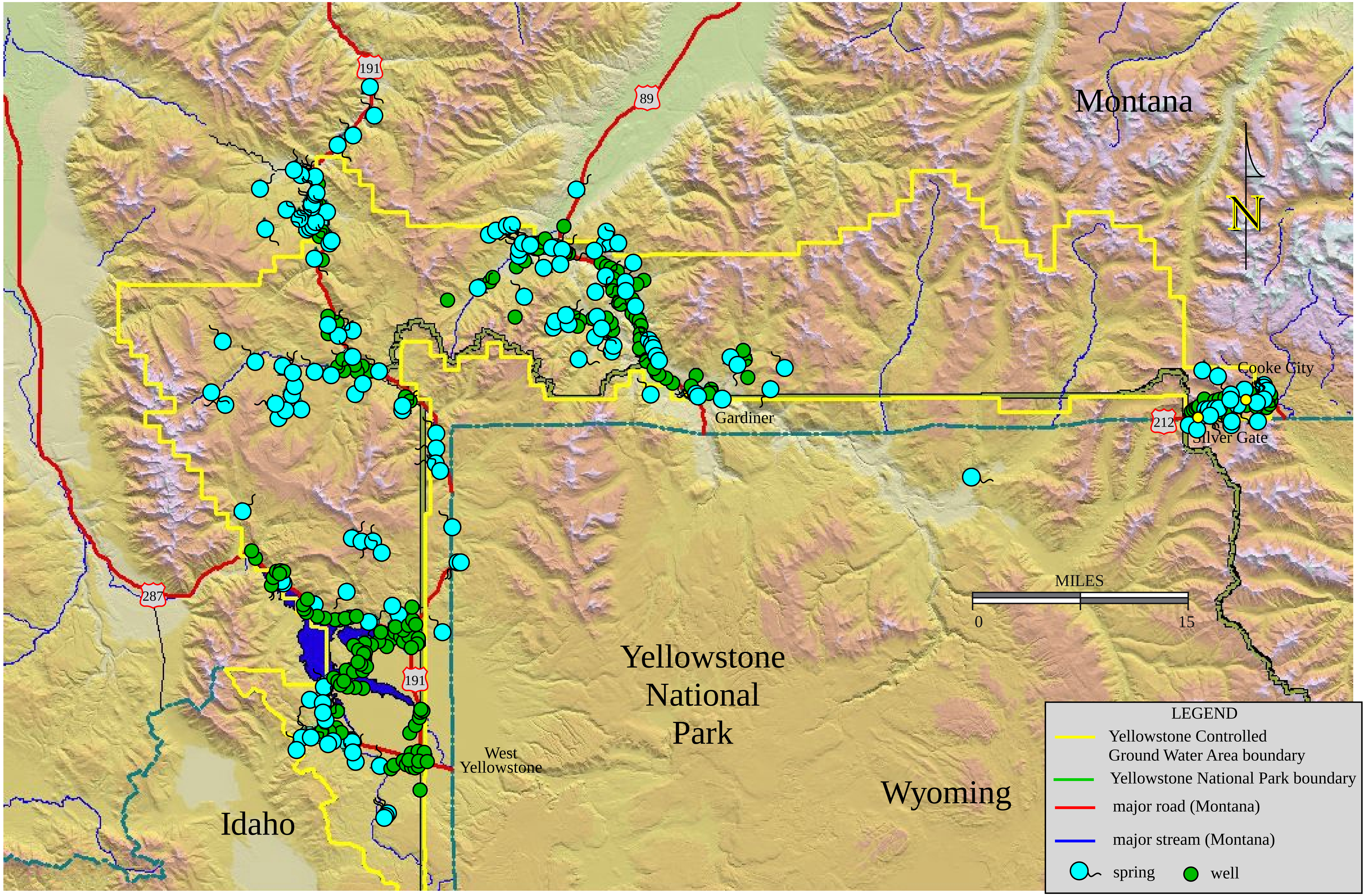


Figure 19. There are about 600 wells (as of 1998) and 330 springs identified (as of 2001) within the Yellowstone Controlled Ground Water Area.

As with wells, all springs with water temperatures greater than or equal to 15^{O}C (59^{O}F) should be monitored. Data to be collected at each site should include spring discharge and those same types of data that are collected at well sites. Fifteen springs were identified has having temperatures greater than 15^{O}C (59^{O}F) in one or more measurements. An additional five cold water springs were selected to provide baseline response to climatic and anthropogenic changes.

Long-term chemistry data provide another valuable tool for evaluating changes to the hydrologic system. Data from the baseline inventory have shown a wide range of concentrations of dissolved constituents. The TOC recommended that the monitored sites also be evaluated with respect to changes in chemistry, both spatially and temporally. Inorganic chemistry and isotope data should be collected from all of the monitoring sites. Maps of springs and wells inventoried, sampled, and those proposed for monitoring are provided in the appendix.

The monitoring program is intended to provide a baseline data set to evaluate the potential effects of anthropogenic activities and natural phenomena both inside and outside the Park. With concern for the potential for large-scale housing or industrial development near the Park, the TOC further recognized the need for additional investigations. If a large-scale natural phenomenon such as an earthquake, volcanic eruption, or large fire occurs, rapid monitoring will be needed to understand such events in the context of long-term monitoring. Over the long term, it is inevitable that changes to the geothermal system in the Park will occur; without monitoring data throughout the greater Yellowstone area, the causes of these changes, whether man-caused or natural, will remain undetermined.

Summary

An inventory of springs in the Yellowstone Controlled Ground Water Area produced about 230 individual developed and undeveloped sites that produce a sustained flow. An earlier inventory of wells indicated approximately 600 sites. Springs and wells in the area reflect their proximity to the large geothermal complex of Yellowstone National Park. While the majority of the springs and wells have water temperatures less than what would be considered geothermal (>15^{O}C), there is often evidence of a geothermal history or influence by geothermal waters. This is particularly true for sites near Gardiner and south of the Madison River near West Yellowstone. The basic chemistry of the springs and wells sampled indicate a wide range of rock-types and flow paths. The isotope chemistry from the sampled springs show a range of values for δ^{18}O that suggest enrichment by interaction with rocks along the flow path; δ^{2}H results generally agree with those from previous studies in the area. Tritium values are also varied and, in some cases, suggest short flow paths from the recharge area for several springs. The inventory and baseline sampling of wells and springs cannot define the relationship between the geothermal system of the Park and the YCGWA, nor can it be used to evaluate pre-existing trends caused by climate changes and anthropogenic activities. The data collected for this study will, however, provide baseline for evaluating future changes.

The inventory and baseline sampling effort reflects only conditions present at the time those data were collected. Only long-term monitoring of springs and wells in the controlled ground water area and inside the Park will provide the basis for establishing trends and evaluating impacts both potential and realized.

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Appendix
Selected Chemistry of Springs in the YCGWA

mnumber	sample_id	site_name	township	range	section	tract	sample_date_	latitude	longitude	water_temp	inventory_pr	type
179653	2001Q0759	USFS * WAPITI SPRING W05500600	09S	04E	19	BBDD	10/5/2000 13:	45.0403	-111.2858	5.7	YNPWSPR	SPRING
184263	2001Q0791	MICKLEWRIGHT FAMILY TRUST	11S	03E	25	AACA	10/11/2000 11	44.8514	-111.2981		YNPGSPR	SPRING
183268	2001Q0788	STINKY SPRING	13S	04E	22	DCDB	10/11/2000 13	44.681	-111.2231	20.6	YNPWSPR	SPRING
184430	2001Q0785	USFS/ DIAMOND P RANCH	13S	04E	22	CDDA	10/11/2000 14	44.6814	-111.2253	12.8	YNPWSPR	SPRING
183242	2001Q0790	U.S.F.S. BLACK SAND SPRING	13S	05E	31	ACDA	10/12/2000 11	44.6592	-111.1594	9.1	YNPWSPR	SPRING
184262	2001Q0849	DOBERT STEPHEN/COLE JIM	09S	08E	5	ABAB	10/17/2000 14	45.0853	-110.7681	13.3	YNPGSPR	SPRING
184260	2001Q0848	POWELL BILL AND DOROTHY/FRIEDI	08S	08E	32	DCCC	10/17/2000 15	45.0868	-110.77	17.6	YNPGSPR	SPRING
184258	2001Q0866	LOSEFF DAVID	07S	06E	35	AAAC	10/24/2000 15	45.1893	-110.9387	8.5	YNPGSPR	SPRING
180879	2001Q0870	LEWIS WILLIAM * W00995900	08S	07E	26	BBBB	10/25/2000 10	45.1149	-110.8411	8.4	YNPGSPR	SPRING
197921	2003Q0520	BEAR CREEK * WARM SPRING	09S	09E	19	DBBC	9/26/2002 11:	45.0296	-110.666	33.6	YNPGSPR	SPRING
183328	2001Q0388	BEAR CR. - UPSTREAM OF MINERAL I	09S	09E	4	ACBC	8/10/2000 15:	45.0819	-110.6256	12.8	GAFORST	STREAM
184261	2001Q0867	USFS * BELOW BEAR CREEK WARM S	09S	09E	19	DCBC	10/25/2000 13	45.0305	-110.6663	23.1	YNPGSPR	SPRING
184259	2001Q0868	USFS * MILLER MTN JEEP TRAIL	09S	14E	26	BDBD	10/26/2000 15	45.0221	-109.9483	4.1	YNPGSPR	MINE
167710	2001Q0869	COOKE RANGER STATION * SPRING #	09S	15E	29	BABA	10/26/2000 11	45.0264	-109.8929	3.4	YNPGSPR	SPRING
167710	1999Q0135	COOKE RANGER STATION * SPRING #	09S	15E	29	BABA	8/6/1998 12:3	45.0264	-109.8929	5.8	YNPCSPR	SPRING
169046	1999Q0363	SILVER GATE * SPRING #16 (BOB SHA	09S	14E	27	CACD	10/31/1998 16	45.0161	-109.9756	5.8	YNPCSPR	SPRING
169046	2001Q0873	SILVER GATE * SPRING #16 (BOB SHA	09S	14E	27	CACD	10/26/2000 12	45.0161	-109.9756	5.8	YNPCSPR	SPRING
169391	2001Q0872	SMITH WG & DEE SPRING #20	09S	14E	34	BDCC	10/26/2000 13	45.0056	-109.9772	3.8	YNPCSPR	SPRING
171215	2001Q0850	LADUKE HOT SPRINGS	08S	08E	32	CACC	10/19/2000 13	45.0908	-110.7746	65	YNPGSPR	SPRING
171227	2001Q0758	USFS/CHURCH UNIVERSAL AND TRIU	08S	07E	13	BBDB	10/3/2000 13:	45.1434	-110.8187	12.2	YNPGSPR	SPRING
179635	2001Q0762	YNP6	11S	05E	1	AACC	10/5/2000 09:	44.9017	-111.0544	4.2	YNPWSPR	SPRING
179632	2001Q0766	YNP3	10S	05E	2	BD	10/5/2000 10:	44.9812	-111.0778	6.1	YNPWSPR	SPRING
179644	2001Q0764	MCCUAIG DONALD	07S	04E	4	CCCB	10/6/2000 10:	45.2483	-111.2494	9.1	YNPWSPR	SPRING
179655	2001Q0765	YNP7	11S	06E	19	BCDA	10/4/2000 15:	44.8619	-111.0468	5.4	YNPWSPR	SPRING
182010	2001Q0787	CINNAMON LODGE	08S	04E	28	ADBA	10/12/2000 14	45.1118	-111.2316	4.9	YNPWSPR	SPRING
182012	2001Q0852	MCPHERSON JACK	08S	07E	12	DBCC	10/19/2000 11	45.1502	-110.8107	13.1	YNPGSPR	SPRING
182014	2001Q0786	MANSHIP MIKE	12S	05E	7	BCCC	10/11/2000 10	44.8036	-111.1725	7.8	YNPWSPR	SPRING
183236	2001Q0761	SHEEP CAMP SPRING/ USFS	09S	03E	10	ABDB	10/15/2000 11	45.0703	-111.3386	6.1	YNPWSPR	SPRING
183239	2001Q0760	TONN GARY	07S	04E	20	CDCB	10/5/2000 15:	45.2049	-111.2645	6.1	YNPWSPR	SPRING
183576	2001Q0763	TONN KENNETH	07S	04E	20	ADBB	10/5/2000 16:	45.2096	-111.2607	6.4	YNPWSPR	SPRING
8929	2001Q0783	USFS * 7 MI W WEST YELLOWSTONE	13S	04E	9	DDDD	10/12/2000 14	44.709	-111.2356	9.5	YNPWSPR	SPRING
171216	2000Q0005	SNOWFLAKE SPRINGS	09S	04E	12	DCAD	7/1/1999 10:4	45.0608	-111.1739	12.3	YNPWSPR	SPRING
163261	1998Q0468	COOKE CITY SPRING	09S	15E	30	ABDA	9/24/1997 09:	45.0247	-109.9058	4.8	YNPCSPR	SPRING
163259	1998Q0466	SILVERGATE TOWN SPRING * SPRING	09S	14E	33	AABD	9/24/1997 14:	45.0111	-109.9858	7	YNPCSPR	SPRING
169047	1999Q0364	SLOAN SPRING * SPRING #21	09S	14E	33	DAAD	10/31/1998 15	45.0039	-109.9833	4	YNPCSPR	SPRING
164216	1998Q1105	LONESOMEHURST WATER USERS AS	13S	04E	4	AADC	6/11/1998 09:	44.7359	-111.2373	13.9	YNPWSPR	SPRING

sample_id	lab_ph	lab_sc	ag	al	as_	b	ba	be	br	ca	cd	cl	co3	co
2001Q0759	7.79	482	<1	<30	<1	<30	195	<2	<50	67.9	<2	4.50	0.0	<2
2001Q0791	7.84	395	<1	<30	1.53	<30	85.0	<2	135	45.4	<2	1.26	0.0	<2
2001Q0788	8.16	601	<1	<30	10.5	31.3	23.3	<2	<50	74.9	<2	1.02	0.0	<2
2001Q0785	7.35	597	<1	<30	8.05	<30	19.2	<2	<50	76.9	<2	1.13	0.0	<2
2001Q0790	6.8	99.1	<1	<30	<1	49.1	2.07	<2	<50	5.54	<2	5.02	0.0	<2
2001Q0849	7.74	508	<1	<30	<1	<30	71.5	<2	<50	34.2	<2	2.44	0.0	<2
2001Q0848	7.75	554	<1	<30	<1	<30	78.3	<2	<50	34.2	<2	3.13	0.0	<2
2001Q0866	7.3	194.5	<1	<30	1.14	<30	25.8	<2	<50	21.0	<2	1.43	0.0	<2
2001Q0870	8.14	1230	<1	<30	3.31	<30	155	<2	59	59.1	<2	39.8	0.0	<2
2003Q0520	6.12	2540	<1	<300	<100	942	26.7	<20	<3000	416	<10	32.7	0.0	<20
2001Q0388	7.54	61.3	<1	.30	<1	<30	23.5	<2	<50	5.64	<2	<.5	0.0	<2
2001Q0867	7.26	2460	<1	<30	16.3	1030	27.8	<2	<500	438	<2	39.0	0.0	<2
2001Q0868	8.03	295	<1	<30	<1	<30	57.9	<2	<50	30.1	<2	.203	0.0	<2
2001Q0869	7.21	141	<1	<30	<1	<30	24.4	<2	<50	16.8	<2	<.5	0.0	<2
1999Q0135	7.04	130.2	<1.	<15.	<1.	<30.	27.86	<2.	<25.	15.53	<2.	<.5	0.0	<22.
1999Q0363	7.46	250	<1	<30	<1	<80	16.6	<2	<25	28.7	<2	<.5	0.0	<2
2001Q0873	7.93	218	<1	<30	1.84	<30	9.33	<2	<50	22.2	<2	<.5	0.0	<2
2001Q0872	8.24	426	<1	<30	<1	<30	29.7	<2	<50	66.3	<2	<.5	0.0	<2
2001Q0850	7.4	2630	<1	329	21.6	459	31.1	<2	<500	333	<2	44.9	0.0	<2
2001Q0758	8.25	571	<1	<30	2.01	<30	82.0	<2	68	30.1	<2	10.3	0.0	<2
2001Q0762	7.27	238	<1	<30	1.64	<30	32.9	<2	<50	32.8	<2	.666	0.0	<2
2001Q0766	7.61	297	<1	<30	2.30	<30	48.4	<2	<50	35.3	<2	.703	0.0	<2
2001Q0764	7.77	504	<1	<30	<1	<30	107	<2	<50	63.4	<2	5.14	0.0	<2
2001Q0765	6.73	128.1	<1	<30	<1	<30	9.64	<2	<50	14.4	<2	12.1	0.0	<2
2001Q0787	7.85	597	<1	<30	<1	<30	52.1	<2	<50	67.9	<2	1.71	0.0	<2
2001Q0852	8.03	548	<1	<30	<1	<30	21.7	<2	62	57.4	<2	11.1	0.0	<2
2001Q0786	7.97	438	<1	<30	<1	<30	31.1	<2	<50	51.9	<2	.565	0.0	<2
2001Q0761	8.13	422	<1	<30	<1	<30	92.5	<2	<50	64.7	<2	.78	0.0	<2
2001Q0760	6.48	79.8	<1	<30	<1	<30	5.08	<2	<50	8.75	<2	.534	0.0	<2
2001Q0763	7.85	372	<1	<30	<1	<30	171	<2	<50	43.3	<2	1.91	0.0	<2
2001Q0783	7.33	157	<1	<30	<1	<30	11.9	<2	<50	15.1	<2	1.59	0.0	<2
2000Q0005	7.74	477	<1	<30	2.78	<60	38.0	<2	<50	61.3	<2	.826	0.0	<2
1998Q0468	8.82	228	<1.	<30.	<1.	<30.	59.9	<2.	<25.	33.6	<2.	<.5	6.72	<2.
1998Q0466	8.78	215	<1.	<30.	1.1	<30.	18.1	<2.		17.9	<2.	<.5	4.8	<2.
1999Q0364	7.64	227	<1	<30	<1	<80	28.6	<2	<25	29.27	<2	.769	0.0	<2
1998Q1105	7.09	114	<1.	<30.	<1.	<30.	27.1	<2.	<25.	10.74	<2.	2.725	0.0	<2.

cr	cu	f	fe	hco3	hg	k	li	mg	mn	mo	no3_n	na	ni	pb
<2	<2	.089	<.005	283.04		1.71	8.84	18.0	<.001	<10	.609	5.95	2.35	<2
<2	<2	.071	.006	251.8		.753	1.30	24.3	<.001	<10	.399	.967	<2	<2
<2	<2	.977	.034	199.2		4.99	37.9	27.1	.029	<10	<.05	7.19	2.57	<2
<2	<2	.973	.013	190.0		4.58	33.5	27.4	.040	<10	<.05	7.10	2.49	<2
<2	<2	3.43	<.005	39.5		1.83	45.2	.813	<.001	<10	<.05	13.4	<2	<2
7.50	<2	.12	<.005	298.7		2.85	15.6	37.1	<.001	<10	.291	10.7	<2	<2
8.48	<2	.134	<.005	306.0		2.99	20.1	37.0	<.001	<10	.222	16.8	<2	<2
<2	<2	.087	<.005	103.1		2.35	2.96	5.1	<.001	<10	.282	6.89	<2	<2
5.0	4.32	.079	.016	632.0		3.45	9.87	85.2	.002	<10	<.05	96.7	4.19	<2
<100	<50	<3.0	1.04	1135.8		38.7	369	81.5	0.050	<100	<3.0	98.7	<20	<100
<2	<2	<.05	.007	34.5	<1	1.07	<1	1.47	<.001	<10	<.05	2.83	<2	<2
7.95	<2	1.94	.020	828.4		43.2	352	89.8	<.001	<10	<.5	104	16.0	<2
<2	<2	<.05	<.005	153.2		.698	1.12	12.7	<.001	<10	.266	.976	<2	<2
<2	<2	<.05	.184	76.1		.495	<1	4.23	.033	<10	<.05	1.69	<2	<2
<2.		<.05	<.005	74.5	<50.	.463	<10.	3.65	<.001	<2.	<.05	1.627	<2.	<2.
<2	<2	.059	.054	136.6		.556	<50	12.1	<.001	<10	.109	1.68	6.96	<2
<2	<2	<.05	<.005	121.5		.74	1.13	10.6	<.001	<10	.221	2.57	<2	<2
<2	<2	<.05	<.005	270.1		1.68	7.34	14.4	<.001	<10	<.05	6.23	2.82	<2
7.70	2.64	3.32	.064	288.9		22.5	239	59.4	.014	<10	<.5	225	3.96	<2
2.32	<2	.13	.006	324.3		7.62	3.98	30.5	<.001	<10	.903	44.4	<2	<2
<2	<2	.062	<.005	133.7		.682	2.28	5.88	<.001	<10	<.05	1.49	<2	<2
<2	<2	.134	<.005	160.8		.87	2.90	13.4	<.001	<10	.145	1.64	<2	<2
<2	<2	.162	.007	253.3		2.21	14.9	18.9	<.001	<10	.601	12.9	2.15	<2
<2	<2	.063	<.005	50.1		.877	2.25	2.89	<.001	<10	.342	3.82	<2	<2
<2	<2	.20	.007	303.2		3.75	29.9	29.8	<.001	<10	.167	11.6	2.52	<2
5.78	<2	.161	<.005	245.0		7.23	23.8	20.4	<.001	16.6	<.05	25.6	<2	<2
<2	<2	.245	.006	189.3		.851	4.38	23.5	<.001	<10	.111	1.58	<2	<2
<2	<2	.075	<.005	274.3		1.99	7.28	13.9	<.001	<10	<.05	6.69	2.32	<2
<2	<2	<.05	<.005	34.2		.595	3.51	1.29	.014	<10	.196	1.65	<2	<2
<2	<2	.105	<.005	220.82		1.42	12.6	18.6	<.001	<10	.221	2.15	<2	<2
<2	<2	.304	<.005	72.22		1.29	7.48	3.95	<.001	<10	.959	4.90	<2	<2
<2	<2	.616	<.01	158.84		1.40	<100	22.4	<.002	<10	.133	1.45	<2	<2
<2.	<2.	.06	<.005	138.1		.746	<2.	6.2	<.001	<10.	.09	1.09	6.77	<2.
<2.	<2.	<.05	<.005	124.7		.847	5.1	6.2	<.001	<10.	.32	17.3	3.6	<2.
<2	<2	.097	.027	140.1		.339	<50	6.229	<.001	<10	.203	9.591	6.90	<2
2.54	<2.	<.05	.018	62.2		3.442	<50.	2.97	<.002	<10.	.40	5.23	<2.	<2.

opo4	sb	se	sio2	sn	so4	sr	ti	v	zn	zr	no2_n	phosphate_to
<.05	<2	<1	9.75		10.9	181	<1	<5	2.04	<2	<.05	<.05
<.05	<2	<1	8.21		<2.50	39.6	<1	<5	17.5	<2	<.05	<.05
<.05	<2	<1	12.0		147	716	<1	<5	<2	<2	<.05	<.05
<.05	<2	<1	12.0		146	704	<1	<5	<2	<2	<.05	<.05
<.05	<2	<1	33.7		<2.50	<1	<1	<5	6.28	2.24	<.05	<.05
<.05	<2	<1	13.4		28.9	1280	<1	<5	<2	<2	<.05	<.05
<.05	<2	<1	12.5		33.4	1230	<1	<5	2.77	<2	<.05	<.05
.053	<2	<1	28.5		3.52	132	<1	<5	<2	<2	<.05	.085
<.05	<2	2.13	20.2		142.2	2520	<1	13.8	2.56	<2	<.05	<.05
<3.0	<100	<150	28.7		705	3350	<10	<100	<20	<20	<3.0	<0.5
<.05	<2	<1	18.8		<2.5	58.5	<1	<5	<2	<2	<.05	<.05
<.5	<2	<1	35.0		849	3460	<1	<5	<2	4.20	<.5	<.05
<.05	<2	<1	7.31		7.87	159	<1	<5	<2	<2	<.05	<.05
<.05	<2	<1	11.6		<2.5	93.0	<1	<5	<2	<2	<.05	<.05
<.05	<1.		12.4	80.8	3.695	<10.	<5.	<2.	<10.		<.05	<.1
<.05	<2	<1	5.2		22.227	162	<10	<5	<2	<5	<.05	<.1
<.05	<2	<1	7.31		7.45	172	<1	<5	<2	<2	<.05	<.05
<.05	<2	<1	8.37		10.3	175	<1	<5	<2	<2	<.05	<.05
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<.05	<2	<1	11.3		18.6	158	<1	<5	<2	<2	<.05	<.05
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.056	<2	<1	18.5		<2.5	69.0	<1	<5	<2	<2	<.05	<.05
<.05	<2	1.33	8.75		71.3	873	<1	<5	<2	<2	<.05	<.05
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<.05	<2	<1	7.37		75.7	363	<1	<5	<2	<2	<.05	<.05
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<.05	<2	<1	6.73		9.25	233	<1	<5	<2	<2	<.05	<.05
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.058	<2	<1	10.948		6.494	113	12.9	7.15	<2	<5	<.05	<.1
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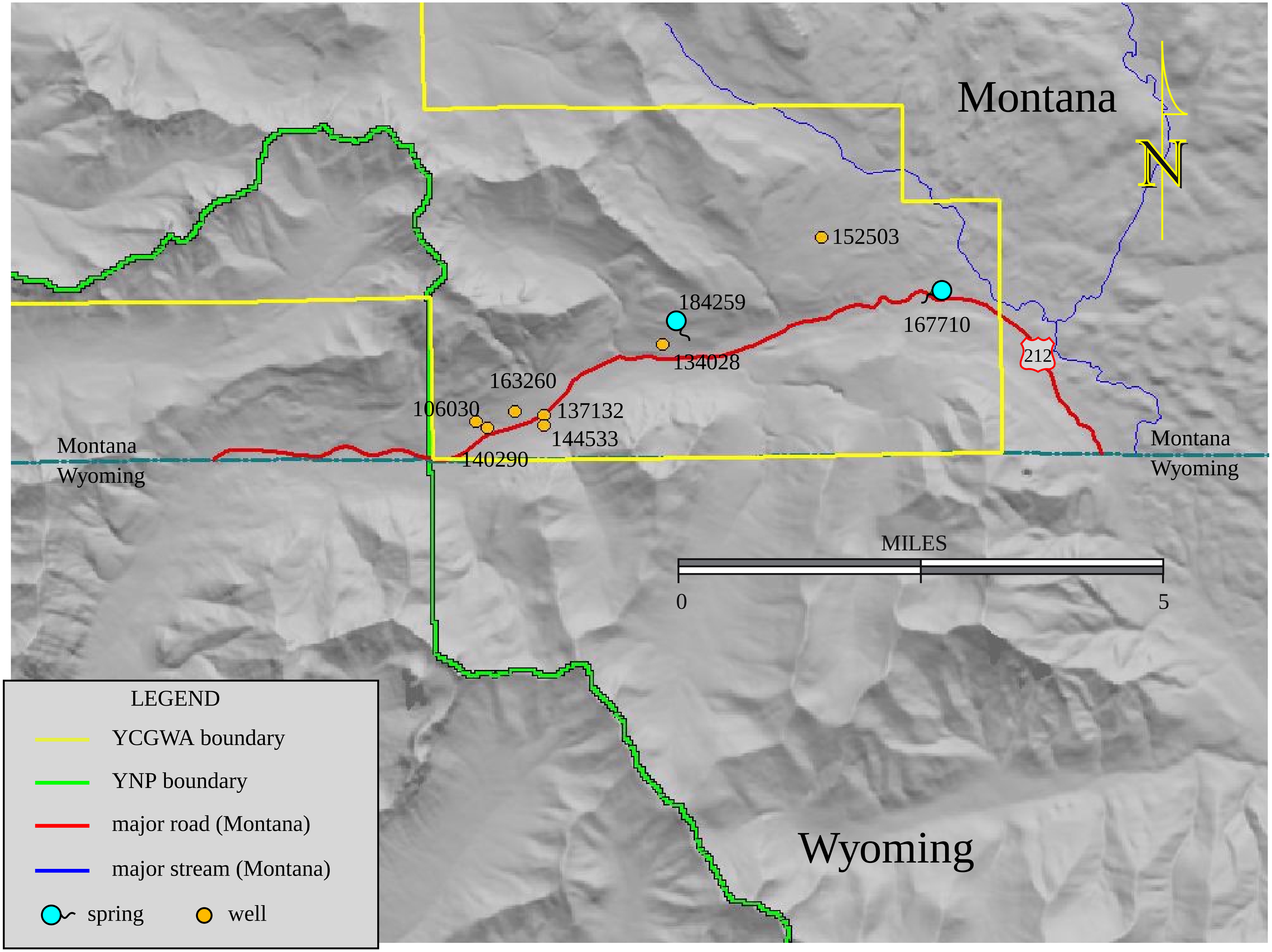

Figure A-1. Isotope sample locations in the Cooke City - Silver Gate area.

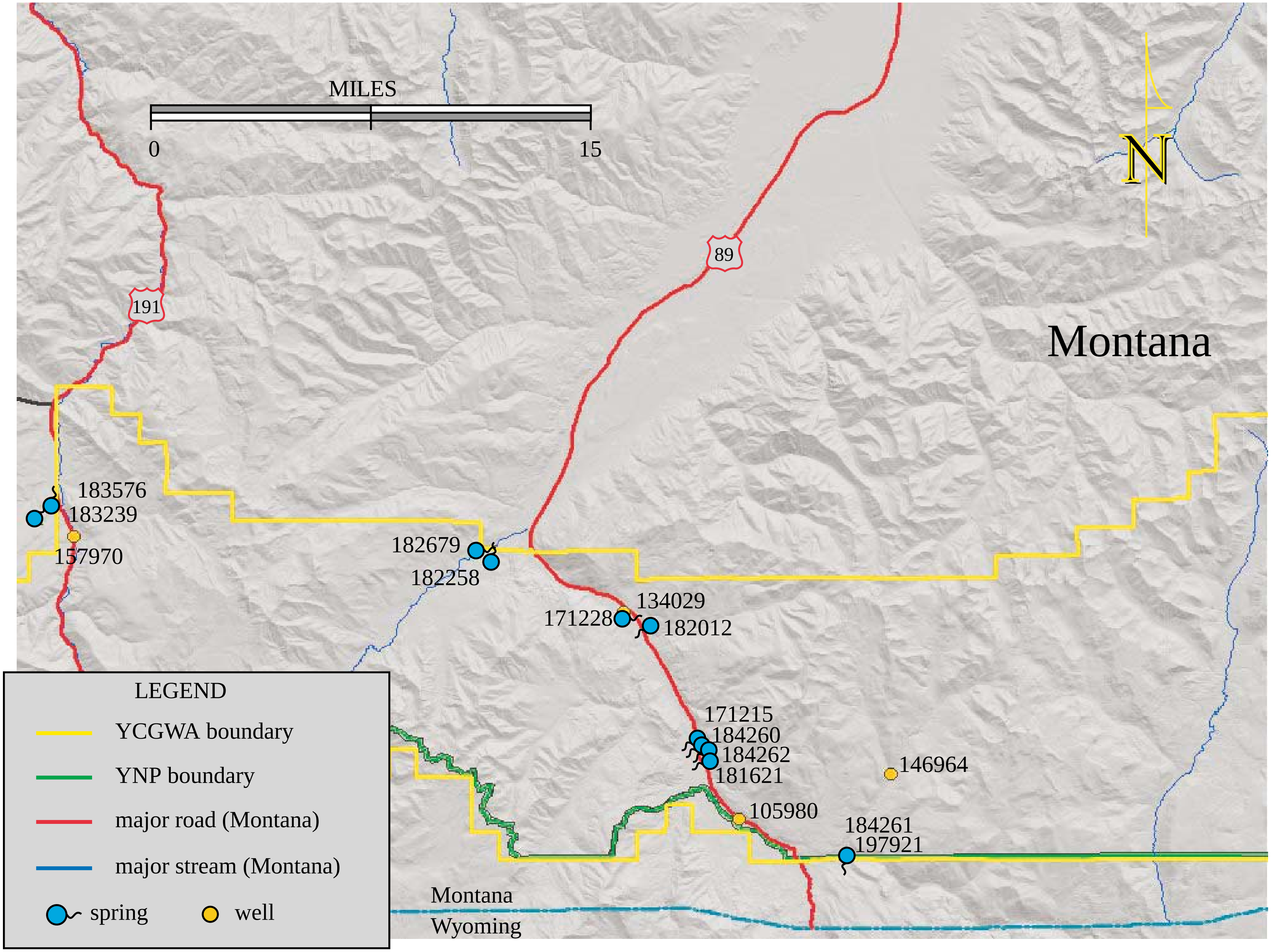

Figure A-2. Isotope sample locations in the Gardiner area.

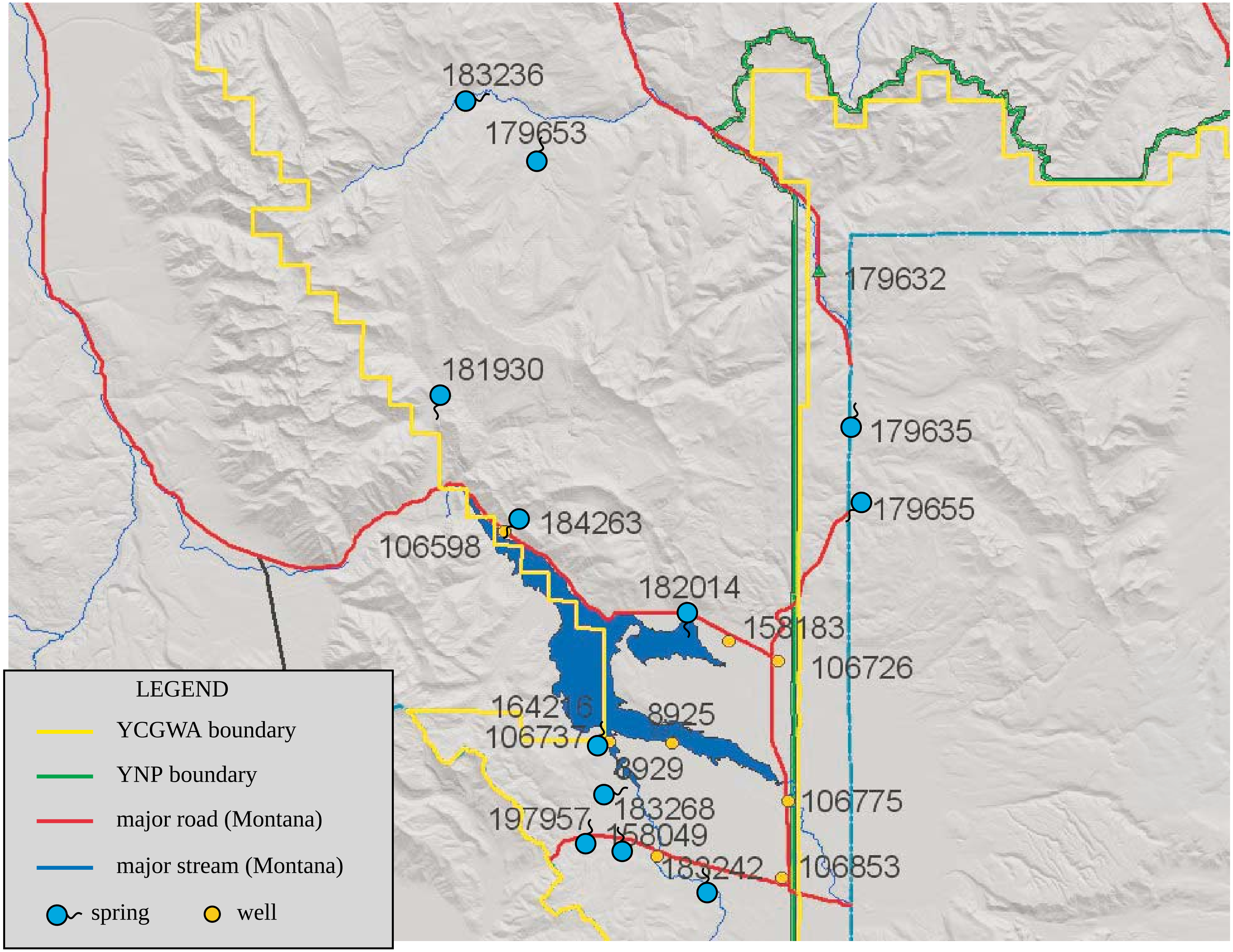

Figure A-3. Isotope sample locations in the West Yellowstone area.

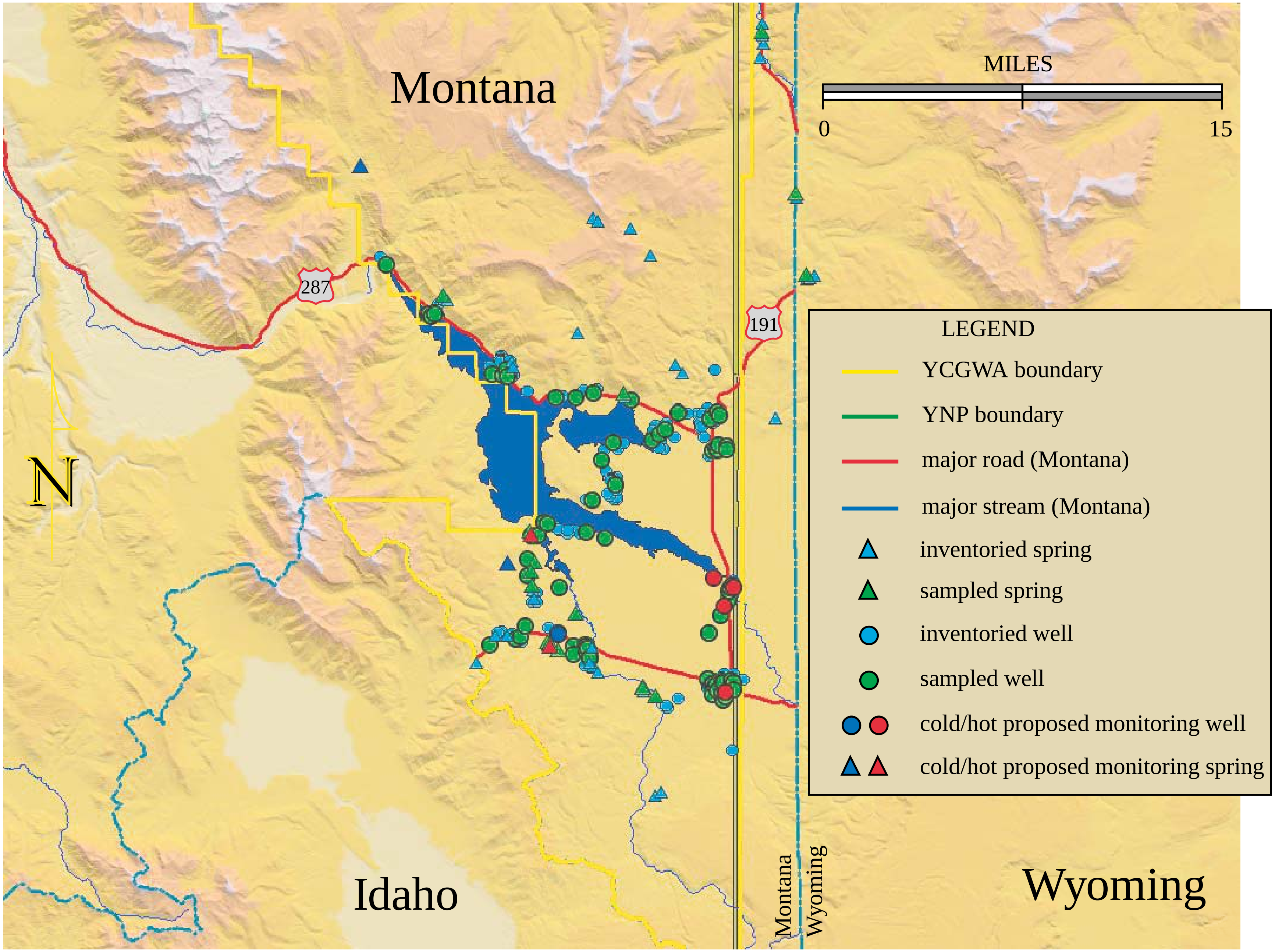

Figure A-4. Springs and wells in all categories for the West Yellowstone area. Standard symbols for springs are not used in order to better differentiate between springs and wells.

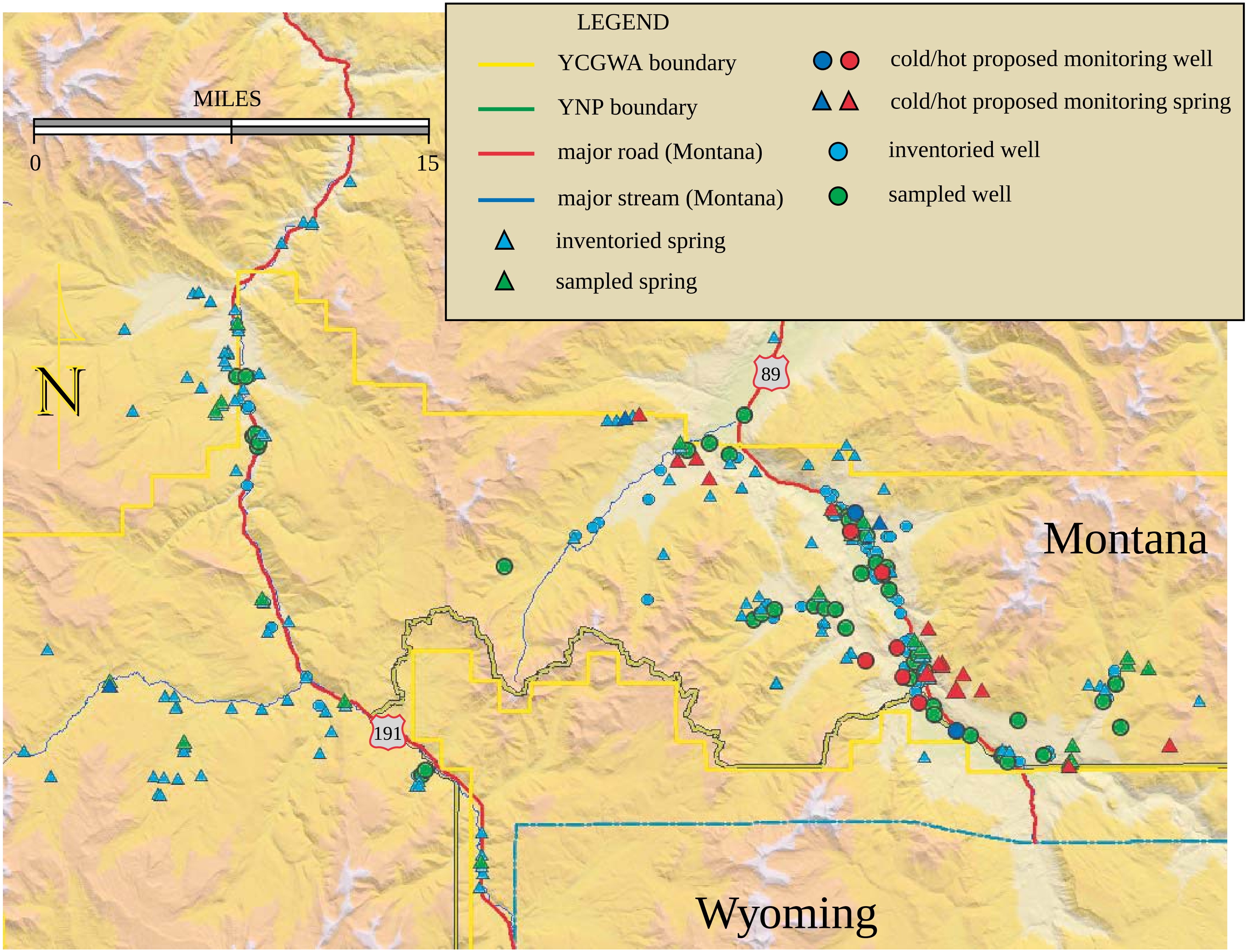

Figure A-5. Springs and wells in all categories for the Gardiner area. Standard symbols for springs are not used in order to better differentiate between springs and wells.

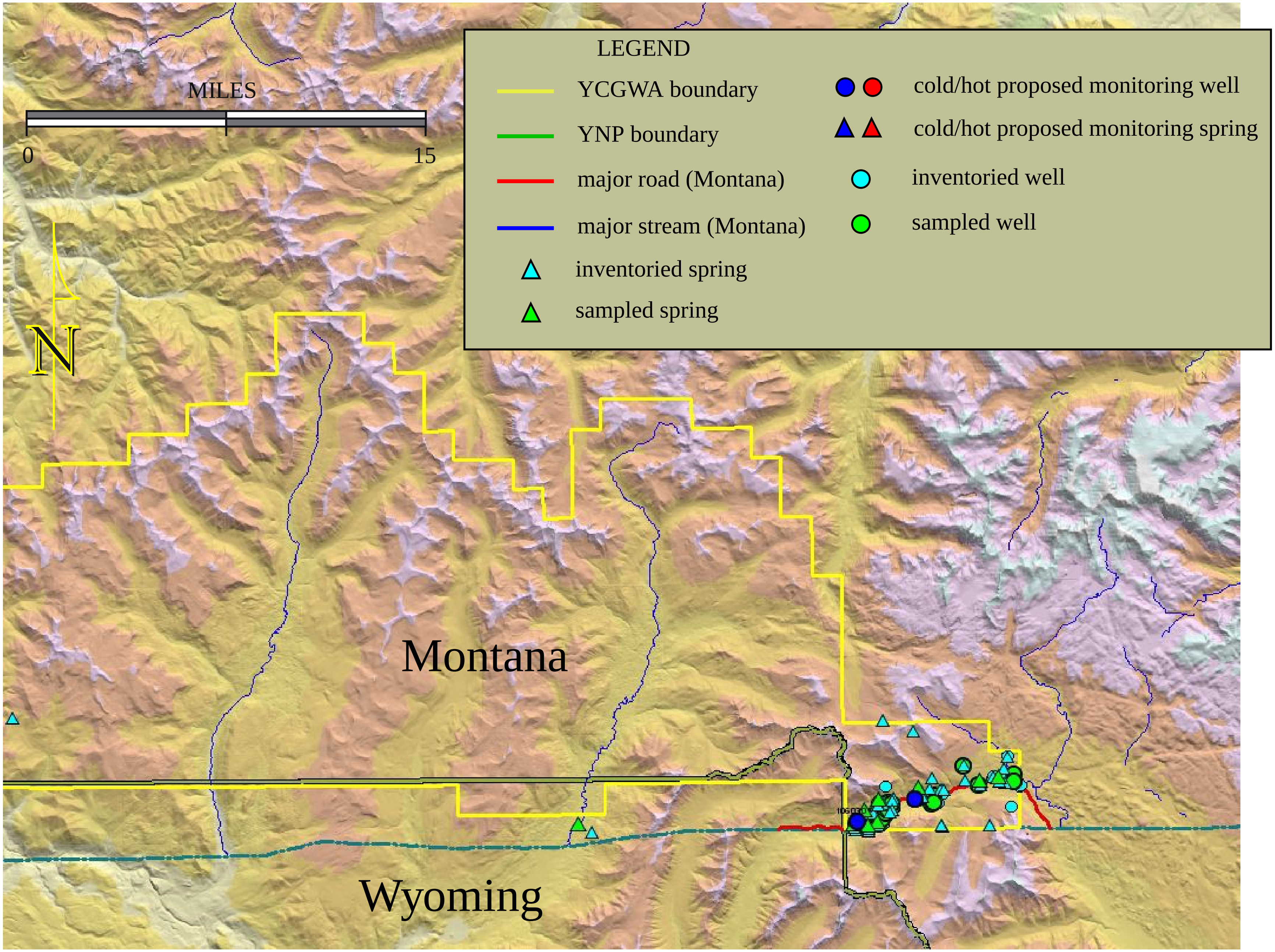

Figure A-6. Springs and wells in all categories for the Cooke City - Silver Gate area. Standard symbols for springs are not used in order to better differentiate between springs and wells.