

# **Hydrogeology of the Upper Soda Butte Creek Basin, Montana**

**With Sections on Climate and Streamflow in  
Soda Butte Creek**



**John Metesh, Alan English, Jeff Lonn,  
Eloise Kendy, and Charles Parrett**

© 1999 Montana Bureau of Mines and Geology

*Cover Photograph:* Aerial view of the upper Soda Butte Creek drainage looking downstream (west) into Yellowstone National Park. Cooke City is in the foreground, and Silver Gate is barely visible in the upper center.

**Hydrogeology of the Upper Soda Butte Creek Basin, Montana**

**John Metesh, Alan English, and Jeff Lonn**

**With a Section on Climate**

**Eloise Kendy and Charles Parrett  
U.S. Geological Survey**

**And a Section on Streamflow in Soda Butte Creek**

**Charles Parrett  
U.S. Geological Survey**

---

# Contents

Introduction .....	1
Climate .....	1
Summary .....	7
Geology .....	7
Bedrock Geology .....	7
Quaternary Geology .....	8
Streamflow in Soda Butte Creek .....	8
Long-Term Flow Characteristics .....	11
Streamflow Correlation Procedure .....	11
Record Adjustment for 1975–1980 .....	14
Streamflow-Record Extension Program .....	14
Results .....	15
Comparisons to Precipitation and Evaporation .....	15
Spatial Variations in Streamflow .....	18
Water Quality .....	21
Summary .....	22
Aquifer Characteristics .....	24
Bedrock Aquifer .....	24
Valley-Fill Aquifer and Valley-Margin Material .....	24
Mill Tailings (t) .....	24
Colluvium and Talus (ct) .....	25
Stream Gravel (sg) .....	25
Fan Gravel (fg) .....	25
Landslide (ls) .....	25
Glacial Till [Pinedale] (pt) .....	25
Fluvial Gravel [Pinedale] (pgu) .....	25
Fan Gravel [Pinedale] (pfg) .....	26
Valley-Fill Aquifer .....	26
Ground Water .....	26
Hydrographs .....	26
Summary of Hydrographs .....	33
Ground-Water Flow .....	33
Vertical Gradients .....	38
Springs .....	38
Spring Development .....	45
Geologic Setting of Springs .....	45
Hydrology of Springs .....	48
Chemistry .....	48
Ground-Water Chemistry .....	48
Spring-Water Chemistry .....	49

---

---

Computer Simulation of Soda Butte Creek .....	49
Modeling Procedure .....	51
Modeling Results .....	53
Tritium-Helium Age-Dating of Ground Water .....	55
Travel-Path Estimates .....	56
Analysis of Ground-Water Resources .....	58
Water Use .....	58
Water Balance .....	60
Aquifer Storage .....	60
Summary: Conceptual Model .....	61
Recommendations for Additional Work .....	61
References .....	62
Appendix A. Inorganic Chemistry for Wells and Springs; Isotope Chemistry for Wells .....	64

## Figures

Figure 1. Location of study area .....	2
Figure 2. The upper Soda Butte Creek drainage .....	3
Figure 3. USGS streamflow-gaging stations .....	4
Figure 4. Mean monthly precipitation and temperature .....	5
Figure 5. Geologic cross section near Cooke City .....	9
Figure 6. Geologic cross section near Silver Gate .....	10
Figure 7. Streambed profile for upper Soda Butte Creek .....	12
Figure 8. Synoptic discharge measuring sites and streamflow-gaging stations .....	13
Figure 9. MOVE. 1 lines for Northeast Entrance .....	14
Figure 10. Box plots of estimated monthly discharge for 1938–1997 .....	17
Figure 11. Precipitation, evapotranspiration, and runoff and snow-water equivalent .....	19
Figure 12. Synoptic discharge measurements during 1996, 1997, and 1998 .....	21
Figure 13. Surficial geology of the main drainage .....	27
Figure 14. Cross-section locations for the Silver Gate area .....	28
Figure 15. Well-log cross section A–A' .....	29
Figure 16. Well-log cross section B–B' .....	30
Figure 17. Well-log cross section C–C' .....	31
Figure 18. Fence diagram for the Silver Gate area .....	32
Figure 19. Cross section location for Cook City area .....	34
Figure 20. Well log cross section D–D' in the Cooke City area .....	35
Figure 21. Location of continuous water-level recorders .....	36
Figure 22. Hydrograph for well 106030 .....	37
Figure 23. Hydrograph for well 140299 .....	37
Figure 24. Hydrograph for well 106004 .....	37
Figure 25. Hydrograph for well 162539 .....	37

---

---

Figure 26. Hydrograph for well 144534 .....	37
Figure 27. Potentiometric map of Silver Gate 9/97 .....	39
Figure 28. Potentiometric map of Silver Gate 6/98 .....	40
Figure 29. Potentiometric map of Silver Gate 9/98 .....	41
Figure 30. Potentiometric map of Cooke City 9/97 .....	42
Figure 31. Potentiometric map of Cooke City 6/98 .....	43
Figure 32. Potentiometric map of Cooke City 9/98 .....	44
Figure 33. Spring location map .....	47
Figure 34. Ground-water sample locations .....	50
Figure 35. Piper plot of ground-water samples .....	51
Figure 36. Stiff diagram of sample sites .....	52
Figure 37. Ground-water flow model area .....	54
Figure 38. Graph of modeled streamflow reduction .....	56
Figure 39. Modeled drawdown .....	57
Figure 40. Tritium-helium sample locations and results .....	59
Figure 41. Distribution of hydrologic cycle components .....	61

## Tables

Table 1. Mean monthly temperatures at climate stations .....	6
Table 2. Mean monthly and annual precipitation at climate stations .....	7
Table 3. Estimated mean pan evaporation at climate stations .....	7
Table 4. Mean bimonthly snow-water equivalents at Northeast Entrance and Fisher Creek climate stations .....	8
Table 5. Streamflow-gaging stations, drainage areas, and periods of records for Soda Butte Creek, Montana, and Yellowstone National Park .....	11
Table 6. Long-term streamflow-gaging stations used as potential base stations for record extension for Soda Butte Creek .....	16
Table 7. Long-term (1938–1997) discharge for Soda Butte Creek .....	16
Table 8. Long-term mean values of precipitation, evaporation, and runoff for Soda Butte Creek basin .....	18
Table 9. Discharge measurement sites and measured discharges .....	20
Table 10. Results of water-quality analyses .....	23
Table 11. Summary of inventoried springs .....	46
Table 12. Seepage velocities and travel-path lengths .....	58
Table 13. Water balance components and estimates .....	60

## Appendix

Appendix A. Inorganic chemistry for wells and springs; Isotope chemistry for wells .....	64
---	----

## Plate

Plate 1. Geology of the main drainage .....	back pocket
---	-------------

---

## Introduction

The upper Soda Butte Creek watershed is in south-central Montana and north-central Wyoming just outside the Northeast Entrance of Yellowstone National Park (figure 1). The creek, which flows into the park, drains about 32 mi<sup>2</sup> of watershed and ranges from an elevation of 7,320 ft msl at the Northeast Entrance to 11,699 ft msl at Pilot Peak. The watershed is bounded on the north and south by the steep, rugged peaks of the Absaroka Mountains and on the east at the headwaters by Colter Pass. Major tributaries of Soda Butte Creek (figure 2) include Republic, Hayden, and Wyoming creeks, which originate in Wyoming. Miller, Sheep, and Silver creeks are tributaries that originate in the north side of the drainage. Except for the high peaks above 9,000 ft and the burn area of the 1988 forest fire, the hillslopes of the watershed are mostly forested by conifers; the Soda Butte Creek valley and the lower portions of the tributary valleys host large thickets of various phreatophytes and grasses.

The valley has two small towns: Silver Gate, near the park entrance, and Cooke City (figure 2). Silver Gate (elevation 7,389 ft) was founded in 1932 to serve the tourist trade and provide building sites for summer residences. The townsite was originally a mining claim that was patented in 1897. Year-round residents are few, but the summer population is around 100. Cooke City (elevation 7,651 ft), once part of the Crow Indian Reservation and originally named Shoofly, was established in 1880 and supplied the numerous mining ventures in the New World Mining district. Present-day Cooke City annually hosts visitors to the nearby wilderness areas as well as to the park. While the winter population is less than 100, the summer population is around 300.

The *health* of a watershed can be described in many terms, but the most basic description includes an evaluation of the hydrologic cycle. The hydrologic cycle describes the way water is transferred and stored on and below the Earth's surface and includes precipitation, evapotranspiration, ground-water recharge/discharge, and streamflow. A variation in water quality or quantity in a single component of this cycle will effect a change in one or more of the other components.

The western United States is a region of moisture deficiency where, on an annual basis, the potential water use by plants is greater than precipitation. In fact, water-rights law in the western states is based on appropriation doctrine in which water quantity is a central feature. Under these moisture-deficit conditions, even small changes in one component of

the cycle can have a great effect on another part of the cycle. Human development of ground-water and surface-water resources over the last 100 years has had significant impacts on the health of many watersheds in terms of quality and quantity.

In 1994, the Secretary of the Interior and the Governor of Montana signed a compact addressing the water rights of several National Park units. Under the administrative procedures established in the compact, the Montana Department of Natural Resources and Conservation (DNRC) notifies the National Park Service's Water Resources Division of applications for beneficial ground-water use in designated areas adjacent to park units. The National Park Service (NPS) then has an opportunity to evaluate the proposed appropriation and determine whether it will withdraw ground water that is *hydrologically connected* to a surface stream.

The short growing season and rugged terrain of the Soda Butte Creek watershed prohibits any large agricultural development; however, its scenic vistas and proximity to Yellowstone National Park have made Silver Gate and Cooke City popular areas for tourists and summer residents. Both towns have developed springs for their primary water supply; however, individuals have installed a total of 150 residential wells throughout the watershed.

An evaluation of this (Soda Butte Creek) or any watershed requires a working knowledge of the geology, hydrogeology, and hydrology. Therefore, to make an informed decision, the NPS requested the Montana Bureau of Mines and Geology (MBMG) and the U.S. Geological Survey (USGS) to (a) evaluate scientific literature and data regarding the hydrogeology, ground-water hydrology, and surface-water hydrology of the upper Soda Butte Creek basin near the northeast corner of Yellowstone National Park, and (b) describe the hydrologic system (ground water and surface water) of the basin, including ground-water/surface-water relationships.

Information collected as part of this investigation is available from the Montana Bureau of Mines and Geology Ground Water Information Center (GWIC). This collection includes well logs, well inventory data, water-level data, ground-water and surface-water chemistry, and standard operating procedures data collection. Streamflow data, including field notes, are available from the Montana office of the U.S. Geological Survey.

## Climate

Climate data have been collected at three sites near Soda Butte Creek (figure 3). The National Oceanic

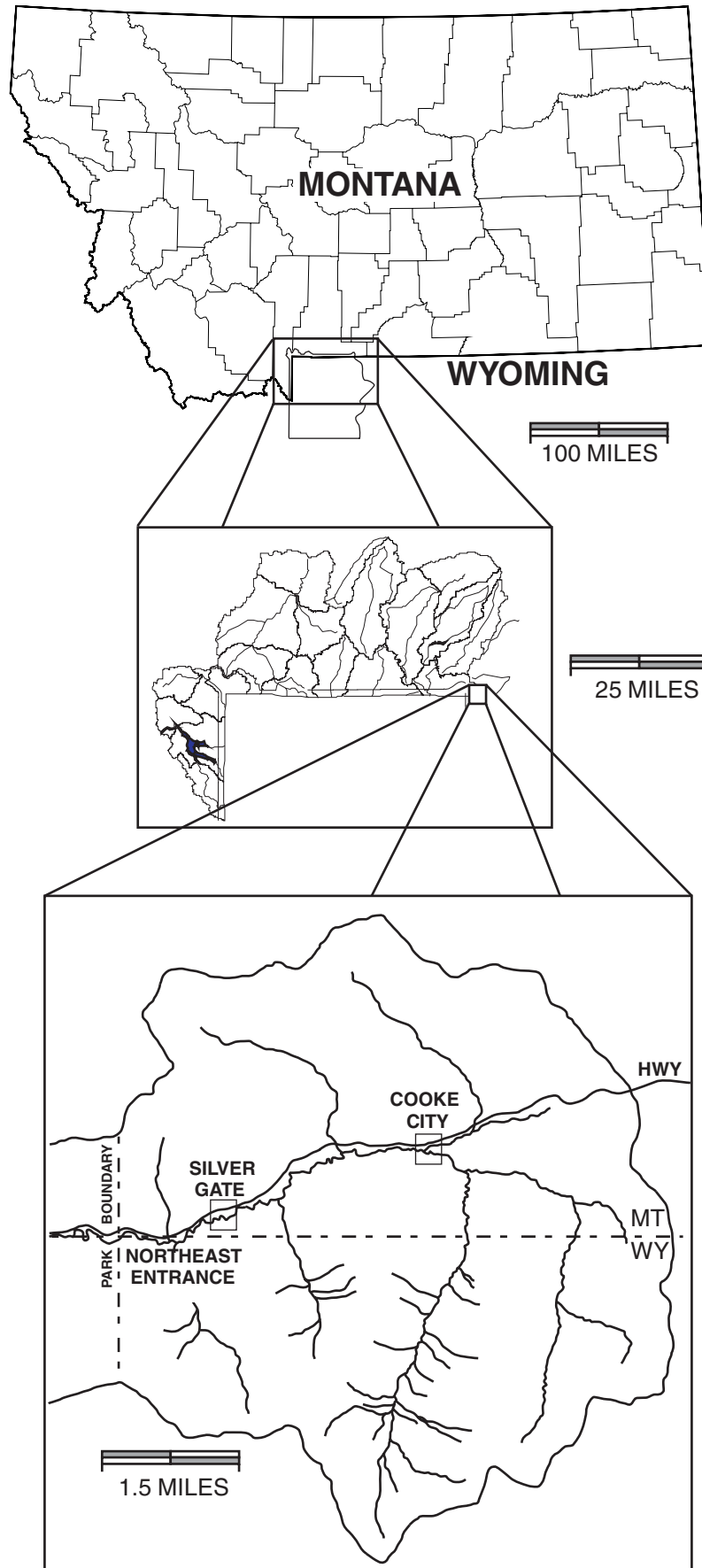


Figure 1. The upper Soda Butte Creek drainage enters Yellowstone National Park at the Northeast Entrance.

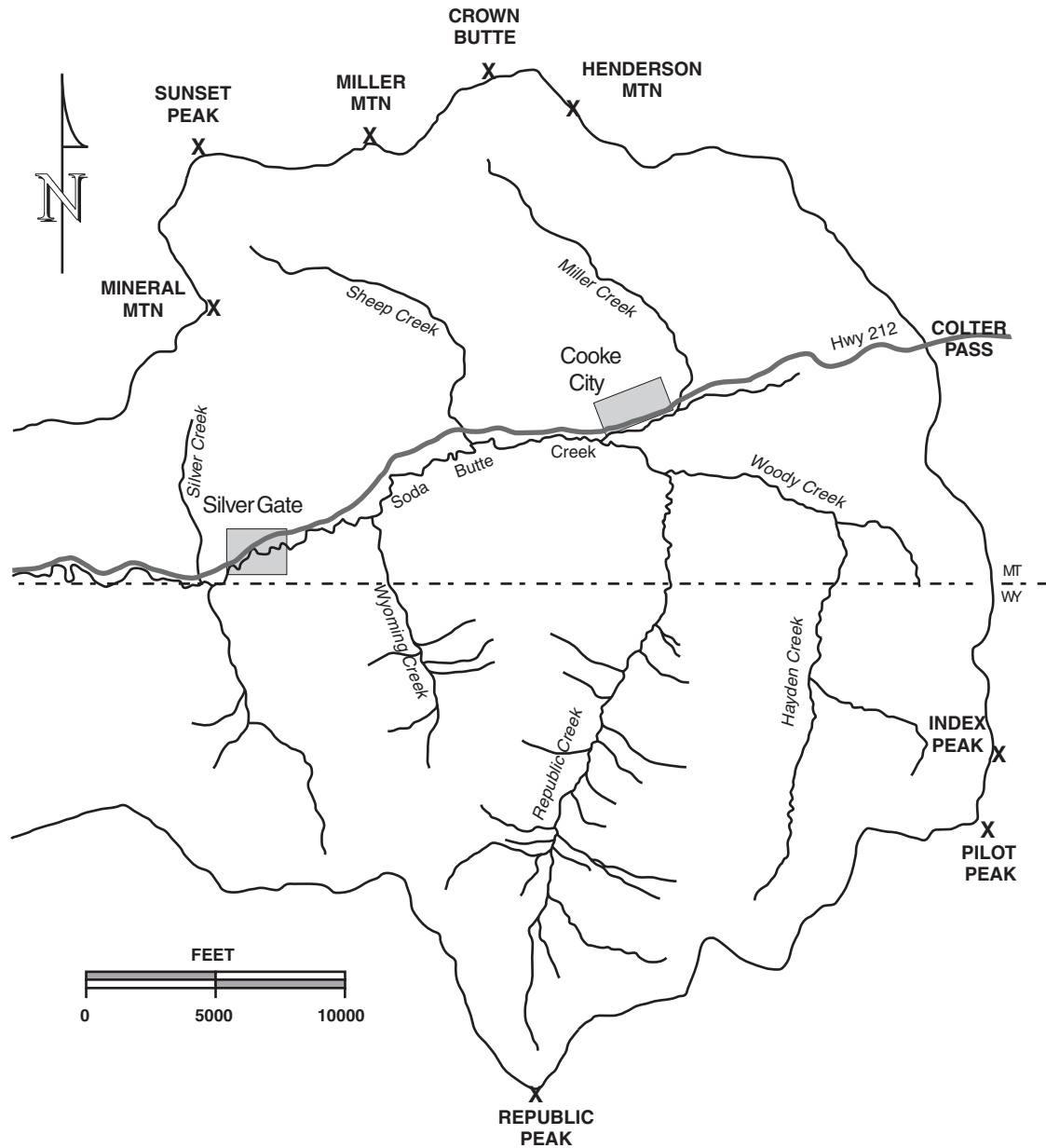


Figure 2. The upper Soda Butte Creek drainage is bounded by high, rugged mountains on the north and south, and by a high-elevation pass (Colter Pass) on the east.

and Atmospheric Administration (NOAA) publishes data for the Cooke City 2W station, which is located two miles west of Cooke City at an elevation of 7,460 ft. Temperature and precipitation data for the Cooke City 2W station are available for the 1961–1990 base period. The Natural Resources Conservation Service (NRCS) records temperature, precipitation, and snow-accumulation data for the Northeast Entrance Snowpack Telemetry (SNOTEL) station, which is located at an elevation of 7,350 ft. In addition, the NRCS records data for the Fisher Creek SNOTEL station, which is located north of the Soda Butte Creek drainage area about four miles north of Cooke City at an elevation of 9,100 ft. Although this station is outside the study area, it is typical of high-elevation sites within the study area.

Temperature data for the two NRCS stations are available for 1986–1995, and precipitation data for both are available for the 1961–1990 base period. The station at Northeast Entrance was operated by NOAA, and some climate data are available in addition to those collected by NRCS.

The Soda Butte Creek watershed has a relatively severe climate that is typical of high-elevation areas in Montana east of the Continental Divide. On the basis of the 1961–1990 climate base period used by NOAA for data compilation, the average annual precipitation at the Cooke City 2W station is 26 in., and the average annual temperature is 32.1°F (NOAA 1992). The average last occurrence of 32°F is July 17, and the average first occurrence is August 13 (NRCS 1996). Mean climate data for the Cooke City

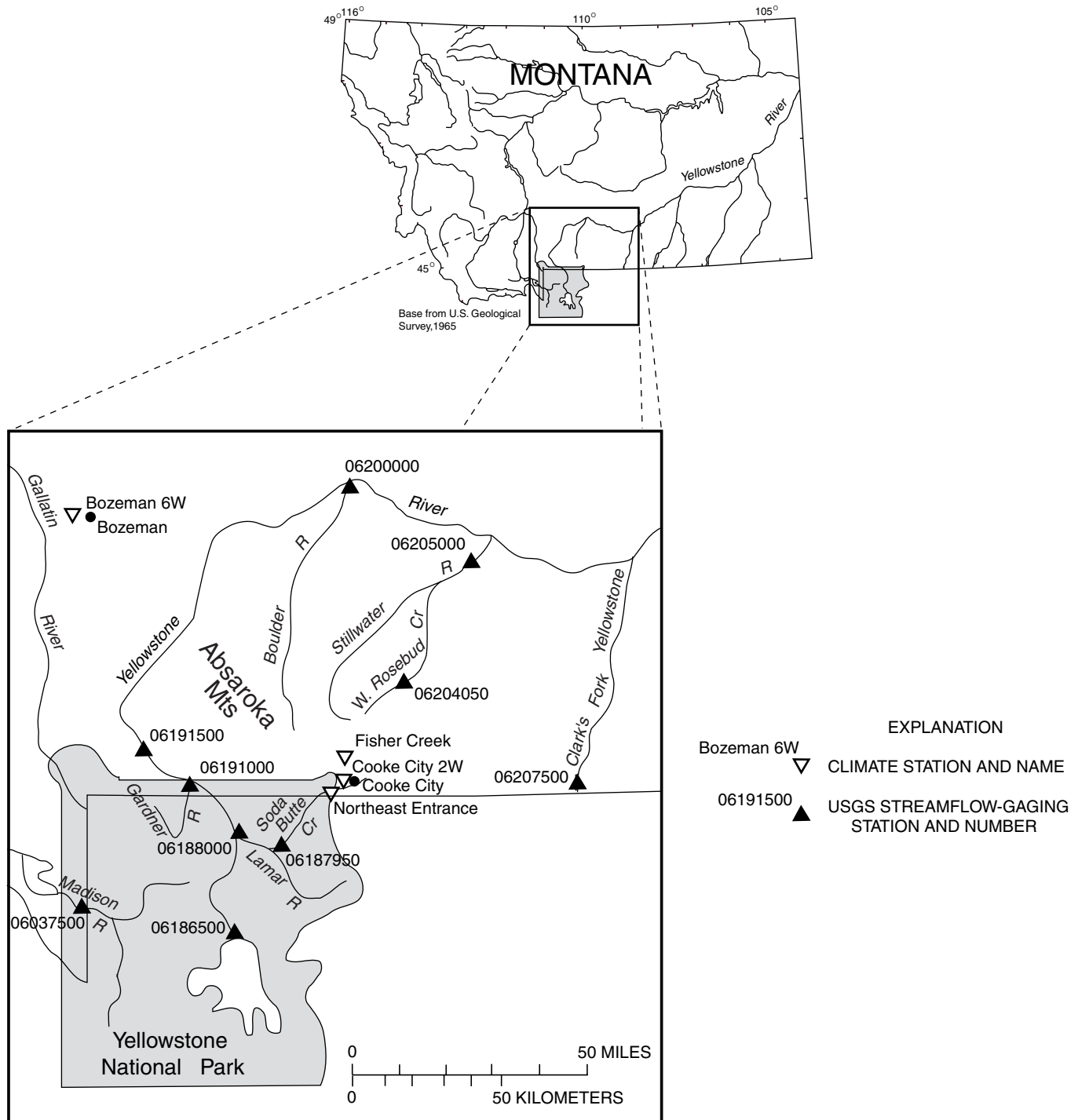


Figure 3. USGS and Climate streamflow-gaging stations near Soda Butte Creek basin, Montana, and Yellowstone National Park.

2W station are shown graphically in figure 4 and are compared with data for the Northeast Entrance and Fisher Creek SNOTEL stations in tables 1 and 2.

Much of the wide temperature variation indicated in table 1 is believed to be the result of a much shorter record length for the two SNOTEL stations than for the Cooke City 2W station during the 1961–1990 base period. On this basis, the temperature records for the two SNOTEL sites are

considered nonrepresentative of the long term and nonreflective of a true temperature spatial variation.

However, precipitation data shown in table 2 are for the same 1961–1990 base period and are believed to represent a true spatial variation. Elevation and mean precipitation depths for the Cooke City 2W and the Northeast Entrance SNOTEL stations are very similar. Because mean annual precipitation tends to increase with higher

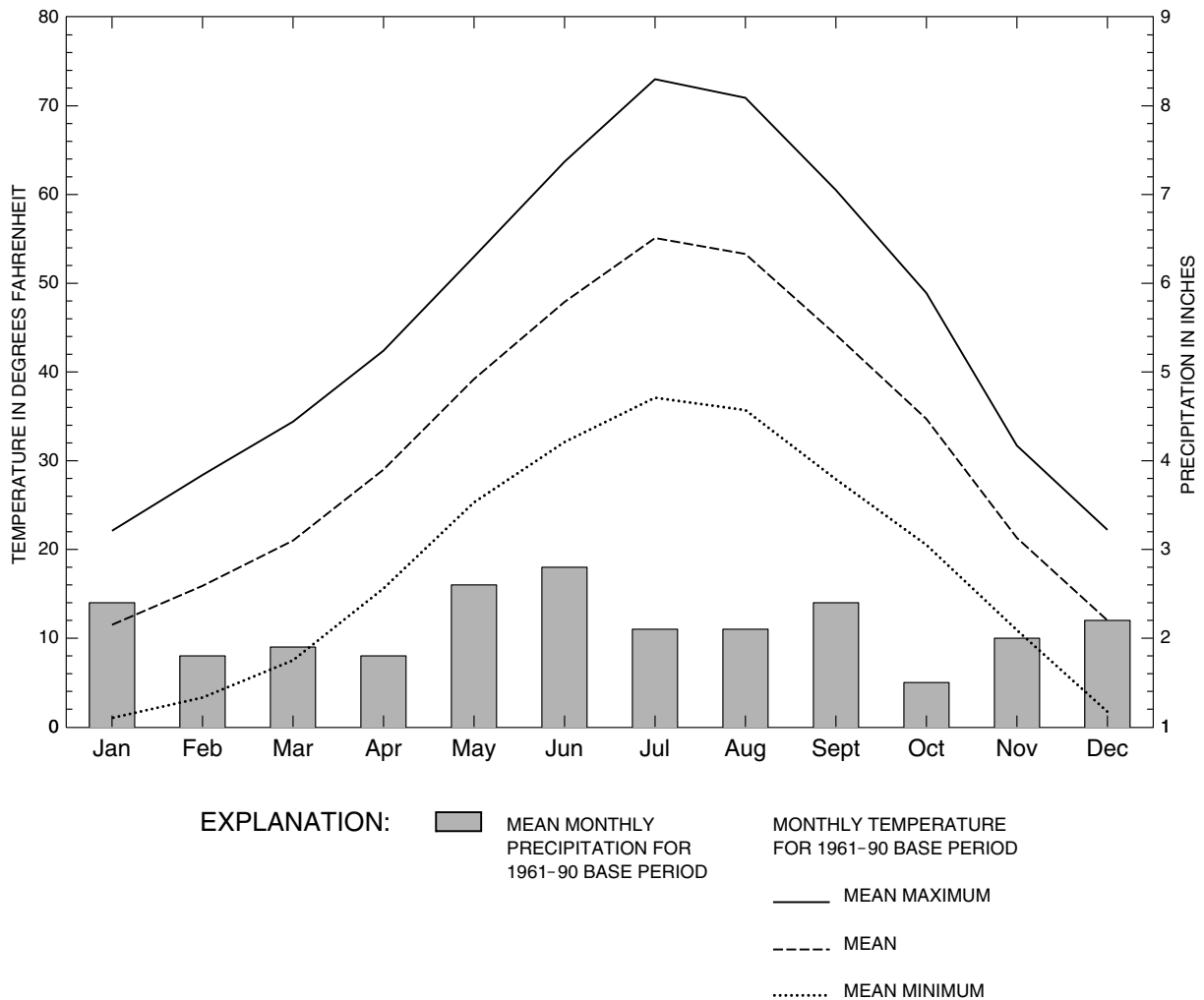


Figure 4. Mean monthly precipitation and temperature, Cooke City 2W climate station, Montana. Data from NOAA (1992).

elevation, the large difference in mean annual precipitation between either the Cooke City 2W or the Northeast Entrance SNOTEL stations and the Fisher Creek SNOTEL station is believed to represent a true spatial variation. Assuming that a basin average value for mean annual precipitation can be approximated by linear interpolation on the basis of elevation between mean annual precipitation values at the climate stations, the estimated mean annual precipitation for the Soda Butte Creek watershed upstream from the Northeast Entrance Ranger Station is 56 in.

Pan evaporation has not been measured in the study area; therefore, mean monthly pan evaporation was estimated using other climate data. The nearest NOAA station with pan-evaporation records is the Bozeman 6W station, which is located six miles west of Bozeman, at the Bozeman Experimental Farm (figure 1). Pan-evaporation data are available for that station for 21–23 years of May through September measurements and 2–11 years of additional April

and October measurements. Although pan-evaporation data are available only for April through October, significant amounts of evaporation can occur during other months. Accordingly, a linear regression, relating mean monthly pan evaporation to mean monthly maximum air temperature, was used to calculate pan evaporation for the Bozeman 6W station for November through March. The coefficient of determination ( $R^2$ ) and significance level ( $P$ ) for the regression between mean monthly pan evaporation and mean monthly maximum air temperature were 0.80 and 0.0063, respectively.

Pan-evaporation data at the Bozeman 6W station were used to estimate pan evaporation at the Cooke City 2W station. First, the ratio of mean maximum monthly air temperatures between the Cooke City 2W station and the Bozeman 6W station was taken. This ratio was then multiplied by the mean monthly pan evaporation at Bozeman 6W station. Mean maximum monthly temperature was used rather than mean monthly temperature because

Table 1. Mean monthly temperatures at the climate stations Cooke City 2W (from NOAA 1992), Northeast Entrance SNOTEL, and Fisher Creek SNOTEL (from NRCS, J. L. Ward 1966). Abbreviations: alt, altitude, ft, feet above sea level; Min, mean minimum monthly temperature in °F; Max, mean maximum monthly temperature in °F; Mean, mean monthly temperatures in °F.

Month	Cooke City 2W alt 7,460 ft (1961–1990 base period)			Northeast Entrance alt 7,350 ft (1986–1995 period of NRCS record)			Fisher Creek alt 9,100 ft (1986–1995 period of record)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Oct	20.5	48.9	34.7	27.1	42.1	33.6	26.3	39.7	32
Nov	10.9	31.7	21.3	20.6	31.7	25.6	19.1	29.4	23.4
Dec	1.7	22.2	12.0	15.7	27.8	21.4	17.9	26.0	20.6
Jan	1	22.1	11.5	16.9	28.6	22.6	16.5	26.7	20.9
Feb	3.3	28.4	15.9	18.0	31.6	24.3	17.5	29.5	22.6
Mar	7.5	34.4	21.0	21.7	36.0	28.4	20.2	34.3	26.4
Apr	15.6	42.4	29.0	25.8	40.6	32.3	23.3	38.8	30.1
May	25.3	53.0	39.2	29.9	45.5	36.8	27.8	42.9	34.3
June	32.1	63.7	47.9	33.8	51.1	41.5	31.6	46.8	38.5
July	37.1	73.0	55.1	35.6	54.2	44.0	34.3	49.9	41.3
Aug	35.7	70.9	53.3	35.1	54.8	44.0	34.5	50.7	41.7
Sept	27.9	60.5	44.2	31.3	49.6	39.5	30.9	45.4	37.1

maximum temperature correlates more closely with pan evaporation (Cary and Parrett 1996). Estimated mean annual pan evaporation at the Cooke City 2W station is 42 in. (table 3).

To estimate pan evaporation at the high-elevation Fisher Creek SNOTEL station, temperature data for the 1961–1990 period are required. Temperature data for 1986–1995 were used to develop an ordinary least squares regression relation between mean maximum monthly temperature at the Fisher Creek SNOTEL and mean maximum monthly temperature at the Northeast Entrance SNOTEL. The coefficient of determination ( $R^2$ ) and significance level ( $P$ ) for the regression were 0.99 and 0.0063, respectively. Because long-term temperatures at the two low-elevation stations (Cooke City 2W and Northeast Entrance SNOTEL) are assumed to be similar, the regression equation developed between Fisher Creek SNOTEL and Northeast Entrance SNOTEL was used to estimate 1961–1990 mean maximum monthly temperature at the Fisher Creek SNOTEL station from mean maximum monthly temperature at the Cooke City 2W station for the same period.

Finally, pan evaporation for the Fisher Creek SNOTEL station was estimated from temperature and pan-evaporation data at the Bozeman 6W

climate station in the same manner as for the Cooke City 2W station. The estimated mean annual pan evaporation for the Fisher Creek SNOTEL station is 38 in. (table 3). Pan evaporation was not estimated for the Northeast Entrance SNOTEL station because it was assumed to be about the same as the Cooke City 2W station.

Assuming that a basin average value of mean annual pan evaporation can be estimated by linear interpolation on the basis of elevation just as for mean and annual precipitation, the mean annual pan evaporation for the basin above Soda Butte Creek at the Northeast Entrance ranger station also is 38 in. Annual pan evaporation commonly is multiplied by a coefficient, typically about 0.7 in the western United States, to approximate lake evaporation (Linsley, Kohler, and Paulhus 1986). Annual lake evaporation, in turn, can be used to approximate annual evapotranspiration from a nearly saturated, vegetated surface (Linsley, Kohler, and Paulhus 1986). Thus, mean annual evapotranspiration for the basin above Soda Butte Creek at the Northeast Entrance ranger station is estimated to be  $0.7 \times 38$ , or 27 in.

Because the study area varies greatly in elevation and aspect, the climate is not uniform throughout, as evidenced by temperature and precipitation data

*Table 2. Mean monthly and annual precipitation in inches for the 1961–1990 base period at the Cooke City 2W, Northeast Entrance SNOTEL, and Fisher Creek SNOTEL climate stations. [Data for the Cooke City 2W station from NOAA (1992); data for the Northeast Entrance and Fisher Creek SNOTEL stations from NRCS (1996)].*

Month	Cooke City 2W	Northeast Entrance SNOTEL	Fisher Creek SNOTEL
Oct	1.5	1.5	3.0
Nov	2	2.2	6.2
Dec	2.2	2.1	6.8
Jan	2.4	2.5	8.6
Feb	1.8	1.9	6.1
Mar	1.9	1.7	6.4
Apr	1.8	2	5.1
May	2.6	2.6	4.8
June	2.8	2.5	3.9
July	2.1	2.1	2.8
Aug	2.1	1.9	2.4
Sept	2.4	2.2	2.9
Annual	26	25	59

(tables 1, 2). In general, higher elevations have lower temperatures and more precipitation than lower elevations. North- and east-facing slopes accumulate greater snowpack than south- and west-facing slopes. Mean bimonthly snow-water equivalents for the Northeast Entrance and Fisher Creek SNOTEL stations are listed in table 4.

## Summary

Climate data for the Soda Butte Creek basin upstream from Yellowstone National Park are available for the NOAA station, Cooke City 2W, and for the NRCS stations, Northeast Entrance SNOTEL and Fisher Creek SNOTEL. Temperature and precipitation data for the Cooke City 2W station are available for the 1961–1990 base period. Temperature data for the two NRCS stations are available for 1986–1995, and precipitation data for the two NRCS stations are available for the 1961–1990 base period. In general, temperatures are lower, and precipitation is greater at higher elevations in the study area; temperatures at lower elevations are higher, and precipitation is less. Basin average annual precipitation was estimated to be 56 in.

Pan evaporation for the Cooke City 2W station was estimated from pan-evaporation data at the Bozeman 6W climate station. To make this estimate, mean monthly pan evaporation at the Bozeman 6W climate station was multiplied by the ratio of mean maximum monthly air temperature at Cooke City 2W to that at the Bozeman 6W station. To estimate pan evaporation at the high-elevation Fisher Creek SNOTEL station, temperature data for the 1961–1990 period were required. A regression equation was used to estimate 1961–1990 mean maximum monthly temperature at the Fisher Creek SNOTEL station from mean maximum monthly temperature at the Cooke City 2W station. Pan evaporation was calculated from temperature and pan-evaporation data at the Bozeman 6W climate station for the Fisher Creek SNOTEL station and the Cooke City 2W station. Basin average annual evapotranspiration was estimated to be 27 in.

## Geology

### Bedrock Geology

Elliott (1979) mapped the bedrock geology of the Cooke City quadrangle at 1:24,000 scale. Bedrock in the upper Soda Butte Creek drainage consists of Precambrian metamorphic, Paleozoic sedimentary, and Eocene volcanic rock (plate 1). The eastern, upstream portion of the watershed is predominantly Precambrian granitic gneiss with slightly younger gabbro and dolerite dike intrusions and small plutons that were later metamorphosed. This crystalline rock is well exposed in the Colter Pass area

*Table 3. Estimated mean pan evaporation in inches at the Cooke City 2W and Fisher Creek SNOTEL climate stations.*

Month	Cooke City 2W	Fisher Creek SNOTEL
Oct	2.7	2.5
Nov	1.6	1.5
Dec	0	0
Jan	0	0
Feb	0.8	0.7
Mar	1.7	1.6
Apr	3.5	3.3
May	5.5	5.1
June	6.7	6.1
July	7.7	7.1
Aug	6.6	6.1
Sept	4.8	4.4
Annual	42	38

Table 4. Mean bimonthly snow-water equivalent in inches at the Northeast Entrance and Fisher Creek SNOTEL climate stations for the 1961–1990 period of record. (Data from NRCS 1996)

Month	Day of month	Northeast Entrance SNOTEL	Fisher Creek SNOTEL
Oct	1	0	0.4
	15	0	.90
Nov	1	0.3	2.6
	15	1	5.2
Dec	1	1.9	8.8
	15	2.9	12
Jan	1	4	16
	15	5.2	20
Feb	1	6.4	24
	15	7.3	27
Mar	1	8.1	30
	15	8.8	33
Apr	1	9.2	36
	15	9	38
May	1	5.9	39
	15	2.6	37
June	1	0.2	32
	15	0	21
July	1	0	5.9
	15	0	0
Aug	1	0	0
	15	0	0
Sept	1	0	0
	15	0	0

but obscured elsewhere by glacial deposits. Outcrops have been mapped as far downstream as Cooke City (plate 1). In the Cooke City area, younger, sedimentary rock overlies the crystalline rock (figure 5).

During the Paleozoic Era, a thick sequence of sedimentary rock was deposited unconformably on a gently sloping erosional surface of Precambrian rock (figure 5). Exposed sedimentary rock is predominantly Cambrian and includes the Flathead Sandstone, the Wolsey and Park shales, and the Meagher and Pilgrim limestones. The Pilgrim Limestone forms the spectacular cliffs on the south side of the valley between Cooke City and Silver Gate. Cambrian rock is overlain unconformably by Ordovician Bighorn Dolomite, which is overlain unconformably by the Devonian Jefferson, and Three Forks formations and the Mississippian Madison Limestone.

The Absaroka volcanic field became active in the Eocene Epoch and deposited the andesitic

volcaniclastic rock and flows of the Lamar River Formation unconformably on the Madison Limestone. The Heart Mountain Detachment fault (Pierce 1957) became active, and Ordovician and younger rock moved eastward on a nearly flat fault plane (figure 6) during the same period. This steep breakaway fault lies just west of the study area. Continued deposition of the Lamar River Formation blanketed the displaced blocks and filled tectonically denuded gaps.

Horizontally bedded, mostly volcaniclastic rocks overlying the Wapiti Formation form the highest peaks and ridge tops of the watershed. Small dikes and sills associated with the volcanism intruded the beds, and high-angle normal faults with minor displacement cut all rock. Despite this complex history, most bedrock remained nearly horizontal (figure 6) and form the striking layers seen in the valley walls today.

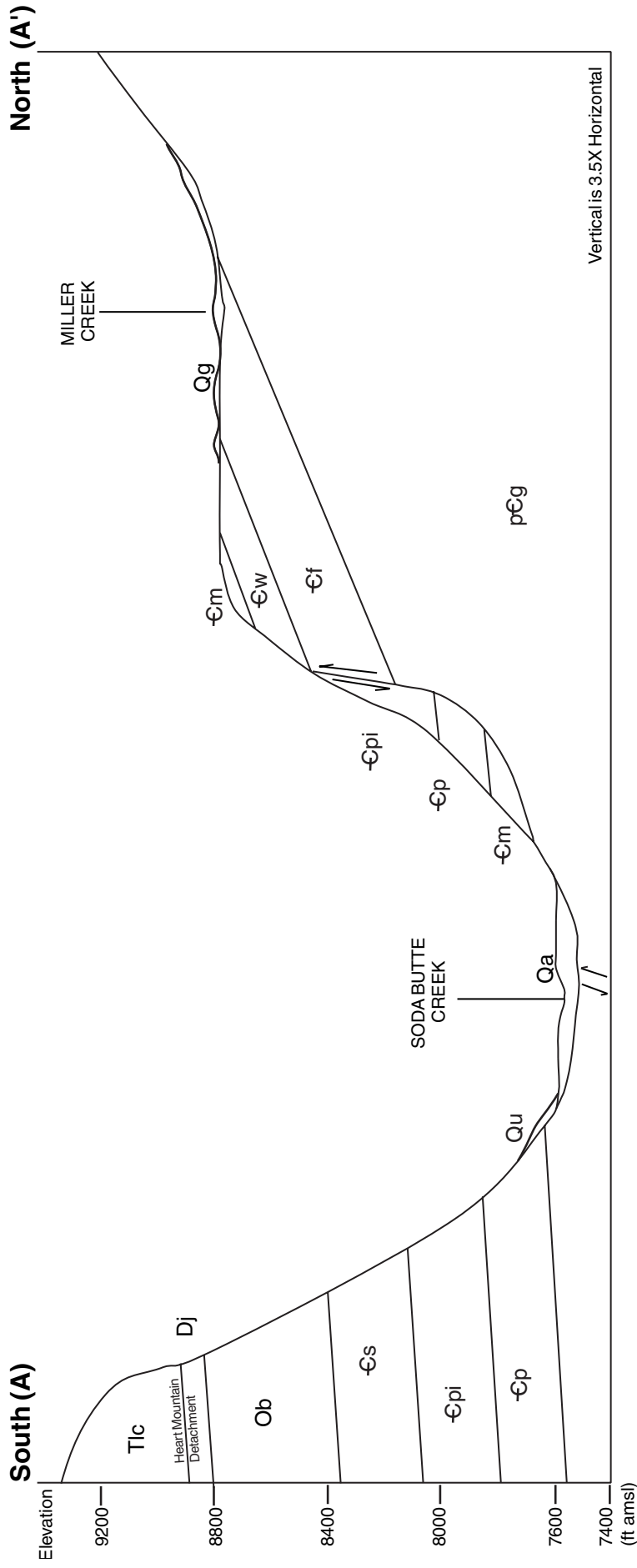
### Quaternary Geology

Prior to this study, area surficial geology was less known than bedrock geology. Pierce (1974) mapped the surficial geology of the adjacent Abiathar Peak quadrangle. Meyer *et al.* (1995b) studied alluvial fans in the Cooke City area and also mapped the surficial geology of lower Soda Butte Creek, downstream of the present study area. Pierce's (1974) units were slightly modified for use on a new 1:24,000-scale surficial geologic map of the Cooke City area, and much of his information on area Quaternary history was used for this study.

Several Pleistocene glaciations buried much of the bedrock beneath unconsolidated deposits. Surficial deposits exposed at present are mostly related to the Pinedale (latest) glaciation. During the Pinedale glaciation, all but the highest peaks were buried by a great ice cap that covered most of Yellowstone National Park and terminated down the Yellowstone valley near Pray, Montana. The Pinedale ice cap completely melted between 4,000 and 7,000 years ago (Pierce 1974, 1979). During the glaciation and subsequent melting, unsorted clay-rich till was deposited in moraines, well-sorted fluvial gravel was deposited in kames and in outwash fans, and the steep valley sides slumped to form large landslides. Modern stream deposits accumulated after the ice melted and consist of reworked glacial deposits and newly eroded bedrock. Fan deposits are still actively forming, particularly in years following forest fires (Meyers *et al.* 1995b).

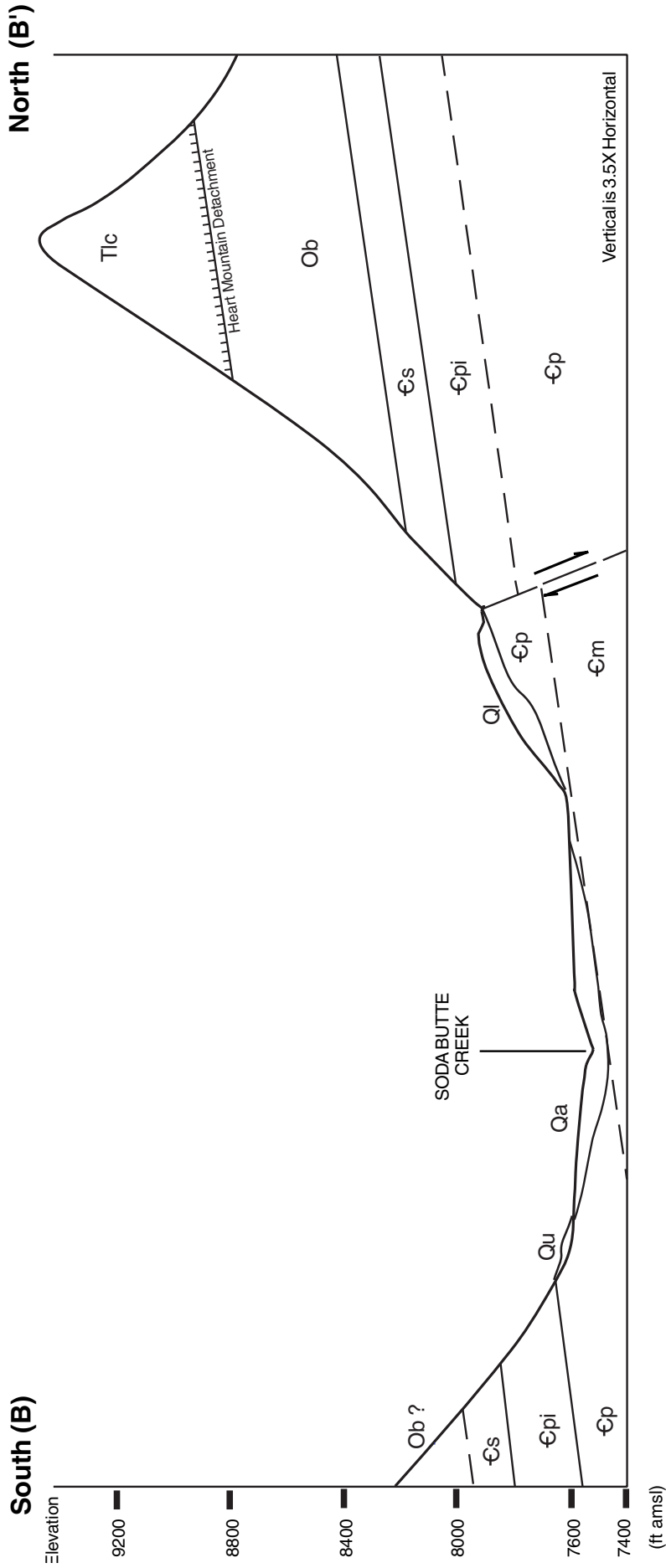
### Streamflow in Soda Butte Creek

Soda Butte Creek, located in the rugged Absaroka Mountains in south-central Montana about



- QUATERNARY**  
 Qa ALLUVIUM  
 Qu UNDIFFERENTIATED SURFICIAL DEPOSITS  
 Qg GLACIAL DEPOSITS: unconsolidated silt, clay, sand, gravel, cobbles, and boulders.
- TERTIARY**  
 Tlc LAMAR RIVER & CATHEDRAL CLIFFS FORMATION:  
 andesitic volcaniclastic rocks, lava flows, and intrusive breccias
- DEVONIAN**  
 Dj JEFFERSON FORMATION: medium-bedded dolomite and limestone
- ORDOVICIAN**  
 Ob BIGHORN DOLOMITE: thick-bedded dolomite and limestone
- CAMBRIAN**  
 -Cs SNOWY RANGE FORMATION: shale, limestone-pebble conglomerate limestone, and dolomite  
 -Cpi PILGRIM LIMESTONE: limestone and limestone-pebble conglomerate  
 -Cp PARK SHALE: thin-bedded shale and limestone  
 -Cm MEAGHER LIMESTONE: thin-bedded limestone  
 -Cw WOLSEY SHALE: thin-bedded limestone and shale  
 -Cf FLATHEAD SANDSTONE: medium-bedded sandstone
- PRECAMBRIAN**  
 pCg GRANITIC GNEISS: weakly to strongly foliated

Figure 5. The alluvium beneath Soda Butte Creek in the Cooke City area is underlain by granitic rock. The overlying sedimentary rock has been tilted slightly and faulted.



**QUATERNARY**

- Qa ALLUVIUM
- Qu UNDIFFERENTIATED SURFICIAL DEPOSITS
- Ql LANDSLIDE DEPOSITS: see text for detailed description

**TERTIARY**

- Tlc LAMAR RIVER & CATHEDRAL CLIFFS FORMATION: andesitic volcanoclastic rocks, lava flows, and intrusive breccias

**ORDOVICIAN**

- Ob BIGHORN DOLOMITE: thick-bedded dolomite and limestone

**CAMBRIAN**

- €s SNOWY RANGE FORMATION: shale, limestone-pebble conglomerate limestone, and dolomite
- €pi PILGRIM LIMESTONE: limestone and limestone-pebble conglomerate
- €p PARK SHALE: thin-bedded shale and limestone
- €m MEAGHER LIMESTONE: thin-bedded limestone
- €w WOLSEY SHALE: thin-bedded limestone and shale
- €f FLATHEAD SANDSTONE: medium-bedded sandstone

Figure 6. Soda Butte Creek alluvium is underlain by the Meagher Limestone in the Silver Gate area. Dashed contacts are inferred from thicknesses reported by Elliott (1979).

one mile east of Cooke City (figure 3), flows south and west through Cooke City to Silver Gate, then west to the boundary of Yellowstone National Park near the Northeast Entrance, and continues generally southwest for about 10 mi to its confluence with the Lamar River near the Lamar ranger station.

From its headwaters to the Northeast Entrance, Soda Butte Creek is a steep, high-mountain stream that drains about 32 mi<sup>2</sup> of mostly forested, rugged terrain. The average channel slope in this upper part of the Soda Butte Creek basin is 81.8 ft/mi (figure 7), and the mean basin elevation is 8,930 ft. Annual flow in Soda Butte Creek is predominantly the result of snowmelt runoff, and the seasonal variation is typical of high-elevation mountain streams with most of the annual runoff occurring in May and June.

Continuous streamflow records for Soda Butte Creek are available at the Montana DNRC streamflow-gaging stations at Cooke City (station 06187900) and Silver Gate, (station 06187910) (figure 8), and the USGS gaging station near Lamar ranger station, Yellowstone National Park (station 06187950) (figure 3), about 1.5 mi upstream from the mouth. Short-term seasonal streamflow record also is available for the NPS gaging station at the Northeast Entrance ranger station, Yellowstone National Park (station 06187915). The gaging stations, drainage areas, and periods of streamflow record through October 1997 are listed in table 5.

To administer provisions of the negotiated compact between the State of Montana and the National Park Service, long-term flow characteristics are needed for Soda Butte Creek at the Northeast Entrance ranger station. In addition, information about flow variation from the headwaters of Soda Butte Creek to the Northeast Entrance ranger

station is needed to determine the interaction between surface water and ground water upstream from the Northeast Entrance ranger station.

The methods for estimating long-term flow characteristics at the Northeast Entrance ranger station and a discussion of the long-term flow characteristics and their relation to long-term climatic characteristics are described in the following sections. The results of synoptic discharge measurements and water-quality analyses used for interpreting the downstream flow variation and surface water to ground water interaction also are addressed.

### Long-Term Flow Characteristics

To determine long-term flow characteristics at the Northeast Entrance ranger station, a streamflow correlation procedure was used to estimate missing daily discharges for the 1988–1997 period. Next, monthly discharges for the 1975–1980 period were estimated from data recorded at the Silver Gate gaging station using an adjustment factor. Finally, a streamflow-record extension program was used to estimate missing monthly flows for the 1938–1997 base period.

### Streamflow Correlation Procedure

Concurrent daily discharge records are available for sites at the Northeast Entrance ranger station and near the Lamar ranger station for June through October 1995, and May through October 1996 and 1997. Because of some uncertainty about the reliability of discharge values determined from the stage-discharge relation for the Northeast Entrance ranger station during 1997, daily discharges from May through July 12, 1997, were not used in the streamflow correlation procedure. Plotting the

Table 5. Streamflow-gaging stations, drainage areas, and periods of record for Soda Butte Creek and Yellowstone National Park.

Agency	Station number	Station name	Drainage area, in mi <sup>2</sup>	Period of record (through October 1997)
DNRC	06187900	Soda Butte Creek at Cooke City	5.88	September 1974 through August 1977
DNRC	06187910	Soda Butte Creek at Silver Gate	27.0	September 1975 through December 1980
NPS	06187915	Soda Butte Creek at Northeast Entrance ranger station, Yellowstone National Park	31.8	June through October 1995 May through October 1996 May through October 1997
USGS	06187950	Soda Butte Creek near Lamar ranger station, Yellowstone National Park	99.0	October 1988 through October 1997

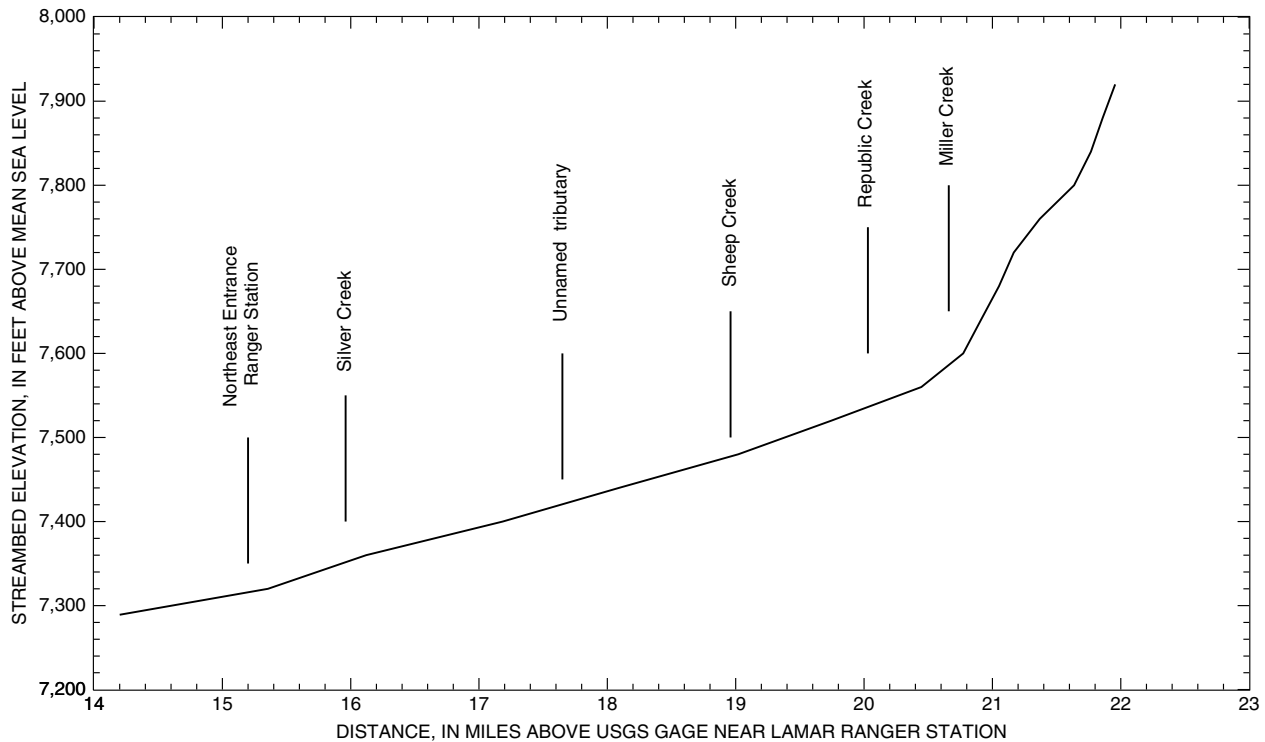


Figure 7. Streambed profile for upper Soda Butte Creek and Yellowstone National Park.

remaining 395 concurrent daily discharges on log-log paper indicates a linear relation between Soda Butte Creek discharges at the Northeast Entrance ranger station and near the Lamar ranger station; however, two lines having different slopes are more appropriate for the data than a single line. Accordingly, various trial-and-error groupings of discharge data were made, and separate Maintenance of Variance Extension, Type 1 (MOVE.1) lines were fit to each data group.

As described by Hirsch (1982), MOVE.1 lines are analogous to ordinary least squares regression lines (OLS), except MOVE.1 lines are derived so that estimates from the equation for the fitted line will have the same mean and variance as the short-term data set. Lines derived for OLS, by contrast, minimize the squared differences between estimated values and the short-term data set. Because the equation for an OLS line produces estimates that consistently have a smaller variance than the original short-term data, Hirsch (1982) has shown that use of a MOVE.1 line is preferable to use of an OLS line for the extension of short-term streamflow records.

The grouping of discharge data, based on a daily discharge of 125 cubic feet per second (cfs) at the USGS gaging station near the Lamar ranger station, resulted in separate MOVE.1 lines that intersected at the division point between the two groups. As shown in figure 9, the MOVE.1 line for discharges of 125 cfs had a steeper slope and less scatter about the line than the MOVE.1 line for discharges of 125

cfs. The flatter slope and greater scatter for larger discharges apparently result from greater variability in tributary inflow during times of snowmelt runoff than later in the season when tributary inflows are relatively small and have little variance. The larger discharges also exhibit a nonrandom scatter that is related to year-to-year snowmelt runoff variations from the upper part of the basin to the lower part. Most of the larger discharges that lie below the MOVE.1 line in figure 9 are from 1996 when snowmelt runoff occurred earlier at the USGS gaging station than at the Northeast Entrance ranger station. Overall, the single MOVE.1 line through the larger discharges provides generally reliable discharge estimates at the Northeast Entrance ranger station, even though the estimates might be biased high for years when snowmelt runoff at the Northeast Entrance site lags that at the USGS site. Standard errors of estimate—calculated as the standard deviation of the differences between values estimated from the equation and actual streamflow values at the Northeast Entrance ranger station (residuals)—are shown in percentages in figure 9.

The equations for the two MOVE.1 lines shown in figure 9 were used to estimate daily mean discharge at the Northeast Entrance ranger station for each day of missing record during the 1988–1997 period. Monthly mean discharges for each year were estimated by summing daily flows for each month then dividing by the number of days in that month.

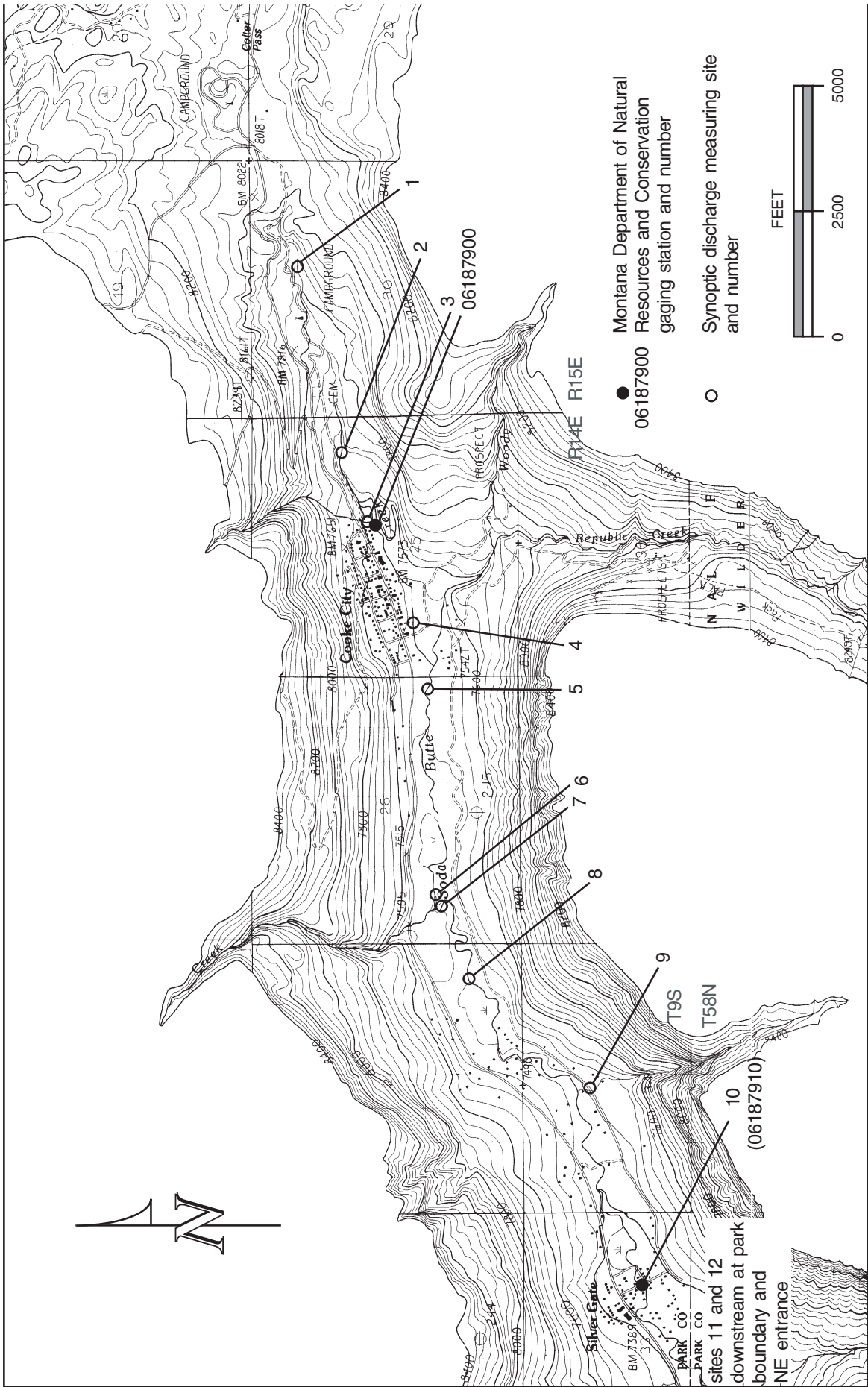


Figure 8. Synoptic discharge measurement sites and Montana DNRC streamflow-gaging stations, Soda Butte Creek area and Yellowstone National Park.

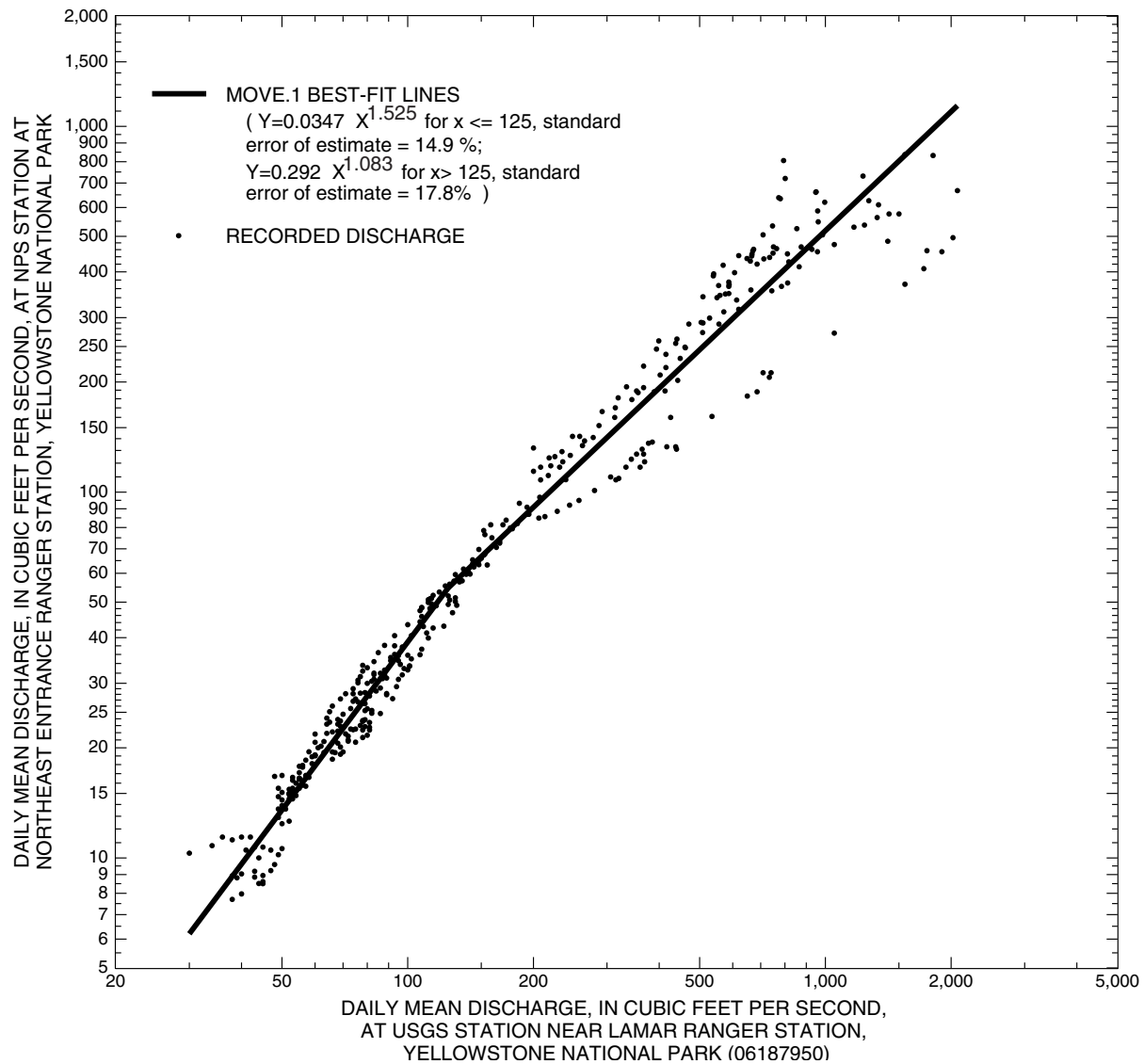


Figure 9. MOVE.1 lines relating Soda Butte Creek discharge at Northeast Entrance ranger station to discharge near Lamar ranger station, Yellowstone National Park.

### Record Adjustment for 1975–1980

The 1988–1997 period of recorded and estimated monthly discharges for the Northeast Entrance ranger station was supplemented by making the following assumption: monthly discharge recorded in 1975–1980 at the DNRC gaging station at Silver Gate would, after multiplying by an adjustment factor, be equivalent to discharge at the Northeast Entrance ranger station. Use of a constant adjustment factor was considered reasonable because the sites at Silver Gate and Northeast Entrance ranger station are only slightly more than a mile apart and have only minor intervening tributaries. Based on three concurrent measurements of discharge at each site in August, September, and October 1996, the adjustment factor for estimation of discharge at the Northeast Entrance ranger

station was determined to be 1.09. Thus, each recorded monthly discharge for the Silver Gate gaging station was multiplied by 1.09 to produce monthly discharge estimates for 1975–1980 at the Northeast Entrance ranger station.

### Streamflow Record Extension Program

The streamflow correlation procedure and record adjustment were used to estimate monthly flows for Soda Butte Creek at the Northeast Entrance ranger station for much of 1988–1997 and 1975–1980. Because hydrologic conditions for this relatively short time period may not be reflective of conditions over a longer time period, a streamflow record extension program was used to estimate monthly flows for the 60-year base period, 1938–1997. This base period was selected because it encompasses extended dry periods and wet periods and is

considered representative of long-term flow conditions for Soda Butte Creek.

A mixed-station record extension program was used for the monthly flow record Northeast Entrance ranger station (Alley and Burns 1983). The program selects one of several long-term base stations to estimate each month of missing record using the MOVE.1 curve-fitting procedure. The MOVE.1 curve-fitting equation is calculated for each base station using two methods. First, the MOVE.1 equation is calculated based only on concurrent flows for the month of missing flow record. For example, if a flow estimate is required for July 1948, the MOVE.1 equation would be calculated from all concurrent July flows at the station of interest and the base station. Next, the MOVE.1 equation is calculated based on all concurrent flows, regardless of month, at the two stations. The selection criterion for a base station for each month of missing record is based on the smallest standard error of prediction for either calculation method. Thus, different base stations may be used to estimate different months of missing record, and the estimates for any month might be based on concurrent flows for only that month or on all concurrent flows.

Nine long-term gaging stations on streams that are located near the Soda Butte Creek basin (figure 3) and considered to have flow characteristics similar to those of Soda Butte Creek were selected as potential base stations for the record extension program. The nine stations are listed with their drainage areas and periods of record in table 6. For the 60-year base period, 549 monthly flow estimates were required for the station at the Northeast Entrance, and table 6 also shows how many were made using each long-term station. The average standard error of prediction for all 549 estimates was 21.9%, which represents only the estimated error of the record extension program, not the total error. Total error would be larger than 21.9% because estimated monthly flows for Soda Butte Creek during much of 1988–1997 and 1975–1980 were used in the program.

## Results

The estimated long-term mean flows and flows having various exceedance percentages for Soda Butte Creek at the Northeast Entrance ranger station for the 1938–1997 base period are shown in table 7. For example, the long-term mean flow for July, 190 cfs, is the average of all 60 July mean flows. The July mean flow, having a 50% exceedance probability, 150 cfs, is the July mean flow that was exceeded in one-half of the 60 Julys during 1938–

1997. As the results in table 7 indicate, the lowest monthly flows occurred in March, and the highest flows occurred in June. Table 7 also indicates that monthly flows had the least variability, or smallest spread between low (90% exceedance probability) and high (10% exceedance probability) flows, in January and the greatest variability in July.

The annual distribution and variability of monthly flows are shown graphically by box plots in figures 10A, B. Because of the difficulty in comparing months having small flows on the box plots with discharge on a linear scale (figure 10A), figure 10B shows box plots with discharge on a logarithmic (base 10) scale. The box plots in figure 10B more clearly show the month-to-month changes and relative variability of monthly flows for low-flow months. Results in figures 10A, B indicate that monthly flow is sustained in Soda Butte Creek well into late summer and fall. Soda Butte Creek does not have the late summer low-flow trait like other Montana streams, probably because of delayed snowmelt distinctive to high average basin elevation and the lack of significant surface-water withdrawals for irrigation purposes.

## Comparisons to Precipitation and Evaporation

Assuming that ground-water inflow and outflow are balanced over the long term, comparison of long-term estimates of annual basin runoff, precipitation, and evaporation provides a gross indication of the hydrologic budget for Soda Butte Creek. Thus, mean annual precipitation minus evapotranspiration should be about equal to mean annual runoff. In this context, mean annual runoff is synonymous with mean annual flow at the Northeast Entrance ranger station. The long-term mean annual flow for Soda Butte Creek at the Northeast Entrance ranger station for the 1938–1997 base period is 66 cfs (table 7). Converting the mean annual discharge to a volume and then dividing by total basin area yields a long-term annual runoff of 28 in. for Soda Butte Creek at the Northeast Entrance ranger station. Comparison of long-term mean annual flow for the Yellowstone River at Corwin Springs for the 1938–1997 base period (3,180 cfs) and the 1961–1990 base period (3,220 cfs) showed that mean annual discharge was about the same for both periods. On that basis, mean annual flow for Soda Butte Creek was assumed to be about the same for the two periods. Thus, for purposes of assessing the hydrologic budget for Soda Butte Creek, the 1938–1997 base period used for flow determination was considered comparable to the 1961–1990 base period used to determine climate data.

Table 6. Long-term streamflow-gaging stations used as potential base stations for record extension for Soda Butte Creek.

USGS station number	Station name	Drainage area, in mi <sup>2</sup>	Period of record	Number of monthly flow estimates for Soda Butte Creek
06037500	Madison River near West Yellowstone, Montana	420	1913–1917; 1918–1921; 1922–1973; 1983–1986; 1988–1997	2
06186500	Yellowstone River at Yellowstone Lake outlet, Yellowstone National Park	1,006	1922–1982; 1983–1986; 1988–1997	11
06188000	Lamar River near Tower Falls ranger station, Yellowstone National Park	660	1923–1969; 1985–1986; 1988–1997	350
06191000	Gardner River near Mammoth, Yellowstone National Park	202	1938–1972; 1984–1997	73
06191500	Yellowstone River at Corwin Springs, Montana	2,623	1910–1997	45
06200000	Boulder River at Big Timber, Montana	523	1947–1953; 1955–1997	50
06204050	West Rosebud Creek near Roscoe, Montana	52.1	1965–1997	0
06205000	Stillwater River near Absarokee, Montana	975	1910–1914; 1935–1997	1
06207500	Clarks Fork Yellowstone River near Belfry, Montana	1,154	1921–1997	17

Table 7. Long-term (1938–1997) discharge in cfs for Soda Butte Creek at the Northeast Entrance, Yellowstone National Park. (QM, mean discharge)

Flow characteristic	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
90	6.3	3.3	2.8	2.4	2	1.5	2.3	57	230	52	20	12	43
80	7.5	3.9	3.4	2.7	2.1	2	3.3	72	280	88	24	13	48
75	8.1	4.4	4	2.9	2.4	2.3	4.2	75	300	100	25	14	50
70	8.6	4.9	4.1	3.2	2.6	2.3	4.8	85	310	110	26	14	55
60	10	5.8	4.3	3.5	2.6	2.6	5.6	99	330	130	28	16	61
50	12	6.8	4.7	4	3.2	2.7	7	110	370	150	32	18	64
40	13	8.6	5	4.1	3.8	3	8.7	130	390	180	37	21	67
30	15	9.2	5	4.4	4.2	3.4	14	150	410	220	45	22	71
25	16	9.7	5.1	4.5	4.5	3.6	16	160	420	250	48	23	73
20	17	10	5.5	4.8	4.9	4	19	180	450	300	53	25	82
10	21	13	6	5	5.8	5.8	27	200	560	390	60	30	92
QM	13	7.6	4.5	3.9	3.5	3.1	11	120	370	190	37	19	66

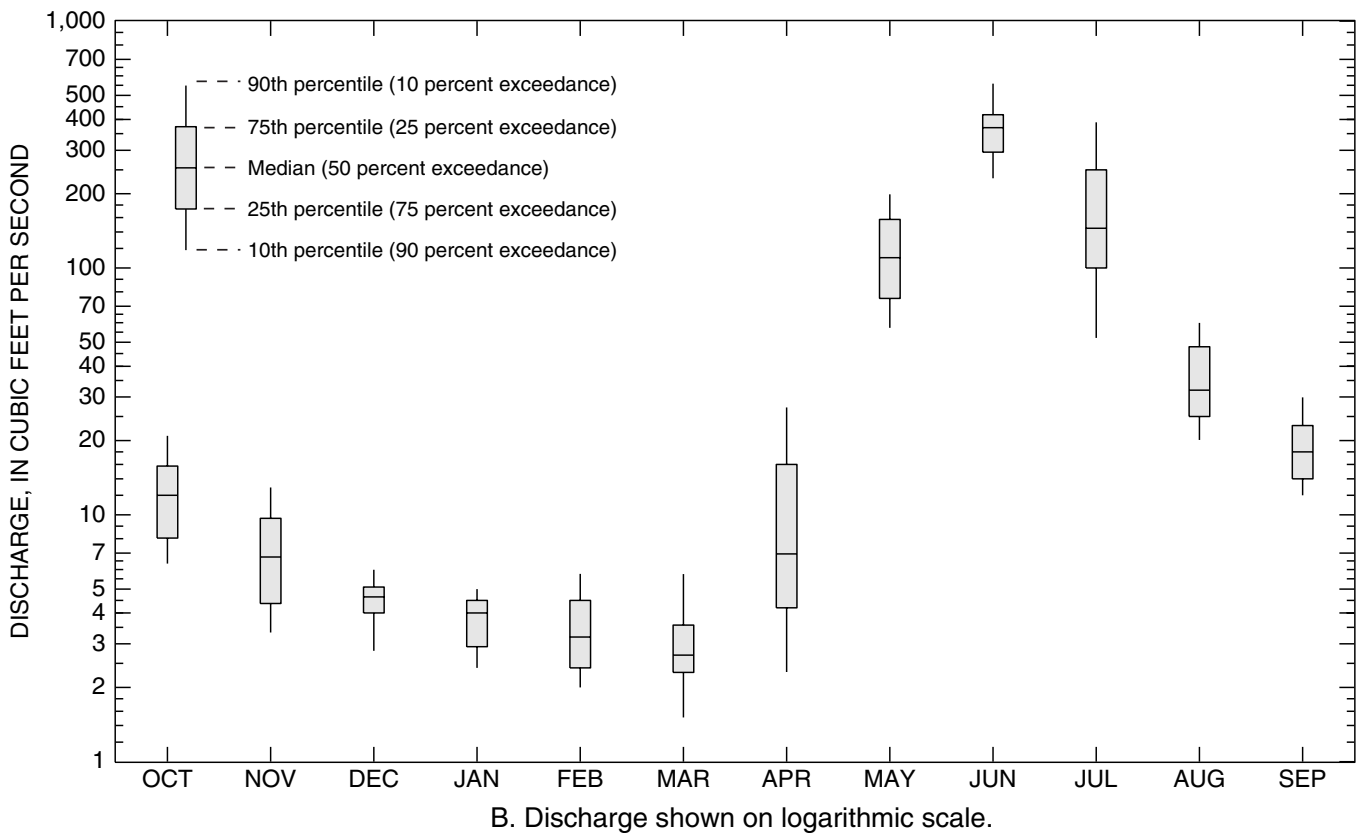
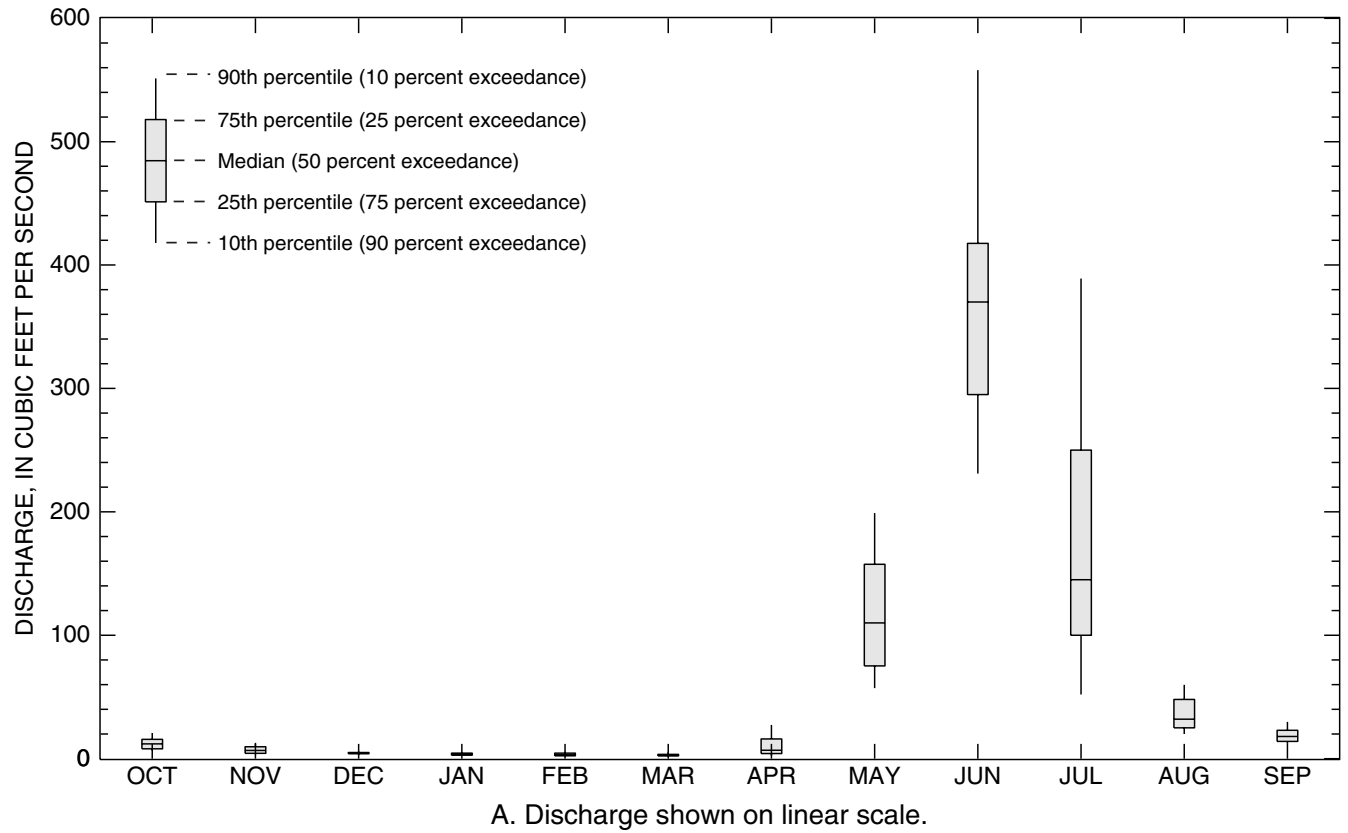


Figure 10. Box plots of estimated monthly discharge for 1938–1997 base period for Soda Butte Creek at Northeast Entrance ranger station, Yellowstone National Park.

Assuming that ground-water inflows and outflows are about equal annually, annual runoff is expected to be equal to annual precipitation minus annual evapotranspiration. For the upper Soda Butte Creek basin (above Northeast Entrance ranger station) mean annual precipitation (56 in., see Climate section) minus evapotranspiration (27 in., see Climate section) is 29 in. Given that this value is only about 4% larger than the estimated mean annual runoff, the basin average approximations for mean annual precipitation and mean annual evapotranspiration are considered reasonable.

A comparison of monthly values of basin average runoff, precipitation, and evapotranspiration shows the seasonal effects of climate on runoff. Long-term mean annual precipitation and evapotranspiration for the upper Soda Butte Creek basin were assumed to have monthly distributions similar to those for the Fisher Creek climate station (figure 3). Thus, long-term monthly values were calculated by multiplying the Soda Butte Creek basin average annual value by the ratio of each monthly value for the Fisher Creek climate station to the annual value for the Fisher Creek climate station. For example, table 6 in the Climate section shows a monthly value of precipitation for November of 6.2 in. and an annual value of precipitation of 59 in. for the Fisher Creek climate station. Therefore, November precipitation for the upper Soda Butte Creek basin was estimated as  $56 \times (6.2/59)$ , or 5.9 in. The estimated basin average monthly values for precipitation and evapotranspiration are shown with estimated basin average values of runoff in table 8. A graphical comparison of long-term monthly values of precipitation, evapotranspiration, and runoff is shown in figure 11A, and a graphical comparison between mid-monthly snow-water equivalent at the Fisher Creek climate station and monthly runoff is shown in figure 11B. Figure 11 shows that precipitation is stored as snow in the winter months, and snowmelt is the predominant component of runoff from upper Soda Butte Creek basin in spring and early summer.

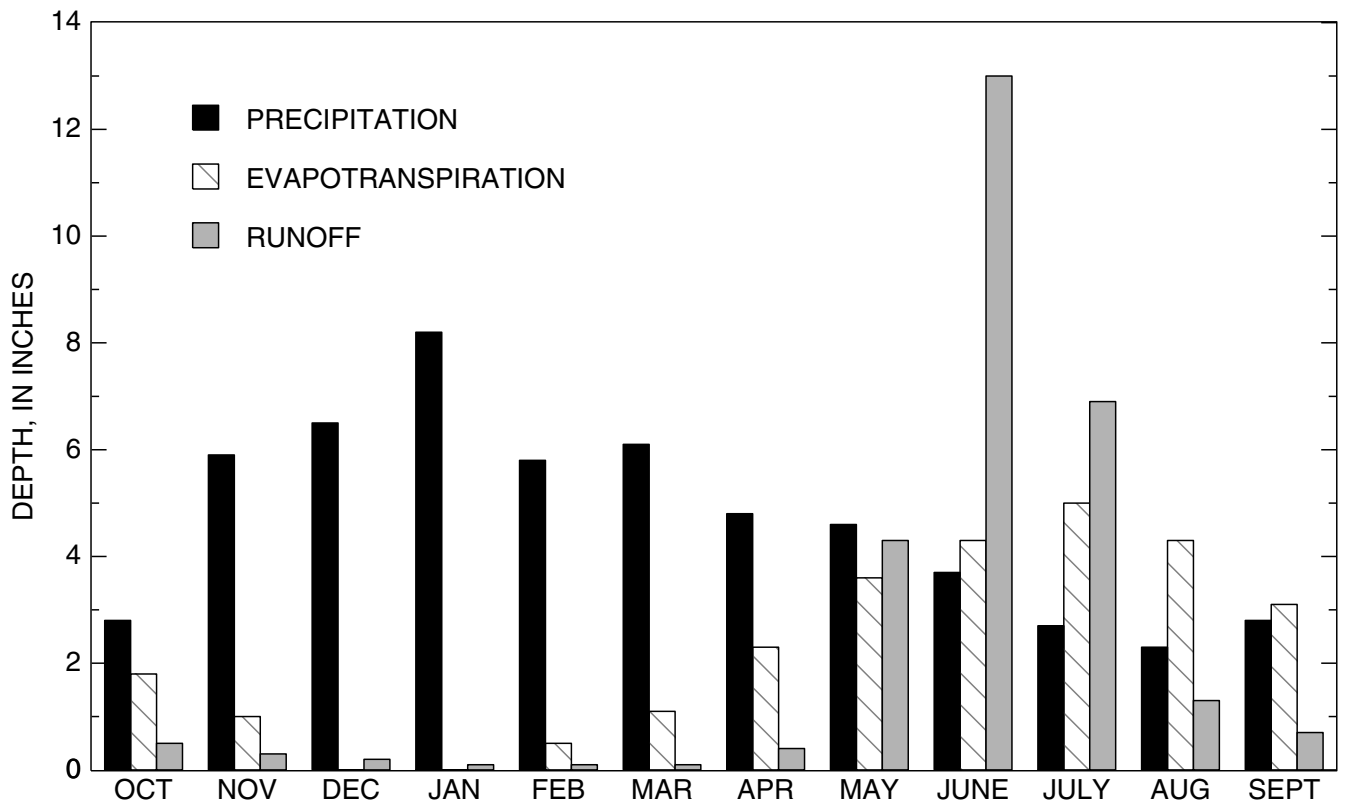
### Spatial Variations in Streamflow

To help determine the streamflow variation between adjacent reaches of Soda Butte Creek, synoptic discharge measurements were conducted in August, September, and October 1996; March 1997; and March 1998. Each series of measurements was taken on the same day or successive days, during times of stable flow, to help ensure that discharge variations among sites were the result of ground-water discharge or recharge and

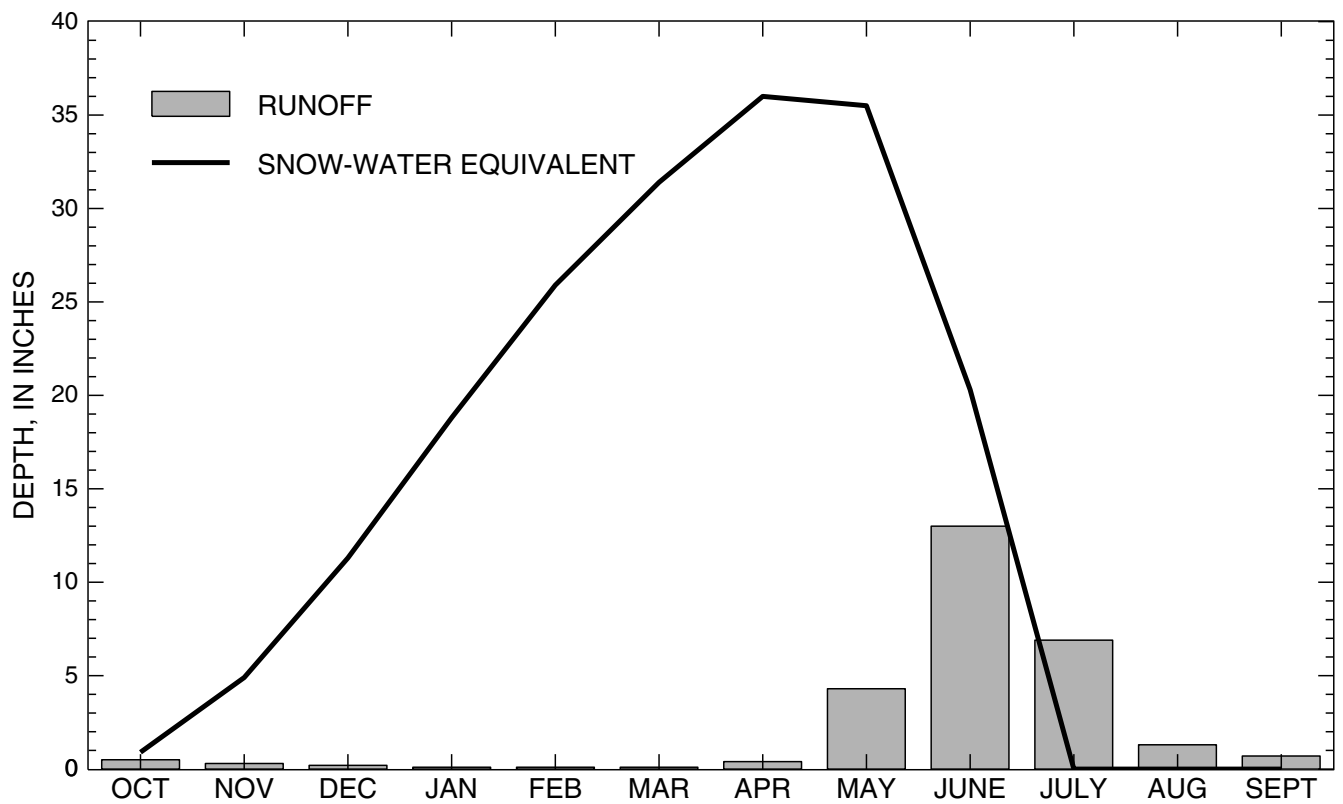
Table 8. Long-term mean values in inches of precipitation, evaporation, and runoff for Soda Butte Creek basin above Northeast Entrance, Yellowstone National Park during the 1961–1990 base period.

Month	Precipitation	Evapo- transpiration	Runoff
Oct	2.8	1.8	0.5
Nov	5.9	1.0	.3
Dec	6.5	0	.2
Jan	8.2	0	.1
Feb	5.8	.5	.1
Mar	6.1	1.1	.1
Apr	4.8	2.3	.4
May	4.6	3.6	4.3
June	3.7	4.3	13
July	2.7	5.0	6.9
Aug	2.3	4.3	1.3
Sept	2.8	3.1	.7
Total	56	27	28

not flow surges. Some measurement sites were selected on a reconnaissance trip in March 1996, and the remaining sites were selected during the first measurement series in August 1996. The locations of the synoptic measurement sites are shown in figure 1. The sites are described and discharge data shown in table 9. Figure 12 displays graphically how discharge changes along Soda Butte Creek under varying runoff conditions. The measured discharges are plotted against measurement site location, expressed in river miles from the synoptic discharge measurement site farthest upstream, and lines are drawn connecting each measured discharge in each series. At two tributary sites, Miller Creek (site 3) and an unnamed tributary (site 9), discharge was measured in the tributary but not in Soda Butte Creek. At these locations, discharge in Soda Butte Creek, just upstream from the tributaries, was assumed to be equal to discharge at the next upstream mainstem site. These reaches of assumed equal discharge are denoted by dashed lines in figure 12. Not all sites were measured in some series because of heavy snow and ice conditions; thus, some lines in figure 12 are discontinuous. Tributary inflows to Soda Butte Creek are indicated by abrupt vertical rises in the lines connecting measurements. For example, the abrupt rises in each line near mile 1.6 indicate tributary inflow from Republic Creek.



A. Precipitation, evapotranspiration, and runoff.



B. Runoff and snow-water equivalent.

Figure 11. Comparisons between long-term mean monthly precipitation, evapotranspiration, and runoff and snow-water equivalent, upper Soda Butte Creek basin.

Table 9. Discharge measurement sites and measured discharges, upper Soda Butte Creek basin. (latitude [Lat] and longitude [long] expressed in degrees, minutes, and seconds; E, estimated discharge)

Site number	Stream name	Location	Date	Discharge (cfs)
1	Soda Butte Creek near Cooke City, Montana	Lat 45°01'30", long 109°54'22", in SE1/4NW1/4 NE1/4NE1/4 section 30, T. 9 S., R.15 E., Park County, Hydrologic Unit 10070001 on logging road 0.05 mi upstream from Cooke City spring/well house, 0.25 mi from USFS Campground on service road, and 1.45 mi northeast of Cooke City, Montana	08/22/99	0.103
			09/11/96	.015
			10/23/96	.001E
2	Soda Butte Creek above Miller Creek, at Cooke City, Montana	Lat 45°01'19", long 109°55'22", in NW1/4SE1/4 NE1/4 section 25, T 9 S., R. 14 E., Park County, Hydrologic Unit 10070001, 100 ft upstream from ford on Soda Butte Creek, 0.3 mi upstream from Miller Creek, and 0.5 mi northeast of Cooke City, Montana	08/22/96	2.65
			09/11/96	1.25
			10/23/96	95
3	Miller Creek at mouth, at Cooke City, Montana	Lat 45°01'16", long 109°56'18", SE1/4SW1/4 NE1/4 section 25, T. 9 S., R.14 E., Park County, Hydrologic Unit 10070001, at downstream end of concrete box culvert under U.S. Highway 212, 200 ft upstream from mouth at eastern edge of Cooke City, Montana	9/11/96	.33
			10/23/96	.2E
4	Soda Butte Creek above Republic Creek, at Cooke City, Montana	Lat 45°01'07", long 109°56'07", in NE1/4NW1/4 SW1/4 section 25, T. 9 S., R.14 E., Park County, Hydrologic Unit 10070001, at snowmobile trail crossing just south of Hi Country Motel, 400 ft upstream from county road bridge, 0.2 mi upstream from Republic Creek, at Cooke City, Montana	08/21/96	3.5
			09/11/96	0.83
			10/23/96	0.99
5	Soda Butte Creek below Republic Creek, at Cooke City, Montana	Lat 45°01'03", long 109°56'28", in SE1/4NW1/4 SW1/4 section 26, T. 9 S., R. 14 E., Park County, Hydrologic Unit 10070001, 500 ft downstream from confluence of Republic Creek and 0.4 mi southwest of Cooke City, Montana	08/21/96	15.2
			09/12/96	6.81
			10/24/96	4.5
			08/21/96	1.52
			03/31/98	0.953
6	Soda Butte Creek above Sheep Creek, near Cooke City, Montana	Lat 45°01'02", long 109°57'27", in SE1/4NW1/4 SW1/4 section 26, T. 9 S., R. 14 E., Park County, Hydrologic Unit 10070001, 250 ft upstream from confluence of Sheep Creek and 1.18 mi west of Cooke City, Montana	08/21/96	17.2
			09/12/96	8.08
			10/24/96	3.06
			03/27/97	0.138
			03/31/98	0.106
7	Soda Butte Creek below Sheep Creek, near Cooke City, Montana	Lat 45°01'02", long 109°57'31", in SW1/4 NW1/4 SW1/4 section 26, T. 9 S., R. 14 E., Park County, Hydrologic Unit 10070001, 50 ft downstream from confluence with Sheep Creek and 1.7 mi west of Cooke City, Montana	08/21/96	23.6
			09/12/95	11.5
			11/24/96	5.06
			03/27/97	1.03
			03/31/98	1.03
8	Soda Butte Creek below Sheep Creek, near Silver Gate, Montana	Lat 45°00'56", long 109°57'52", in NW1/4SE1/4 SE1/4 section 27, T. 9 S., R. 14 E., Park County, Hydrologic Unit 10070001, near powerline crossing, 0.55 mi downstream from Sheep Creek, and 1.4 mi northeast of Silver Gate, Montana	04/03/96	2.14
			08/21/96	24.2
			09/12/96	11.9
			10/24/95	6.42
			03/27/97	2.97
9	Unnamed tributary of Soda Butte Creek at Silver Gate, Montana	Lat 45°00'32", long 109°58'22", in NE1/4SE1/4 NW1/4 section 34, T. 9 S., R. 14 E., Park County, Hydrologic Unit 10070001, 50 ft upstream from USFS bridge, 0.95 mi downstream from Sheep Creek, and 0.85 mi east of Silver Gate, Montana	10/24/96	5E
			08/21/96	1.78
			09/12/96	0.67
			10/24/96	5E
10	Soda Butte Creek at Silver Gate, Montana (06187910)	Lat 45°00'21", long 109°59'17", in SE1/4SW1/4 NE1/4 section 33, T. 9 S., R. 14 E., Park County, Hydrologic Unit 10070001, on right bank 30 ft downstream from county bridge at Silver Gate, Montana, at river mile 18.8.	04/03/96	0.91
			08/21/96	27.8
			09/12/96	14.6
			10/24/96	6.92
			03/27/97	2.87
11	Soda Butte Creek at Park Boundary, at Silver Gate, Montana	Lat 45°00'11", long 110°00'04", in SW1/4NW1/4SW1/4 section 33, T. 9 S., R. 14 E., Park County, Hydrologic Unit 10070001, at Yellowstone Park Boundary, 0.25 mi downstream from Silver Creek, and 0.75 mi south west of Silver Gate, Montana	03/31/98	2.46
			04/03/96	1.27
			08/21/96	29.7
			09/12/96	13.9
			10/24/96	7.61
12	Soda Butte Creek at Northeast Entrance ranger station, Yellowstone National Park (06187915)	Lat 45°00'12", long 110°00'37", unsurveyed, Park County, Hydrologic Unit 10070001, 600 ft southwest of Northeast Entrance ranger station, 0.75 mi downstream from Silver Creek, and 1.0 mi west of Silver Gate, Montana	03/27/97	2.88
			03/31/98	2.77
			08/21/98	30.9
			09/12/96	14.7
			10/24/96	7.86

Gradual rises in the lines in the downstream direction among measurement sites indicate gains in streamflow from ground-water inflow or unmeasured small flows from small tributaries or springs. Similarly, gradual decreases in the lines in the downstream direction indicate losses of streamflow to evapotranspiration or to the underlying aquifer.

As figure 12 indicates, the three measurements made during low-flow conditions showed a streamflow loss between Republic and Sheep creeks. Although the magnitude of loss is small (less than 1.5 cfs), it is a significant percentage of the small flow in the stream, and it is significantly greater than the estimated measurement error of about 5–10%. Measurements during higher flow conditions in August and September 1996 showed a gain in streamflow between Republic and Sheep creeks.

Figure 12 also indicates that small streamflow losses occurred in Soda Butte Creek between Miller Creek and Republic Creek (sites 3, 4) and between Silver Gate and the Yellowstone National Park boundary (sites 10, 11) in September 1996. These differences are within the range of expected

measurement error and may not be true losses. For all other stream reaches, the synoptic discharge measurements indicated stable or slightly increasing streamflows.

Based on recorded discharges at the USGS streamflow-gaging station near the Lamar ranger station, the synoptic discharge measurements made during March 1997 and March 1998 were near the time of annual low flow for Soda Butte Creek. These baseflow conditions, prior to the beginning of snowmelt runoff, represent the times when flow in Soda Butte Creek is predominantly supplied by ground-water inflow. As indicated in figure 12, baseflow in upper Soda Butte Creek was slightly greater in 1997 than in 1998.

### Water Quality

Water-quality analyses may be used to help infer ground-water/surface-water interaction along stream reaches as well as provide a general indication of water quality at the time of sampling. For example, surface water tends to have smaller concentrations of most water-quality constituents than does ground

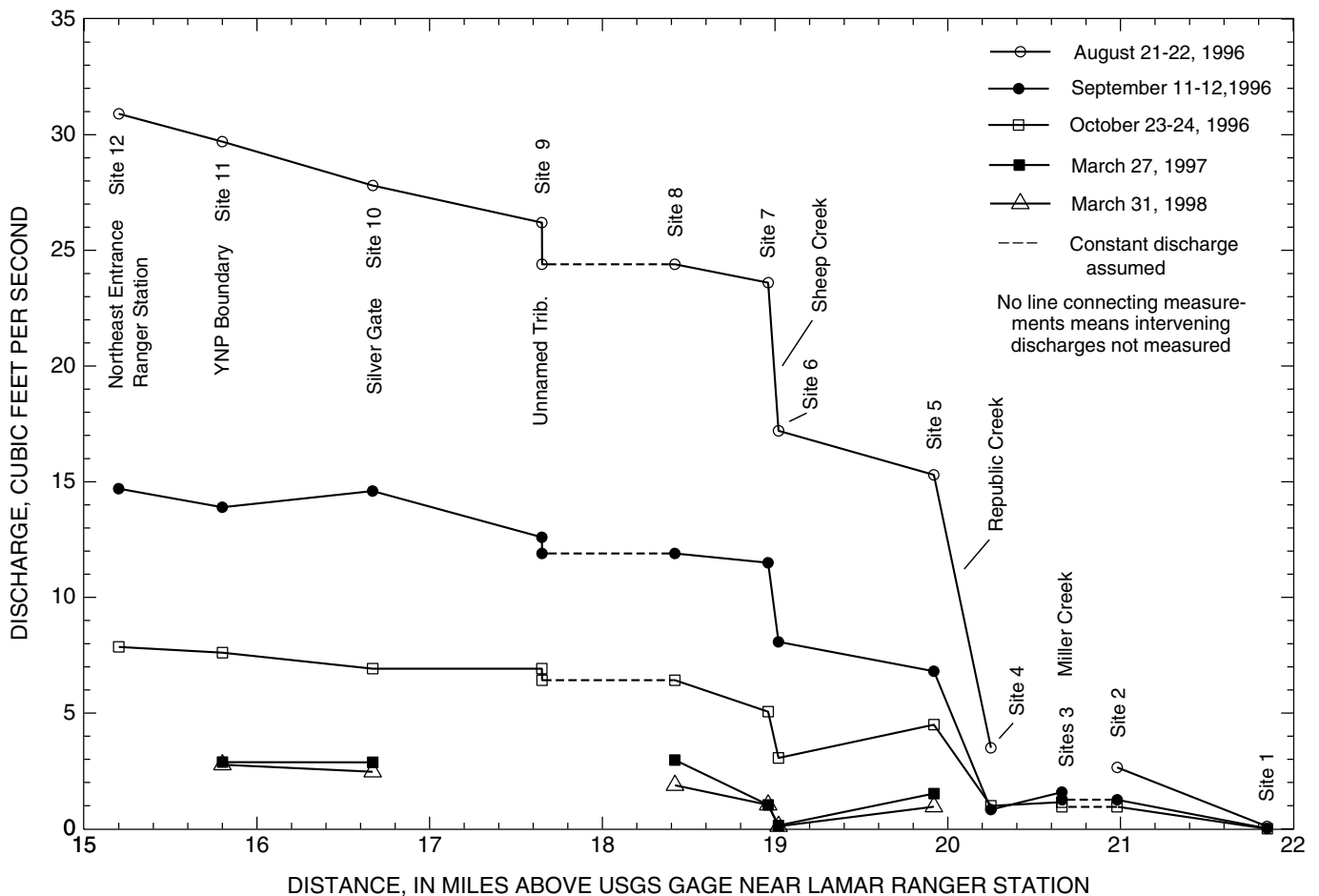


Figure 12. Synoptic discharge measurements during 1996, 1997, and 1998 on upper Soda Butte Creek and Yellowstone National Park.

water. Thus, a decrease in a constituent concentration from one sampling site to another may indicate some surface-water inflow between the sites. Conversely, an increase in concentration may indicate some ground-water inflow between the sites.

Water-quality samples were collected at six sites during the base flow measurements of March 27, 1997. Samples were analyzed by the Montana Bureau of Mines and Geology in Butte. The results of the water-quality analyses for the six sites are shown in table 10. Although Soda Butte Creek upstream from Cooke City typically is affected by some mine-waste discharge, that portion of the stream was frozen during the time of sampling. Thus, the water-quality data reflect conditions in Soda Butte Creek downstream from Republic Creek, a major tributary. Although some mining has occurred in the Republic Creek watershed, the water quality at the mouth probably is not affected appreciably by mining; therefore, inflow from Republic Creek probably dilutes any elevated metal concentrations in Soda Butte Creek.

The results of the water-quality analyses in table 10 show an increase in concentration of most constituents from site 5 to site 6. Although these increases may indicate ground-water inflow, measured discharge on March 27, 1997, (table 9) decreased from site 5 to site 6. The increased concentrations may be the result of some ground-water inflow followed by subsequent flow losses to the underlying aquifer. The increases, particularly in  $\text{CaCO}_3$ , Ca, and  $\text{HCO}_3$ , may also reflect the downstream change in drainage-basin geology from granite to limestone and shale.

Concentration of most constituents decreased, and discharge increased somewhat from site 6 to site 7, probably as a result of inflow of relatively dilute water from Sheep Creek. From site 7 to site 11, concentrations generally decreased by a small amount, while discharge increased from site 7 and site 8, then generally remained about constant from site 8 to site 11. The slight decrease in constituent concentration indicates that the inflow between sites 7 and 8 was probably mostly surface water.

The analyses shown in table 10 indicate that the surface-water quality from the sampled reach of Soda Butte Creek generally is acceptable for most uses. No trace-element concentration exceeded aquatic-life or drinking-water standards established by the State of Montana, Montana Department of Environmental Quality (1995), and the U.S. Environmental Protection Agency (1986). Nitrate levels, while not a threat to human health, are higher than the minimum reporting level and generally increase in the downstream direction.

## Summary

Continuous streamflow records for Soda Butte Creek are available for Montana DNRC streamflow-gaging stations at Cooke City (station 06187900) and at Silver Gate (station 06187910) and the USGS streamflow-gaging station near Lamar ranger station, Yellowstone National Park (station 06187950) located about 1.5 mi upstream from the mouth. The short-term seasonal streamflow record also is available at the NPS streamflow-gaging station at the Northeast Entrance ranger station, Yellowstone National Park (station 06187915).

To estimate long-term flow characteristics for the Northeast Entrance ranger station, a streamflow correlation procedure first was used to estimate monthly flows for the 1988–1997 period, based on concurrent flows at the station near the Lamar ranger station. Monthly flows for the 1975–1980 period also were estimated for the Northeast Entrance ranger station by applying an adjustment factor to recorded discharges at Silver Gate. A streamflow record extension program then was used to extend the estimated short-term record at Northeast Entrance ranger station to a long-term base period, water years 1938–1997. The base period contains extended dry periods and wet periods and is considered representative of long-term flow conditions for Soda Butte Creek. For the 60-year base period, 549 monthly flow estimates were required for the station at Northeast Entrance ranger station.

The long-term mean annual discharge for Soda Butte Creek at the Northeast Entrance ranger station, based on the 1938–1997 base period, is 66 cfs. Converting this mean annual discharge to a volume and then dividing by the total basin area above the Northeast Entrance ranger station yields a long-term annual runoff for Soda Butte Creek of 28 in. Comparing the long-term annual runoff for the upper Soda Butte Creek basin to estimated long-term annual precipitation minus evapotranspiration showed only about a 4% difference. On this basis, estimates of annual runoff, precipitation, and evapotranspiration were considered reasonable.

Three series of measurements taken during low-flow conditions showed a streamflow loss between Republic and Sheep creeks. Measurements during higher flow conditions in August, September, and October 1996 showed a streamflow gain between Republic and Sheep creeks. Based on recorded discharges at the USGS streamflow-gaging station near Lamar ranger station, the synoptic discharge measurements made during March 1997 and March 1998 were near the time of annual low flow for



Soda Butte Creek. These baseflow conditions prior to the beginning of snowmelt runoff represent the times when flow in Soda Butte Creek is predominantly the result of ground-water inflow.

Water-quality samples were collected at six sites during the baseflow measurements of March 27, 1997. Changes in constituent concentrations were used to infer that some ground-water inflow probably occurred between sites 5 and 6, even though measured streamflow decreased. Changes in constituent concentrations also were used to infer that increased flow from sites 7 to 11 was probably from surface water. Quality generally was good, with no measured constituent concentrations exceeding aquatic-life criteria or drinking-water standards.

## Aquifer Characteristics

The definition of the term *aquifer* is generally broad and taken as any natural material that is saturated and capable of transmitting ground water. There are many individual lithologic units within the Soda Butte Creek basin that fit this definition; however, for the purposes of discussion, there are two principal aquifers: the bedrock aquifer and the unconsolidated, valley-fill aquifer. A third, minor aquifer is the material on the valley margins, which includes landslide deposits, fan deposits, and colluvial material in the Silver Gate area and glacial till, fluvial gravel, and some fan deposits in the Cooke City area. Information on the hydrogeologic characteristics of these aquifers is generally restricted to that gained from domestic wells in the lower elevations of the basin and from investigations related to the New World mining district in the Miller Creek tributary drainage.

### Bedrock Aquifer

As noted in the description of the area geology, the bedrock within the lower elevations of the basin consists of Paleozoic limestone, dolomite, shale, and sandstone in the area of Silver Gate. The basin upstream of Cooke City also includes granitic rock. Domestic wells completed in these aquifers are rare; only eight of the approximately 150 wells in the basin are known to be completed in bedrock. Aquifer tests and analyses conducted by Maxim Technologies, Inc. (1995) concluded that the hydraulic conductivity of the Meagher Limestone in the upper reaches of Miller Creek is about 0.004–0.045 ft/d and the hydraulic conductivity of the Wolsey Shale in the lower reaches of Miller Creek is on the order of 42–66 ft/d. The shale is unlikely to be conductive, unless extensively fractured. As might

be expected, the hydraulic conductivity in both formations is related to the degree of fracturing. Kirk (1995) reported a value of 0.14 ft/d for the hydraulic conductivity of the Precambrian granite bedrock and 0.85 ft/d for the Tertiary volcanic rock in the adjacent, Fisher Creek drainage. Information collected during this investigation suggests yields of less than one gallon per minute (gpm) from wells completed in the Park Shale, underlying the lower reaches of Soda Butte Creek. Limited specific-capacity data suggest a hydraulic conductivity value of about 0.5 ft/d or less. Wells completed in the upper 100 ft of the granite above Cooke City have sustained yields of 10 gpm or more. The hydraulic conductivity, which is certainly controlled by the extent of fracturing, is on the order of 20 ft/d based on the specific capacity of two wells. Overall, the bedrock aquifers produce only a small amount of water. The granite above Cooke City is probably capable of producing enough water for domestic use, but only in areas where fracture density is sufficient. The Park shale and other sedimentary bedrock in the lower reaches of the drainage are unlikely to produce much water.

### Valley-Fill Aquifer and Valley-Margin Material

The valley-fill aquifer comprises Quaternary stream-laid gravels and cobbles derived from reworked glacial, landslide, and fan deposits. These valley-margin materials have exerted local controls on the stream and, consequently, on near-stream ground-water flow. Figure 13 presents new mapping of the surficial deposits in the main stem of the upper Soda Butte Creek drainage. The descriptions of each lithologic unit are based on field mapping and, where available, lithologic logs for domestic wells.

#### Mill Tailings (t)

The largest tailings deposit in the upper Soda Butte Creek drainage is upstream of Cooke City and is known as the McLaren tailings. These tailings were the subject of an investigation by Sonderegger *et al.* (1975) who estimated the hydraulic conductivity of the tailings material to be 1.3 ft/d, which is slightly higher than the bedrock aquifers, but much lower than the natural valley-fill material discussed later. The tailings were recontoured and stabilized after the large, local forest fires in 1988. A smaller, unrelated tailings deposit and smelter slag can be observed on Republic Creek near its mouth. Streamside tailings can be found along the creek well into the park. Within the study area, they are characterized as small (<100ft<sup>2</sup>) areas of tan-to-light brown, fine-

grained sand usually devoid of vegetation. Stringers or discontinuous layers of tailings can be observed in freshly eroded stream banks.

#### Colluvium and Talus (ct)

These deposits consist of unconsolidated, unsorted, locally derived accumulations of angular boulders, cobbles, pebbles, sand, and silt on slopes and include the talus (ta), talus flow (tf), avalanche debris (ad), and rubble veneer (pr) of Pierce (1974). Several wells in the Silver Gate area and upstream have been drilled through this material, but no wells have been completed in this unit.

#### Stream Gravel (sg)

This material is moderately to well-sorted, stratified gravel and sand and includes considerable clay and silt in overbank deposits as well as the fine-grained humic alluvium (fa) of Pierce (1974). Gravels and cobbles are subrounded to well rounded and include lithologies from the entire drainage basin. In the subsurface and active stream bed, the material is dominated by coarse gravels and cobbles in the Cooke City area. Grain sizes generally decrease downstream, and fine-grained materials, including silts and clays, become more common near Silver Gate. This grain size reduction may be caused, in part, by the introduction of finer grained material from fans actively depositing on the flood plain. As shown in figure 13, the stream-gravel unit underlies active stream channels and flood plains and is also the principal aquifer for the basin. The vast majority of area domestic wells are completed at various depths within this unit. For this reason, a more detailed discussion of the hydrogeologic properties of the stream-gravel materials unit will be presented in later sections.

#### Fan Gravel (fg)

Fan-gravel deposits are moderately-to-poorly sorted, stratified pebble-to-boulder gravel in alluvial fans. These subangular clasts are locally derived and include debris flow, hyperconcentrated flow, and the streamflow facies of Meyer *et al.* (1995a); consequently, the sedimentary structures and hydrologic characteristics are quite variable. For example, the Miller Creek fan is a poorly sorted, boulder debris-flow deposit while at least some of the Silver Creek fan represents a well-sorted, stratified streamflow deposit, 10–50 ft thick (Pierce 1974).

The influence of these deposits on Soda Butte Creek is particularly evident in the area between the park boundary and Sheep Creek. Two large fans are located just downstream and upstream of Silver Gate, and a third lies at the mouth of Sheep Creek.

Upstream of each fan are large, flat areas of shallow ground water. A few wells are completed near the edge of these marshy areas, but it appears that houses are built only after fill material is brought in. Wells have been drilled into these fans around Silver Gate, but all appear to have been completed in the underlying stream gravels.

#### Landslide (ls)

Landslide deposits are unsorted and unstratified mixtures of locally derived material that has been transported down steep slopes. In the upper Soda Butte Creek drainage these deposits are characterized by irregular hummocky surfaces and the presence of angular boulders, up to 15 ft in diameter. Although several houses have been constructed at the base of landslide deposits, near Silver Gate north and south of Soda Butte Creek, no wells have been completed within landslide material. Springs are nearly nonexistent in this material, which appears to be moderately to well drained. Lithologic logs do not distinguish the landslide material from the underlying stream deposited materials.

#### Glacial Till (Pinedale) (pt)

Glacial till deposits are unsorted, mostly unstratified clay, silt, sand, and gravel with subrounded boulders up to 10 ft in diameter. Tills are mostly found in thin ground moraines overlying bedrock. In the Cooke City area, they are characterized by subrounded granitic and gneissic boulders that have been transported from outside the present-day drainage basin. Based on lithologic logs of domestic wells, the till thickness ranges from about six feet near the Fisher Creek–Soda Butte Creek drainage divide to more than 20 ft in the lower elevations of the main valley. This till is poorly drained and has numerous springs emanating from slope breaks. Spring flow steadily decreases through the summer and fall months, but during the two years of this study, flow continued until snow cover. All domestic wells for houses built on the till are completed in the material underlying the till, which is most often bedrock.

#### Fluvial Gravel (Pinedale) (pgu)

Fluvial (stream-laid) deposits consist of well-sorted, well-stratified sand and gravel in outwash, kame, and stream deposits. Clasts in these deposits are usually subrounded-to-well rounded. The pgu map unit in figure 13 includes the kame deposits (pkg and pks) of Pierce (1974); this unit is well exposed between Cooke City and the drainage divide at Colter Pass. The spring used as the Cooke City water supply is at the base of a 120-ft-thick

deposit. This material is well drained and probably has a much higher transmissivity relative to the bedrock aquifers. No wells have been completed in the fluvial gravel.

#### Fan Gravel (Pinedale) (pfg)

Pinedale fan gravels comprise poorly to moderately sorted, moderately stratified boulders, cobbles, and sandy silt deposited in alluvial fan environments during the last glacial recession. Clasts are locally derived and subangular. Fan fronts are commonly 40 ft or more above the present stream channels, and fan surfaces are often irregular. The largest deposit within the study area is on a steep slope, upstream of Silver Gate. No wells have been completed in this material, which is moderately well drained, especially as compared to the nearby glacial till.

### Valley-Fill Aquifer

The stream-laid valley fill material associated with Soda Butte Creek is the principal aquifer of the area. Geophysical data indicate a thickness of about 150 ft just downstream of Silver Gate (Nyberg 1996). The few deep wells near the center of the valley indicate maximum thicknesses of about 200 ft at Cooke City and 160 ft at Silver Gate. Most wells are less than 100 ft deep, which is only sufficient to provide water for domestic use.

In the subsurface, the grain sizes range from cobbles to fine-grained silts and clay. Individual beds are discontinuous and can rarely be correlated in more than a few wells (figures 14–17).

There is an exception, however, in the Silver Gate area. Nearly all wells in the area have water levels that are near ground surface, regardless of depth. There are at least four wells whose water levels are above the ground-surface in the spring and most of the summer, and at least two of these wells exhibit flow through early summer. Using the same wells as shown in the cross sections (figures 15, 16, 17), figure 18 shows the distribution of a near-surface, *blue* clay layer that overlies the gravels and sands in which the wells are most often completed. This clay was probably deposited as sediment in a small lake that formed when rapid deposition of the alluvial fan downstream of Silver Gate (figure 13) temporarily restricted or blocked the stream. A similar layer of clay, probably associated with the large fan upstream of Silver Gate (figure 13), also was observed.

Aquifer tests confirm the existence of artesian conditions near Silver Gate. The transmissivity of the valley-fill aquifer near the pumped well (well 106030) ranged from 10,000 to 15,000 ft<sup>2</sup>/d. Well logs

indicate an aquifer thickness of about 150 ft; the hydraulic conductivity ranged from 66 to 100 ft/d, which is as much as two orders of magnitude higher than the bedrock aquifers. The storage coefficient for the Silver Gate well was less than 0.001, which suggests an aquifer with a low-transmissivity, confining layer on top and helps explain the above ground-water levels and the flowing wells. The clay acts as a confining layer, while the pressure exerted by ground water in the underlying sands and gravels causes water levels in the wells to be above the bottom of the clay, or as noted, above ground surface. Recharge to the confined sands and gravels can be from upstream, from areas where the clay layer does not exist from the surficial deposits on the valley margin or from the underlying bedrock.

The coarse-grained stream gravels in the Cooke City area are indicated by the Soda Butte Creek and Republic Creek streambeds, observations of shallow excavations, and a few reliable lithologic logs. The coarse nature of the deposits might suggest higher transmissivity values, but the analysis of an aquifer test conducted at a well near Cooke City (well 106004) indicates transmissivities similar to that obtained at Silver Gate (10,000–15,000 ft<sup>2</sup>/d). The aquifer thickness is estimated at 120 ft, slightly thinner than near Silver Gate. Thus, the hydraulic conductivity of the material is slightly lower than that of the aquifer near Silver Gate and is probably caused by the relatively poor sorting of the aquifer material and the discontinuous nature of the beds. Lithologic logs from wells along the north side of the valley (figures 19 and 20) indicate that clay-bound gravels and boulders are common. This material is probably derived from glacial till that has not been extensively reworked by Soda Butte Creek.

## Ground Water

### Hydrographs

Continuous water-level recorders were installed at five wells throughout the watershed to monitor seasonal trends under various conditions (figure 21). The wells were selected with the cooperation of the owners and were not pumped throughout the recording period.

The well at Silver Gate (well 106030) is 51 ft deep and completed in valley-fill material. Its hydrograph (figure 22) shows strong responses to climatic conditions, such as spring runoff and storm events and to flow in Soda Butte Creek. The water level in the well changes by about 10 ft between its lowest level in March and its highest level in early

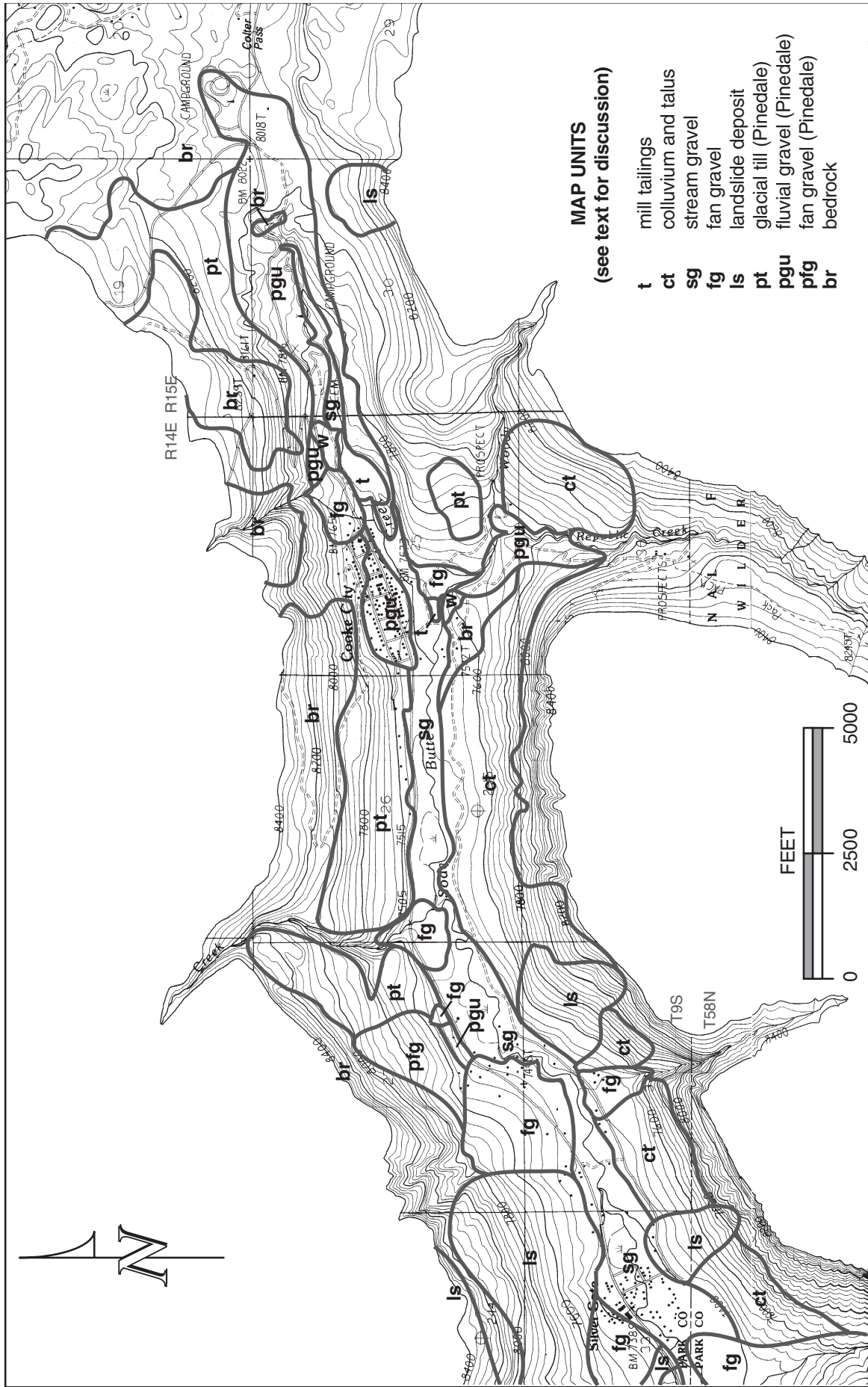


Figure 13. Surficial geology of the main drainage of Soda Butte Creek is the primary control for ground-water and surface-water flow.

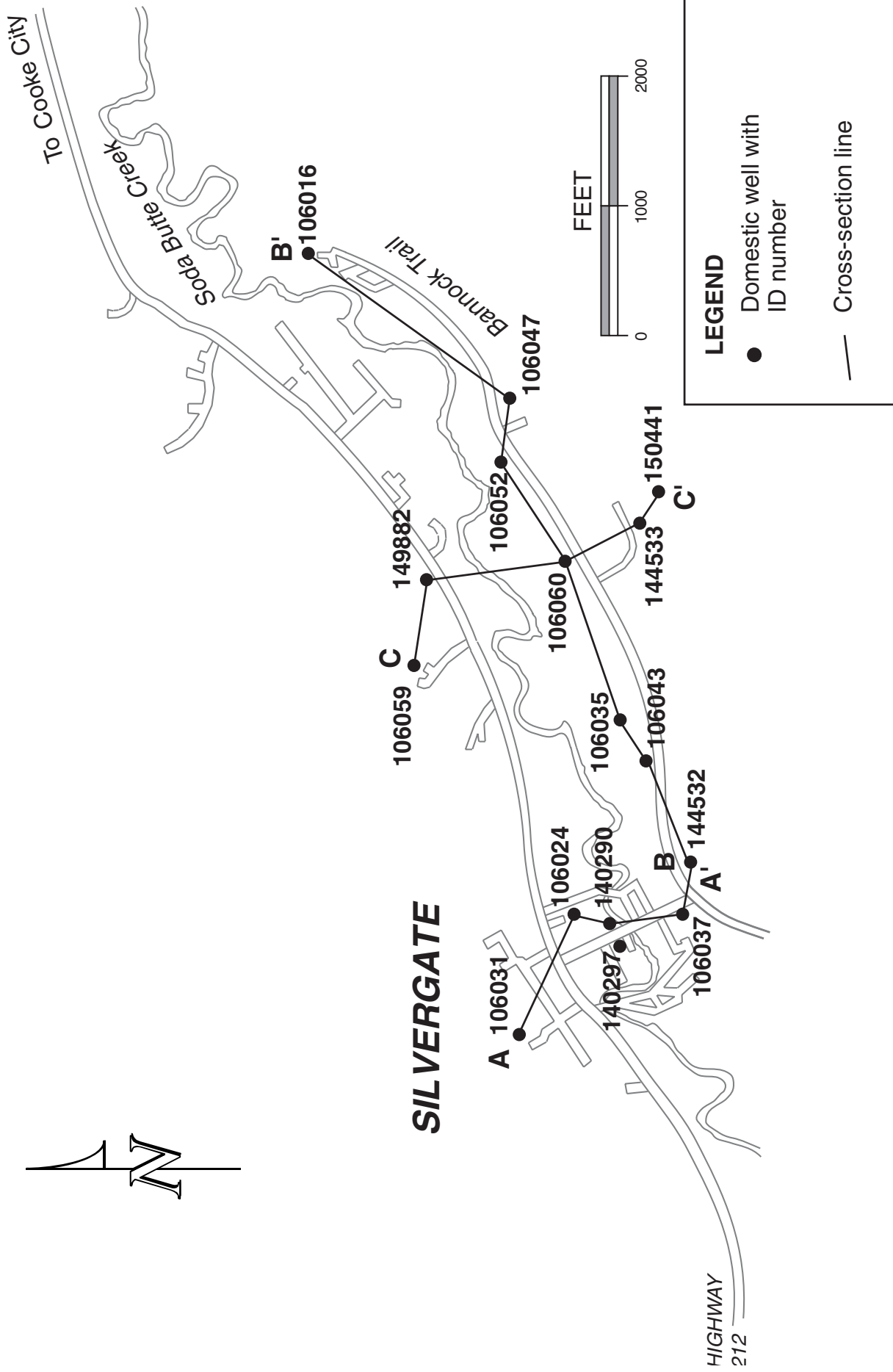


Figure 14. Cross-section locations for the Silver Gate area. Well-log cross sections (figures 15, 16, 17) were based on drillers' logs and surveyed elevations.

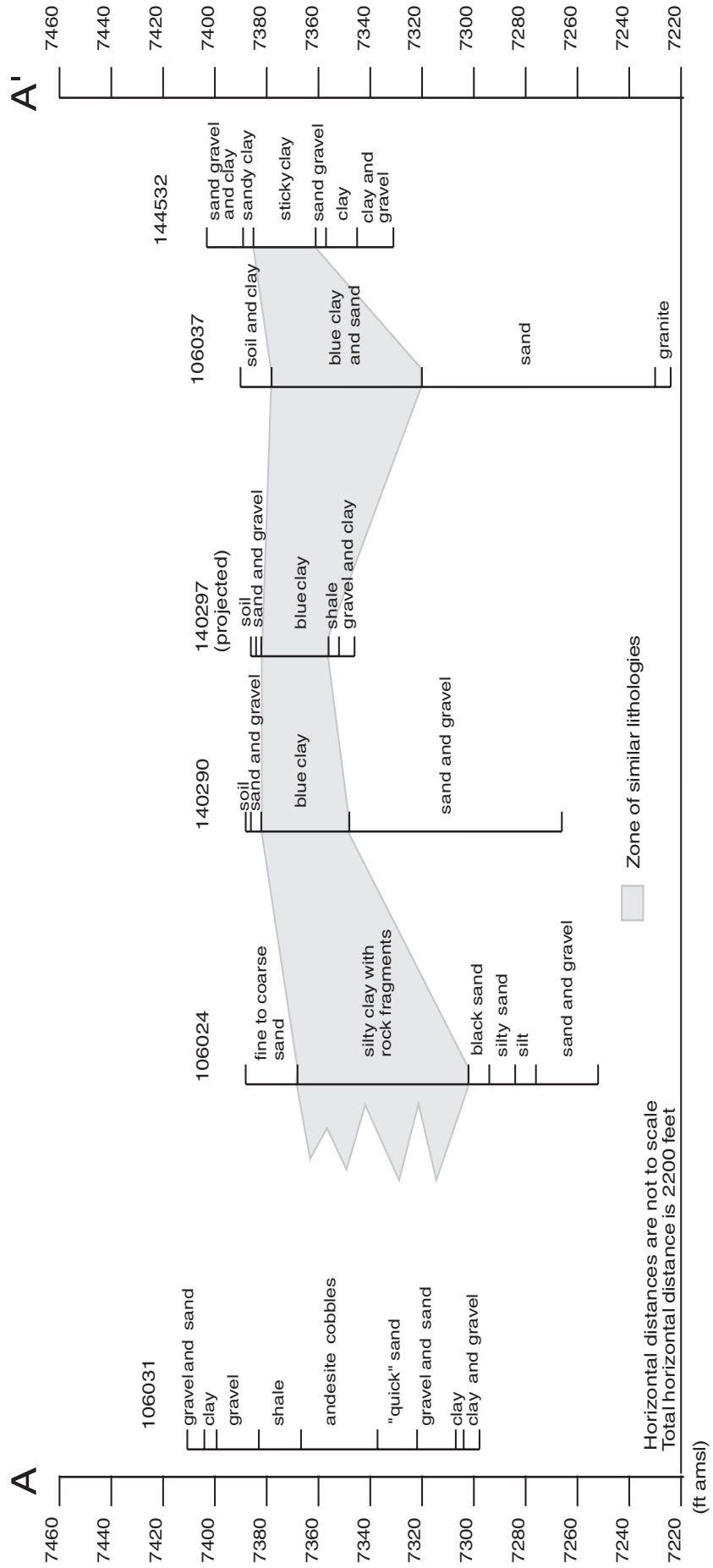


Figure 15. Cross section A-A' extends from Silver Gate across Soda Butte Creek near well 140290 to the south side of the valley. (See figure 14 for locations.)

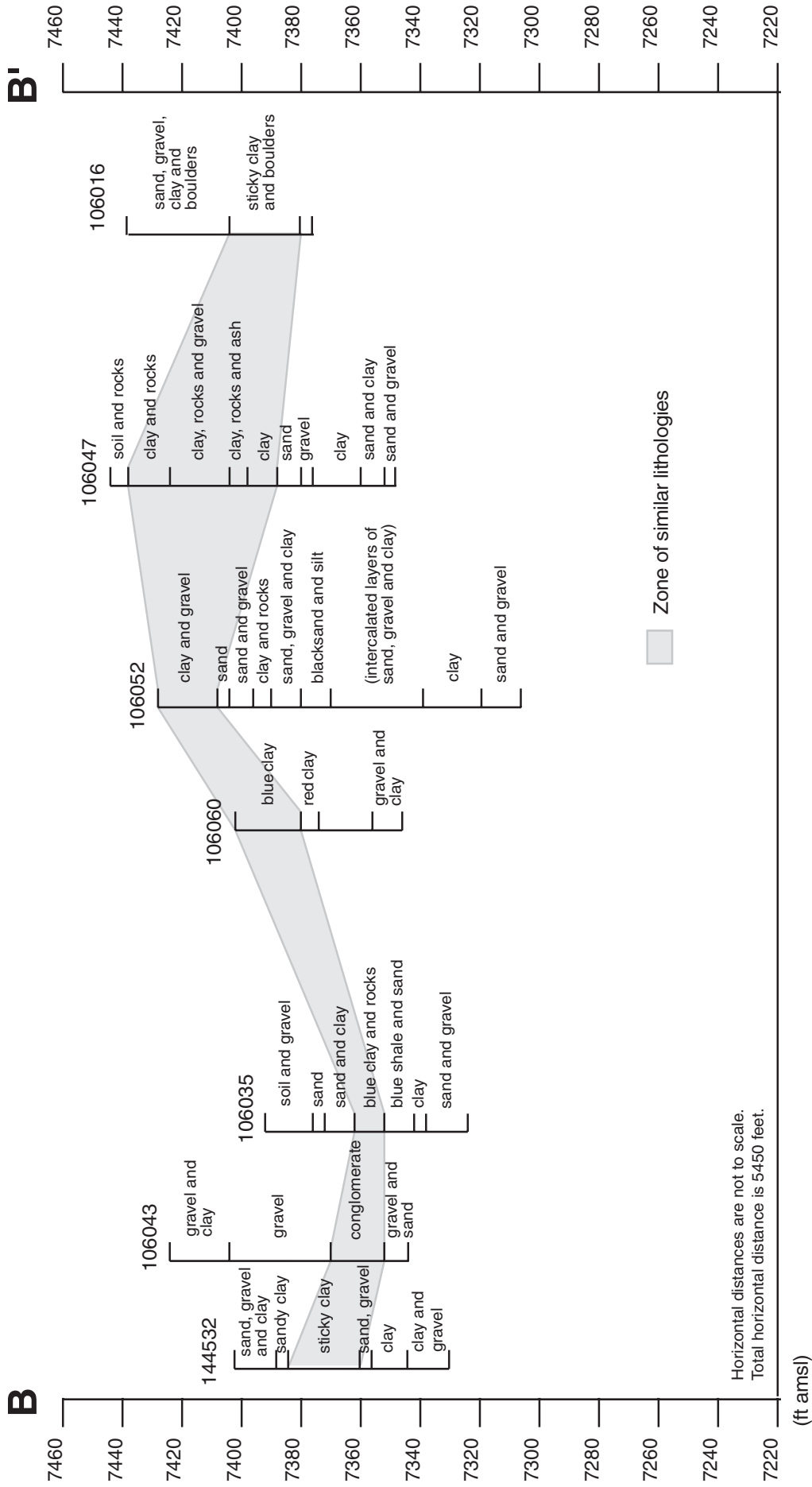


Figure 16. Cross section B-B' extends from A' on the east upstream along the Bannock Trail. (See figure 14 for locations.)

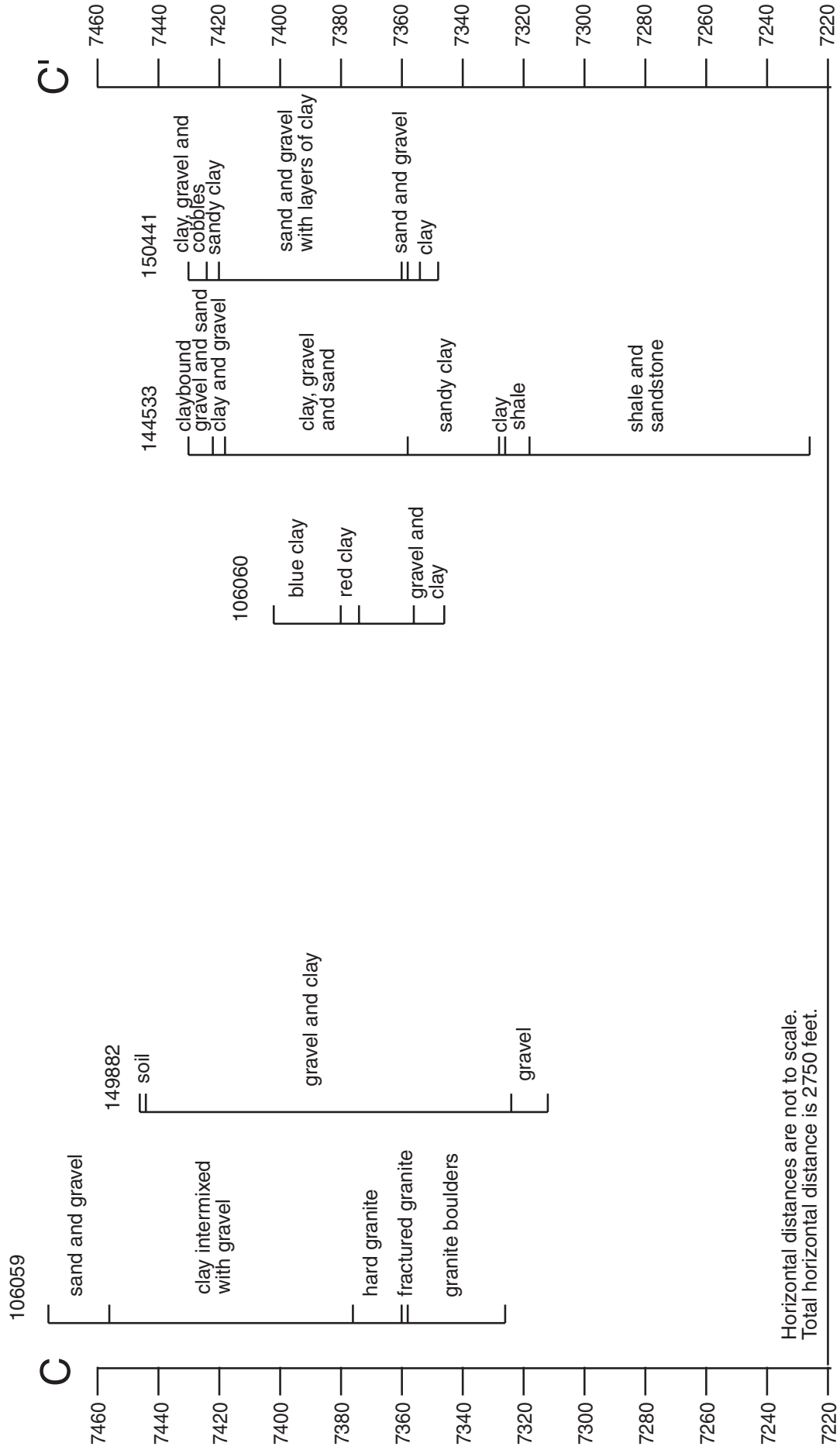
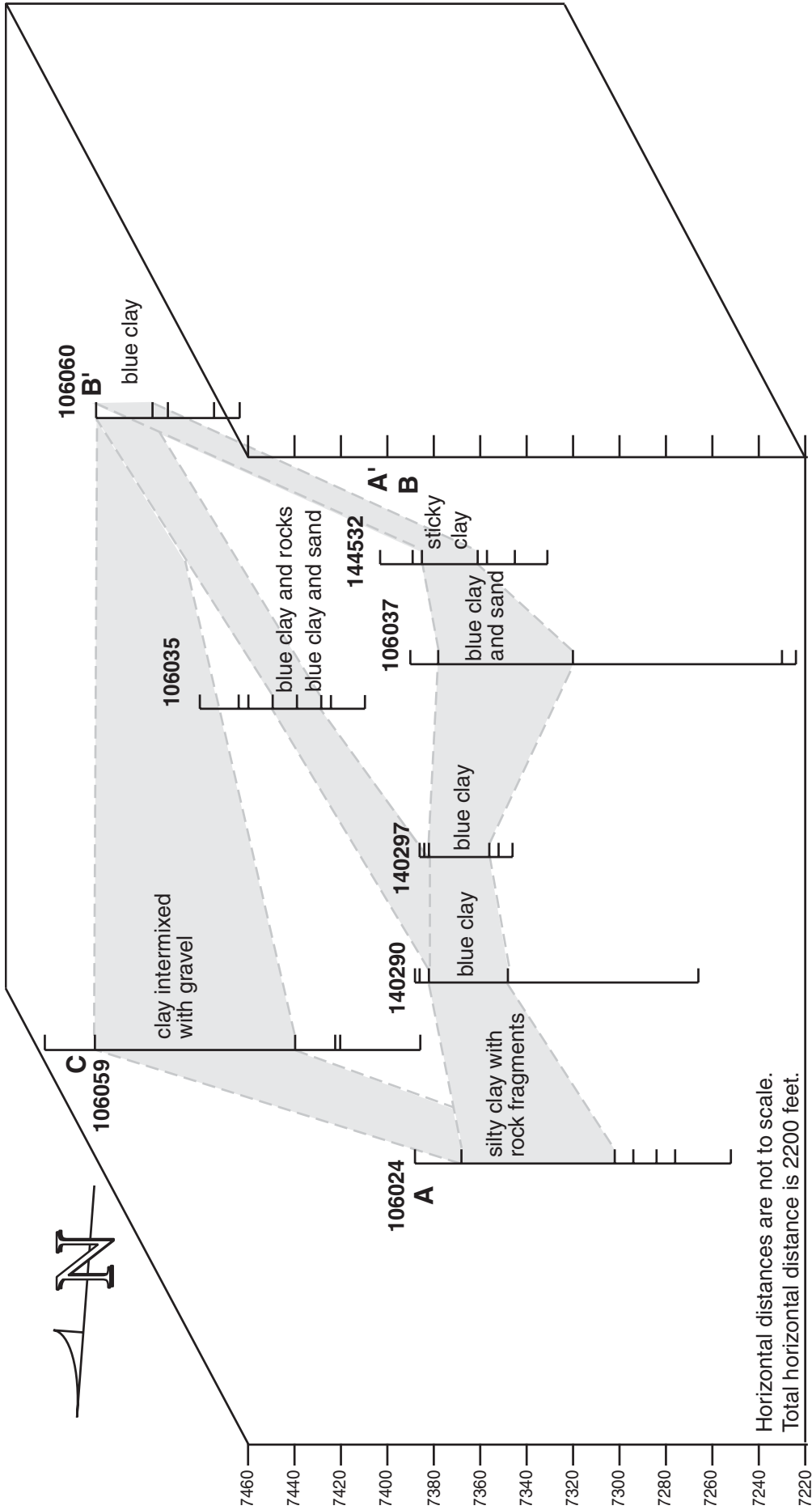


Figure 17. Well-log cross section C-C; Silver Gate area. (See figure 14 for locations.)



Horizontal distances are not to scale.  
 Total horizontal distance is 2200 feet.

Figure 18. The layer of blue clay is logged in wells throughout the Silver Gate area. All of the wells shown are in previous cross sections.

June. This change is coincident with the high and low flow of Soda Butte Creek.

The well upstream of Silver Gate (well 140299) is deeper and farther away from Soda Butte Creek than the Silver Gate well (well 106030). A recorder was installed to evaluate the effects of water flowing through the alluvial fan toward the creek. The hydrograph (figure 23) has a similar shape, and the annual water-level change of about 15 ft is similar to that of the Silver Gate well. The water level in the well seems to respond less to shallow ground water in the fan and more to the conditions of the main valley, although recharge to the fan aquifer began several weeks later than along the main creeks.

Well 162539 is completed near the base of the valley-fill material on the north side of the valley. There are active wells nearby: one in the granite bedrock and one in the valley-fill material. The record shows, that similar to shallower wells (wells 106030, 140299), the highest water level was observed in early June and the lowest was observed in March; water levels varied about seven feet over the year (figure 24). Interviews with well owners and observations made during times when the nearby wells were active indicated that pumping in the bedrock well, which is about 400 ft away, produced a maximum drawdown of about one foot; more often, the drawdown was less than 0.5 ft. Although no detailed investigation of well interference among the three wells was conducted, it did not appear that the well completed in the valley-fill materials, about 800 ft away, produced any drawdown in well 162539.

A shallow well near Cooke City (well 106004) is located near the confluence of Soda Butte and Republic creeks. The hydrograph for this well (figure 25) indicates a water-level response to surface flows very similar in timing and magnitude to the wells near Silver Gate (wells 106030, 140299).

Well 144534 is completed in the granitic bedrock near the Soda Butte Creek–Fisher Creek drainage divide in an area known locally as Pilot’s Roost. Bedrock in this area is overlain by several feet of poorly drained glacial till. The hydrograph shows a similar response to seasonal trends, but the water-level change is more rapid, and the timing of the change is earlier than wells in the lower valley (figure 26). This rapid water-level change is probably a function of the low porosity/storativity of the bedrock compared to the unconsolidated valley-fill material. The reason for the earlier water-level change is evident in the timing of the spring snowmelt; the south-facing upland areas of the drainage are barren of snow several weeks before the lower elevations of the main valley. The water-level range is about five

feet based on the data that could be obtained; however, there was evidence that the water level was slightly above the top of the casing, and the well flowed for a short period of time.

#### Summary of Hydrographs

While the timing of water-level response to recharge events might be expected to be similar throughout the watershed, the magnitude of the response at each well should reflect the type of aquifer in which the well is completed. Water-level change in an aquifer is a function of the quantity of recharge or discharge and the storativity, which is the amount of water going into or out of the aquifer as the water-level changes. In unconfined aquifers, the storativity is generally equivalent to the effective porosity of the material, whereas in confined aquifers where the aquifer is capped by a low permeability layer, the storativity can be less than  $10^{-3}$  (dimensionless). Unconfined bedrock aquifers, especially those composed of granitic rocks, have a small storativity (most commonly 1–10%) while unconfined, unconsolidated sand and gravel aquifers have a larger porosity (most commonly 10–20%). Both types of aquifers would have small storativity values if confined. Assuming unconfined conditions, the same amount of recharge to the bedrock and the valley-fill aquifers should produce a much higher water-level in a well completed in the bedrock.

As noted in the climate discussion, precipitation is greater in the higher elevations on the basin, so the recharge potential is much greater for the bedrock aquifer near the drainage divide. The higher precipitation, along with a smaller storativity, should result in much greater water-level fluctuations in the bedrock than in the valley fill. The hydrograph data, however, indicates a greater rise (10–15 ft) in the valley-fill aquifer near Cooke City and Silver Gate than in the bedrock aquifer (5 ft) near the drainage divide. The glacial till, which covers most of the bedrock near the drainage divide, and the steep slopes of the valley, where bedrock is exposed, prevent a great deal of recharge to the bedrock. Overland flow and shallow ground-water flow moves rapidly downslope to recharge the more permeable valley-fill material. The result is much greater recharge to the valley-fill aquifer than to the bedrock aquifer in the higher elevations.

#### Ground-Water Flow

Streamflow measurements (figure 12) indicate that Soda Butte Creek generally gains water along its entire reach. This flow increase is due to the addition of ground water discharging from the near-stream

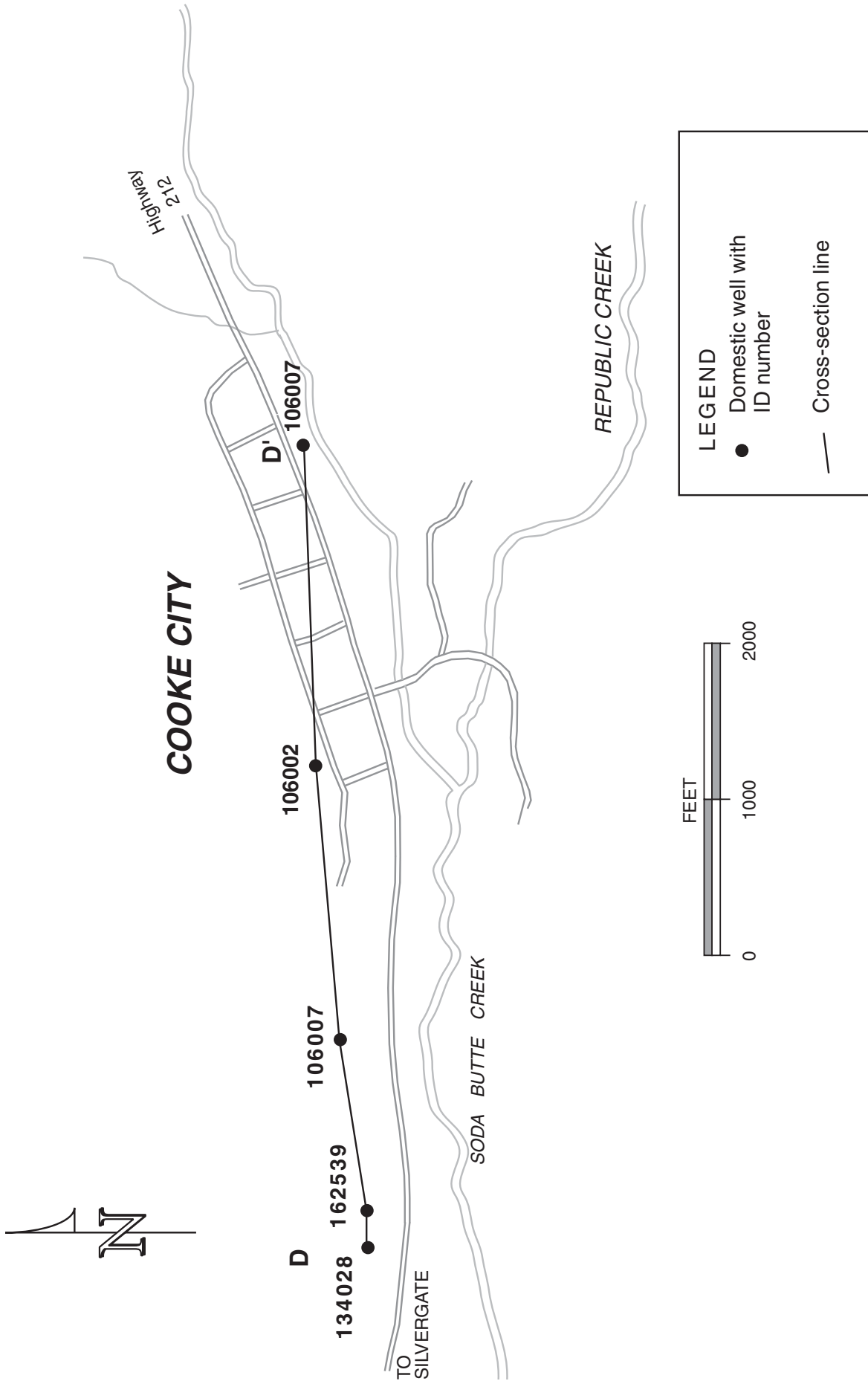


Figure 19. There are few wells and even fewer reliable well logs in the Cooke City area. The cross section D-D' is shown in figure 20.

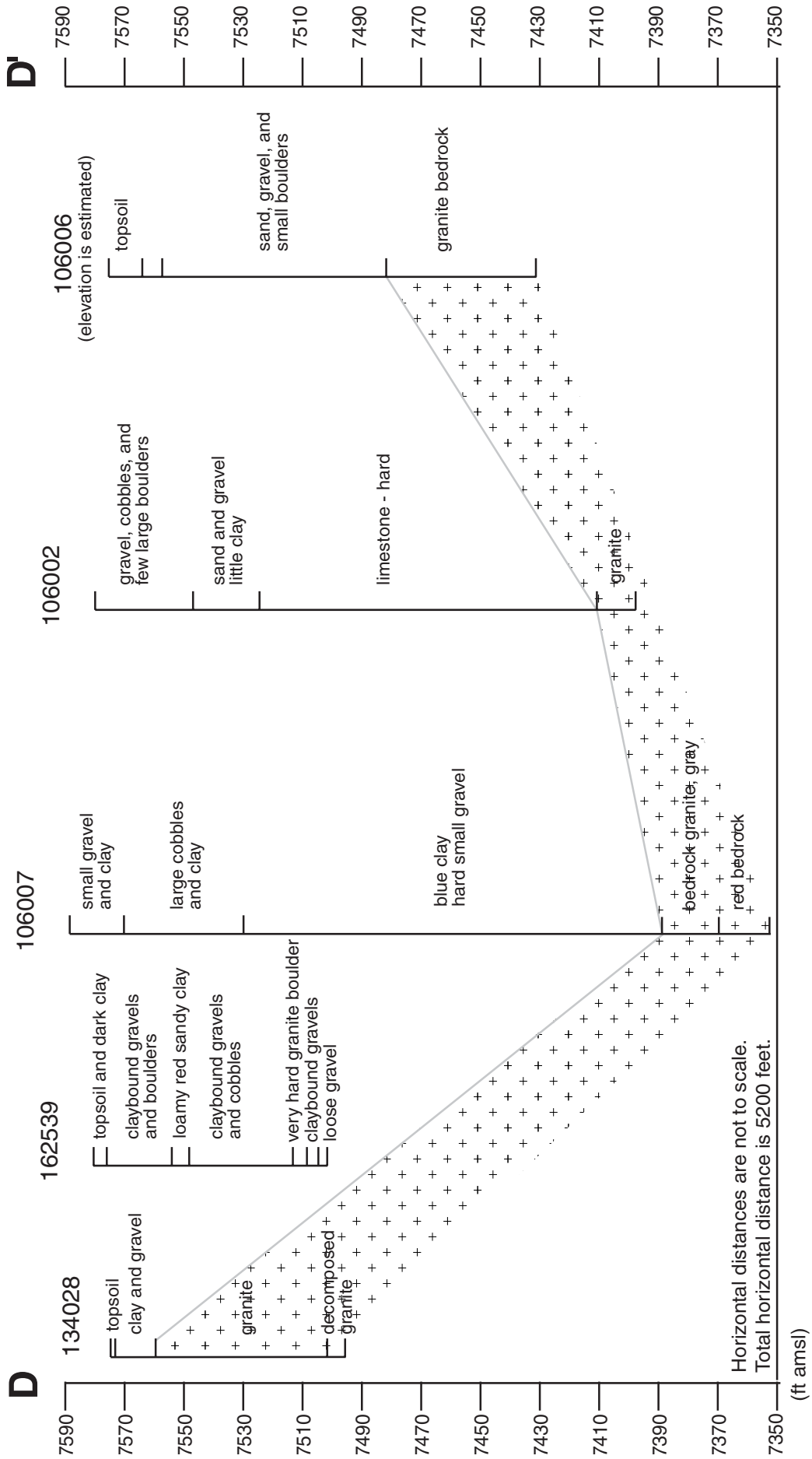


Figure 20. Cross section D-D' in the Cooke City area lies along the north side of the valley. Well 106006 was never completed, but the lithology log was available.

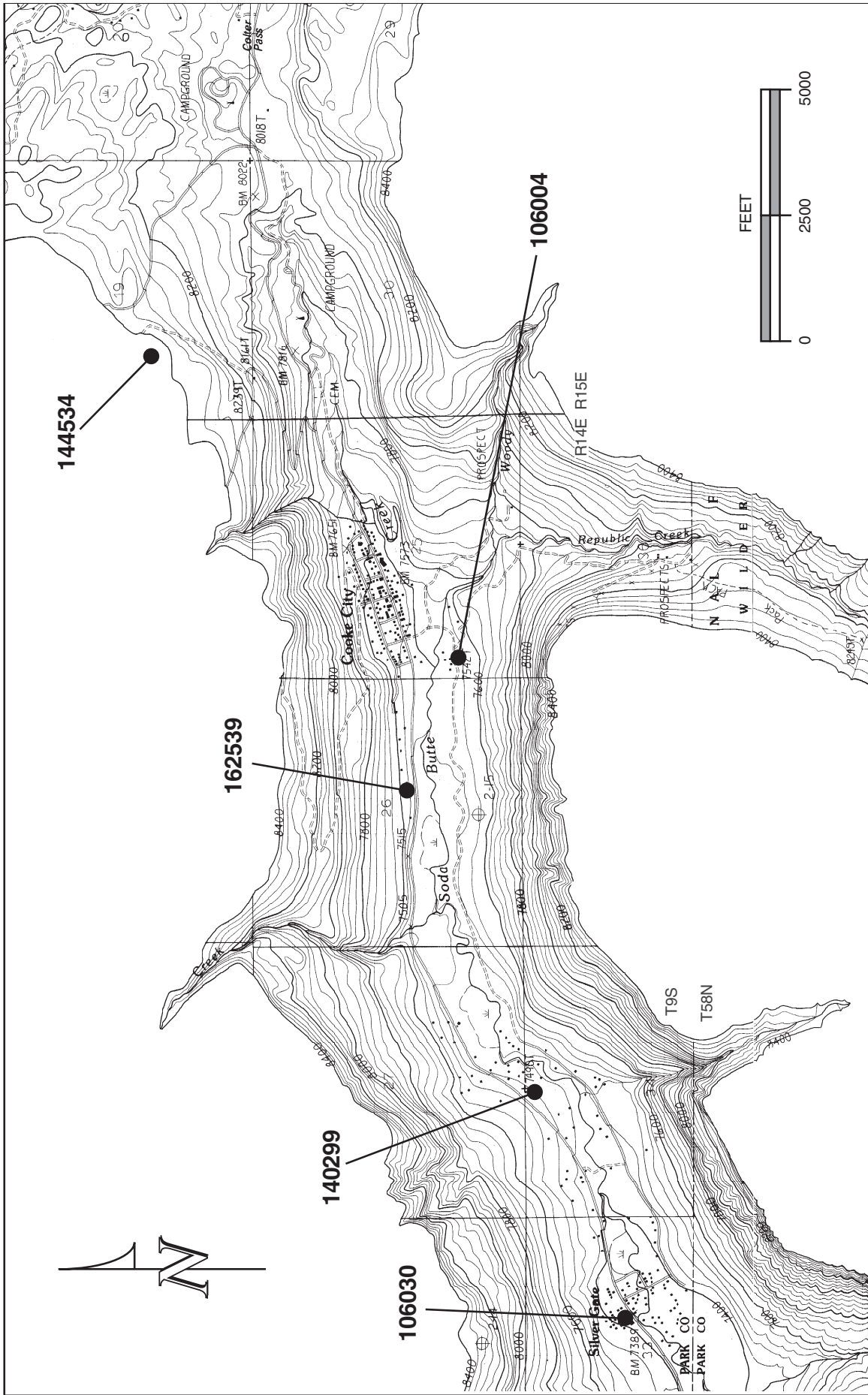


Figure 21. Recorders were placed throughout the watershed where wells were available but unused.

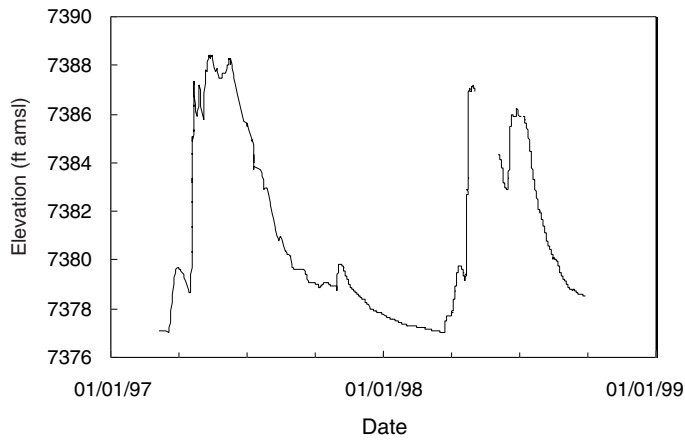


Figure 22. The hydrograph for the well (106030) in Silver Gate shows similar trends over the 2-year period of record.

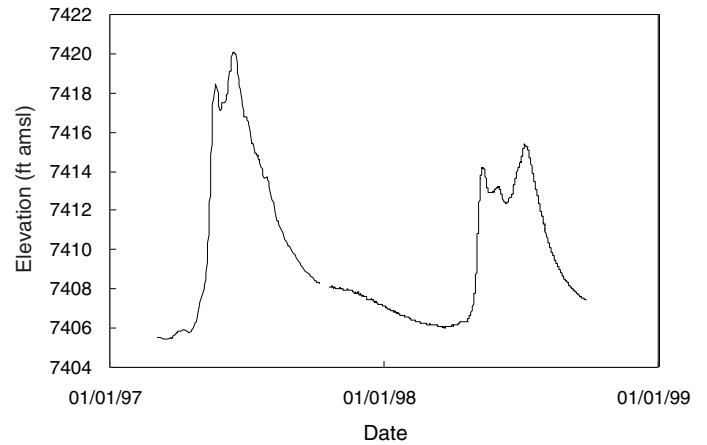


Figure 23. The hydrograph for the well (140299) upstream of Silver Gate shows trends similar to the well at Silver Gate (106030).

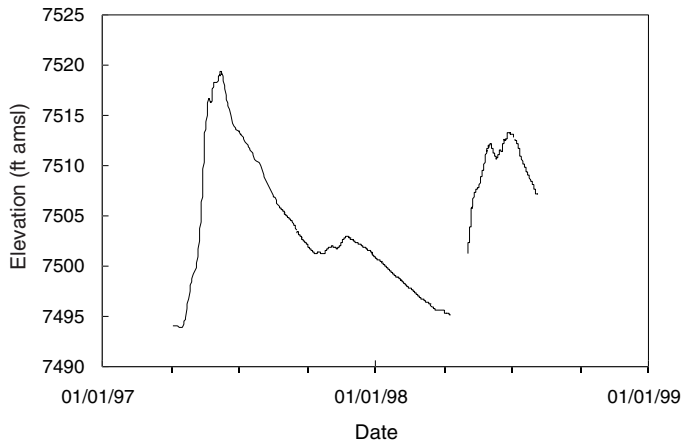


Figure 24. Well 106004 is near Cooke City and the confluence of Soda Butte Creek and Republic Creek.

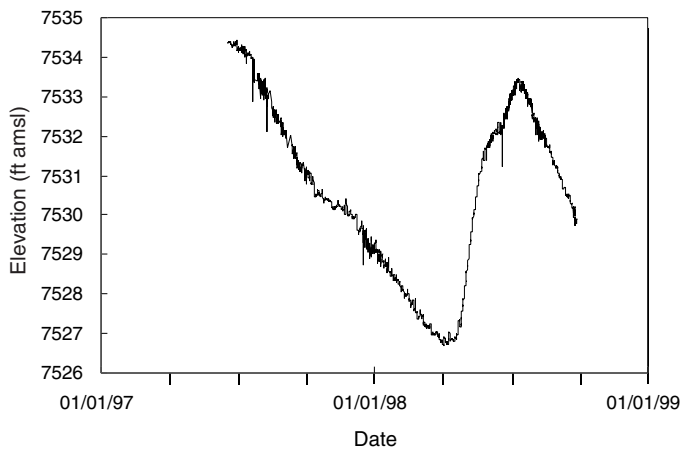


Figure 25. The hydrograph for the well (162539) completed near the base of the valley fill shows the effect of pumping from a nearby well.

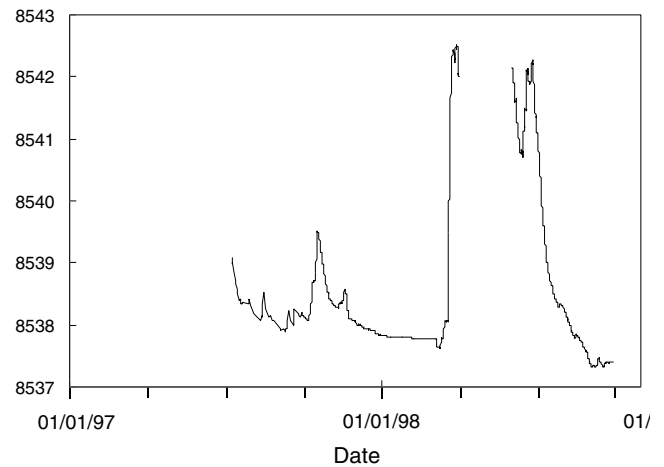


Figure 26. Well 144534 is completed in the granitic bedrock aquifer and is near the drainage divide.

valley-fill aquifer. Where the well density and position permit more detailed water-level measurements, the controls on ground-water flow through the valley-fill aquifer are more evident. The casing-top elevation of many domestic wells and bridge supports in the stream throughout the basin were surveyed, and water elevations were based on the elevation of the measuring point and field measurements of depth to water. This survey had an estimated error of about  $\pm 0.5$  ft. The USGS topographic base maps used (Cooke City, Pilot Peak, Cutoff Mountain, and Abiathar Peak, at 1:24,000) have a contour interval of 40 ft; the standard for elevation accuracy for USGS maps is  $\pm 1/2$  the contour interval.

The large alluvial fan deposit (fg) on the north side of the valley upstream of Silver Gate has not only restricted surface-water flow, but apparently ground-water flow as well (figure 27). The influence of Wyoming Creek discharge from the south is probably typical for the valley. The deflection of the water-level contour at the mouth of the tributary shows that the stream loses water to the fan material, which loses water to the underlying valley-fill material. The flow loss in the small creek is especially evident in the fall.

Ground-water flow patterns in the broad, flat area from Silver Gate upstream to the larger fan change appreciably with the seasons. In early summer, the abundance of ground-water recharge from snowmelt results in high water levels and increased discharge to the stream (figure 28). The fall ground-water flow patterns (figures 27, 29) show that ground water still discharges to the stream, but gradients are smaller and more perpendicular to the valley axis.

There are fewer wells in the Cooke City area, but the ground-water/surface-water relationship and seasonal variations still can be observed. The confluence of Soda Butte and Republic creeks is a broad, flat area of cobbles and gravel with sparse vegetation caused by lack of soils. Ground water flows toward the stream in the area of the confluence (figure 30). During spring runoff, which generally peaks in June, there appears to be localized water loss from Republic Creek to the aquifer. This loss is indicated by the downstream shift of the 7,510 elevation contour in figure 31 from that shown in figure 30. These wells, south of Soda Butte Creek and downstream of the confluence, show a greater increase in water levels than others farther away. During the fall and probably throughout the rest of the year, ground water flows from the valley-fill aquifer to the stream (figures 30 and 32).

## Vertical Gradients

There are only a few wells that are close enough together to be considered *nested pairs* for the evaluation of vertical gradients. The two nested pairs that do exist are shallow, hand-dug wells next to deep, replacement wells. Located near Silver Gate, the deep well has a higher water level than the shallow well; the gradient is upward. There are at least three wells in the Silver Gate area that have flowing water in the early summer. In late summer and fall, water levels in these wells are below the tops of the casings, but still above land surface. Deep snow would not permit winter water-level measurements, but the gradient likely remains upward throughout the year. In the Silver Gate area, water elevation comparisons in Soda Butte Creek to ground-water elevations in nearby wells, using hand levels, invariably showed an upward gradient. This consistent, upward gradient between the deep and shallow portions of the aquifer and between the aquifer and the creek indicates the potential for ground water to flow upward. Although the potential exists, it is important to note that actual flow from the deep aquifer to the shallow aquifer is probably prevented by the low-permeability clay shown in figures 15–18. In areas where the clay is not present, upward flow will occur. Similarly, although the potential exists for ground water to flow upward into Soda Butte Creek in the Silver Gate area, the actual flow is small. There are two lines of evidence for this: 1) flowing wells are partial evidence that the ground water has the potential to flow up the casing to a height several feet above the stream, but 2) the amount of streamflow gain in the area below Sheep Creek is small compared to the rest of the basin (figure 12).

## Springs

Perennial and intermittent springs occur in the upper Soda Butte Creek basin. While some of the springs discharge at distinct points, many of them discharge in clustered locales with several clearly defined discharge points and numerous seeps within a general area. Most of the springs were visited during the fall to determine the locations of perennial springs. The perennial springs are likely to have larger source (recharge) areas and contribute to surface-water flow throughout the year. The locations of 23 spring sites are shown on figure 33. Water-quality field parameters were measured, and flows were either measured or estimated for each spring. Only location and flow estimates were



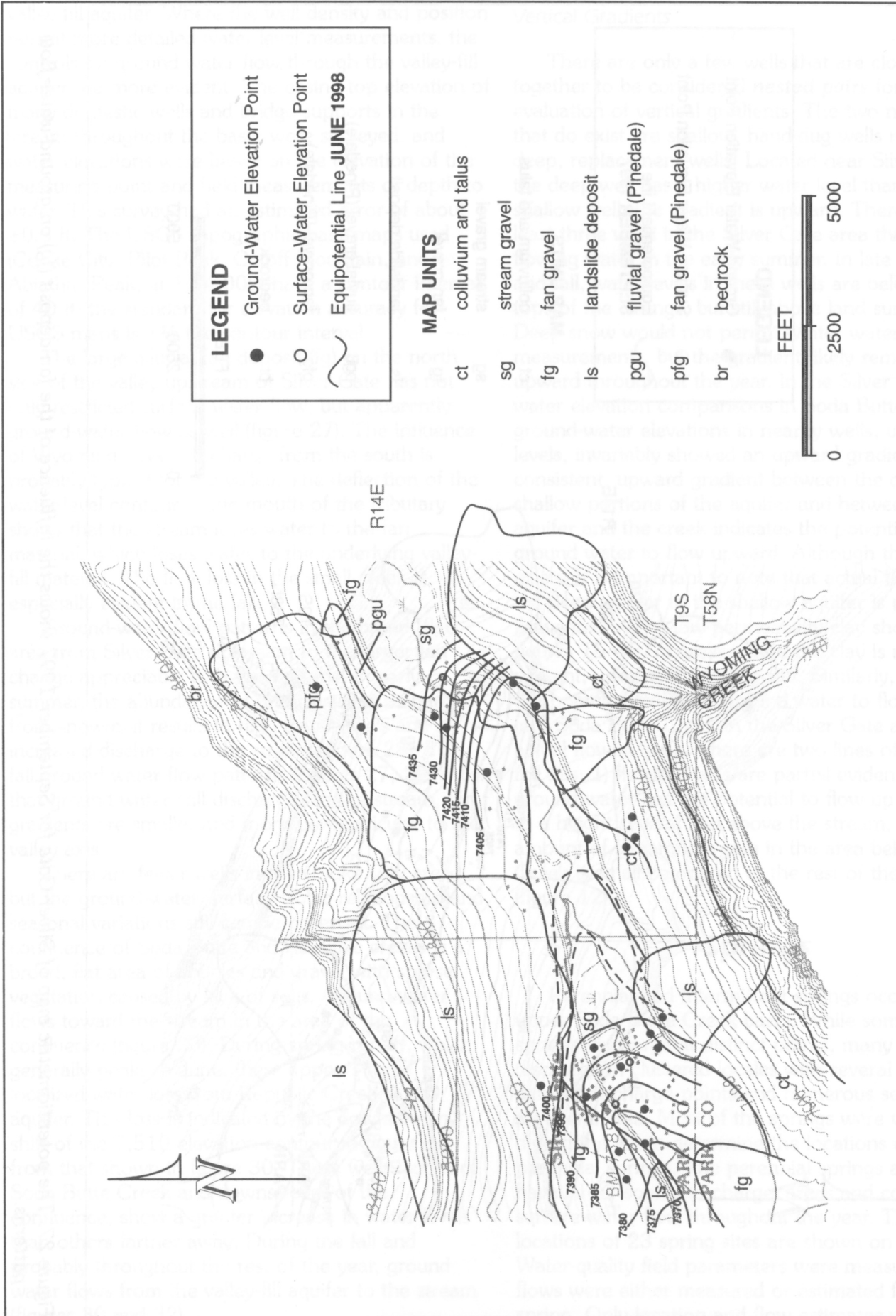


Figure 28. Potentiometric map of Silver Gate for June 1998. June 1998 water levels are generally highest of the year; ground-water gradients toward the creek are at their greatest.

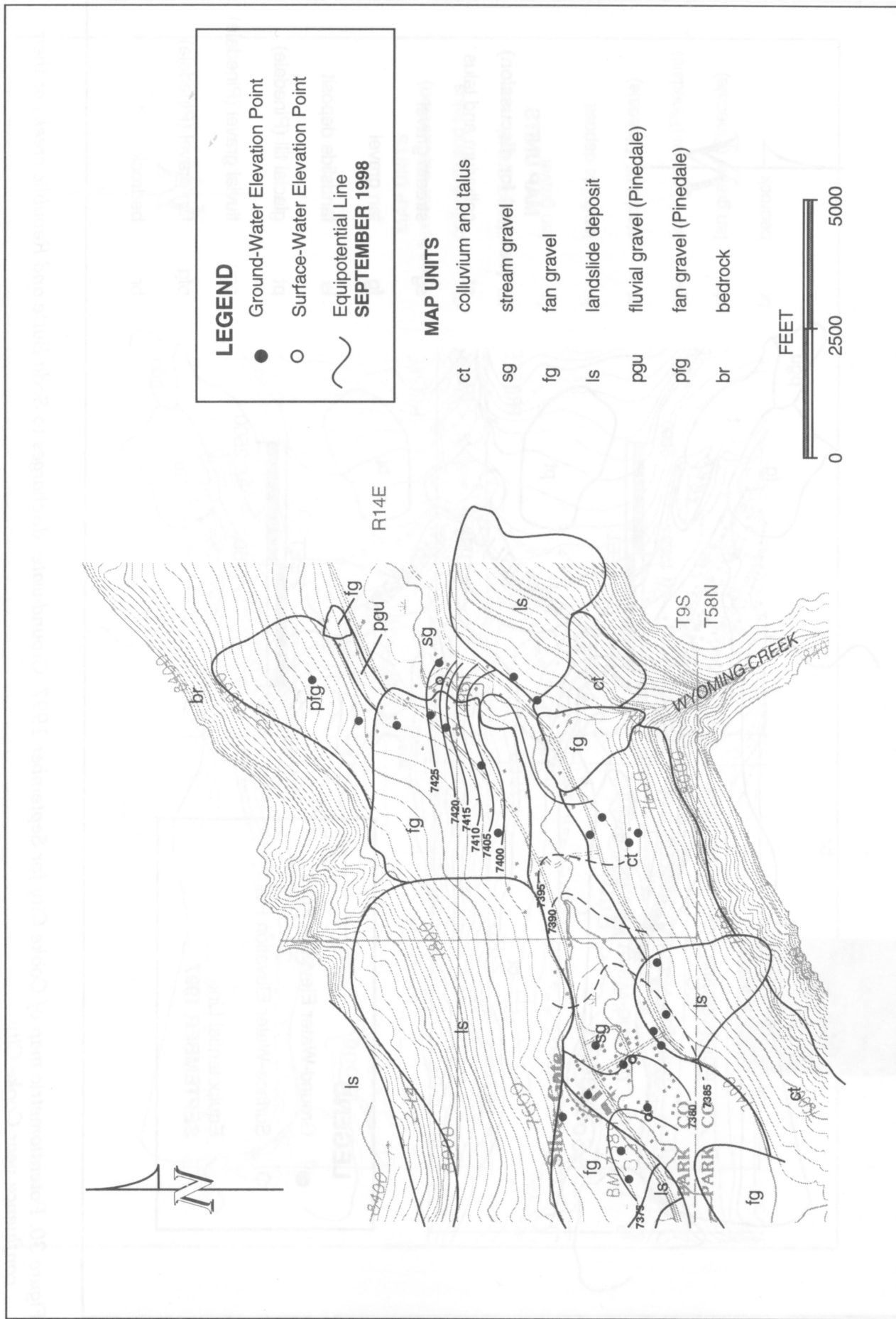


Figure 29. Potentiometric map of Silver Gate September 1998. Although slightly higher than the previous year, the fall ground-water flow patterns are similar to those of 1997.

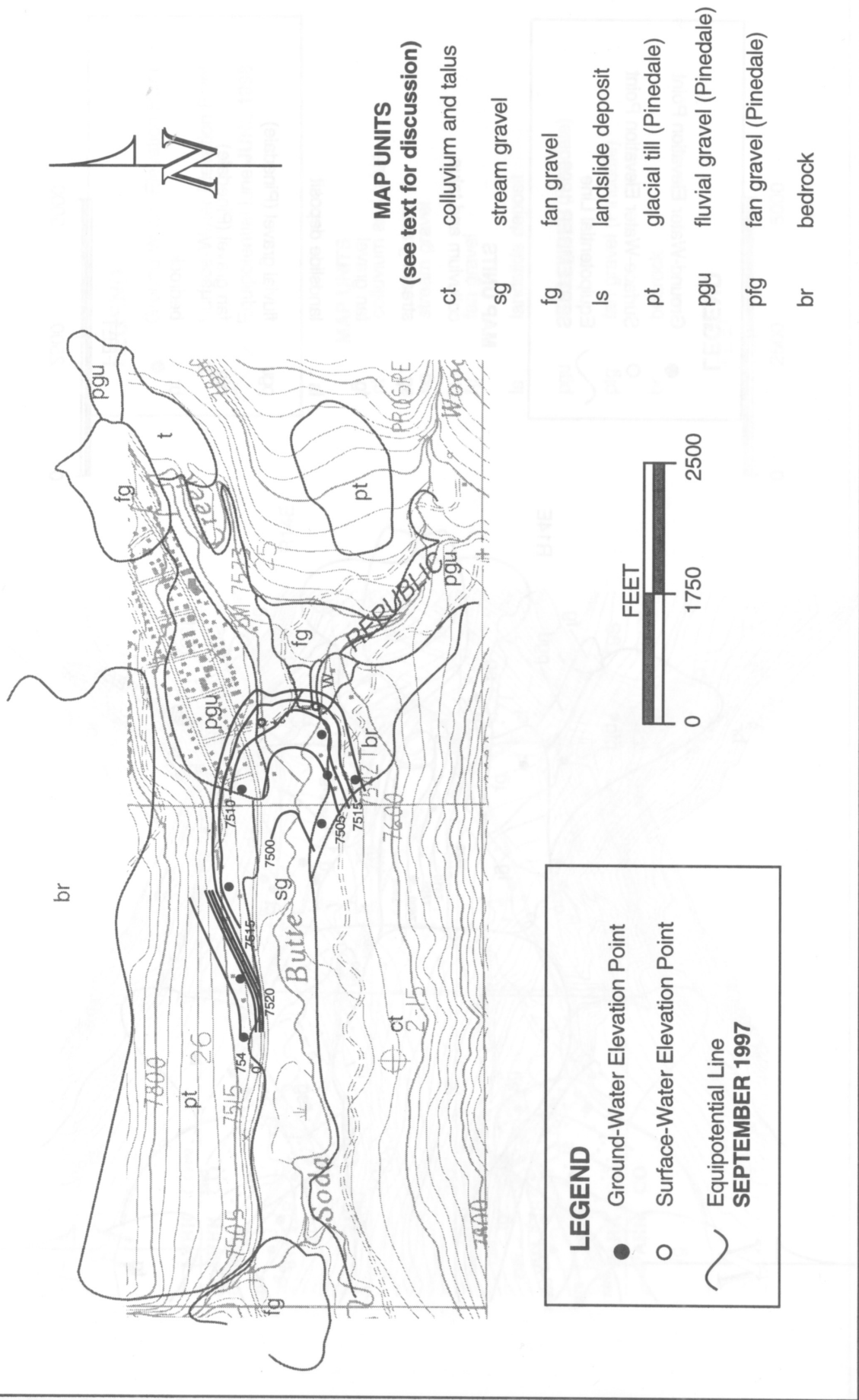


Figure 30. Potentiometric map of Cooke City for September 1997. Ground-water discharges to Soda Butte and Republic creeks at their confluence near Cooke City.

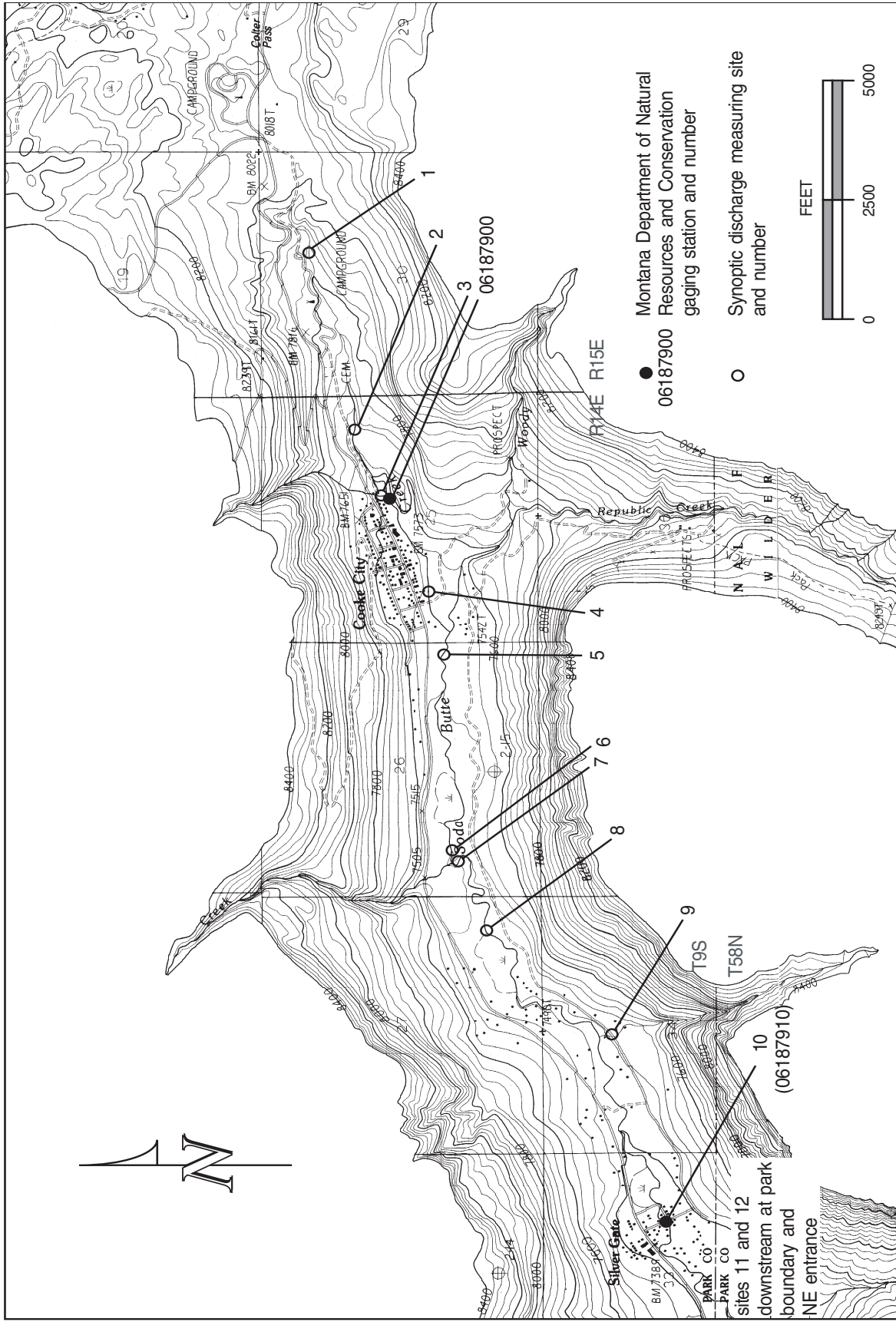


Figure 31. The ground-water flow pattern on the south side of the valley suggests significant loss from Republic Creek toward the valley.

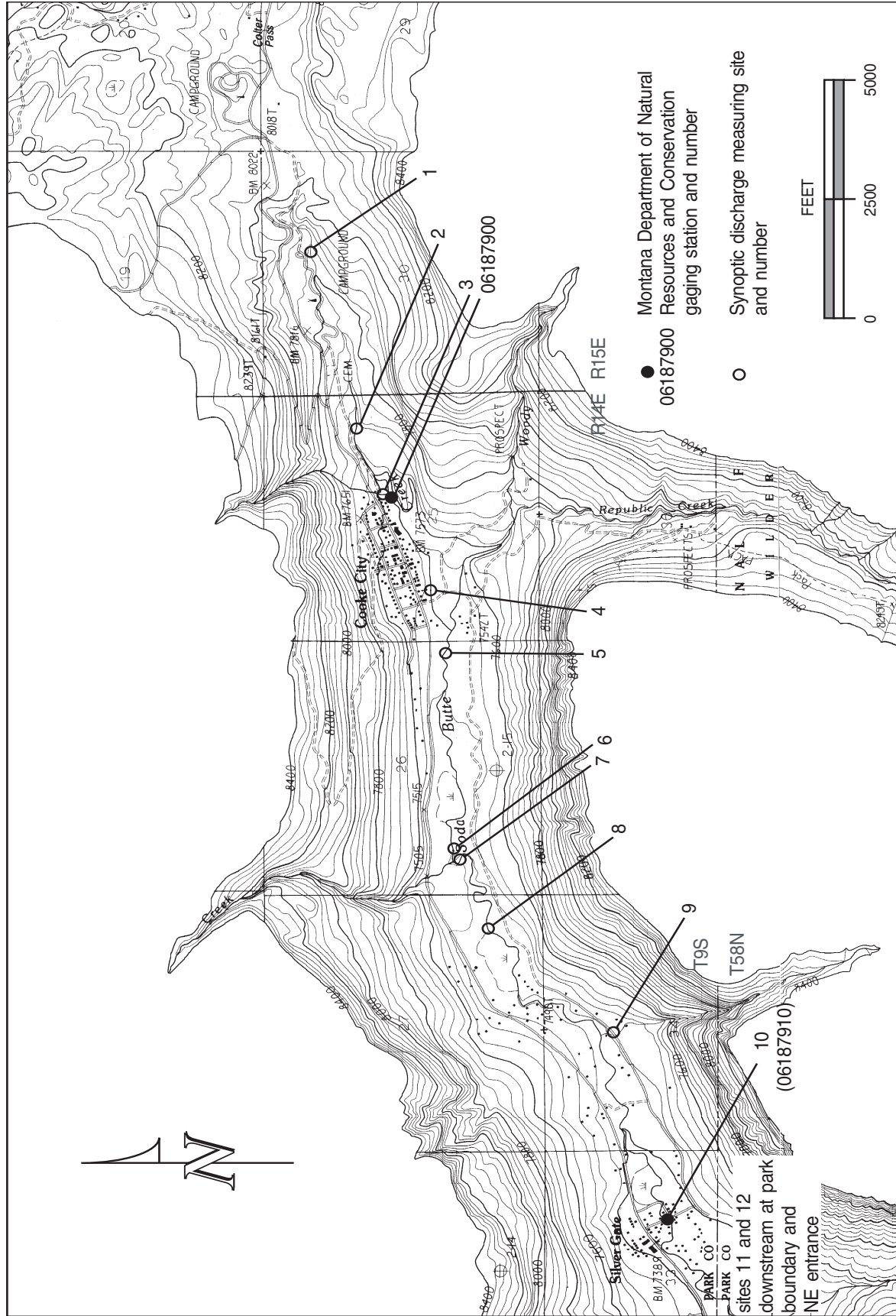


Figure 32. As with the Silver Gate area, the water levels were slightly higher in fall 1998, but flow patterns are similar to those 1997.

obtained from a few springs on private land where permission to sample was not obtained. Samples were collected from selected springs for inorganic chemical analysis. Table 11 summarizes the data collected on flow, specific conductance, temperature, pH, and Eh for each inventoried spring.

### Spring Development

Perennial springs have been the preferred choice for development as private and public water supplies, and 17 of the 23 spring sites (figure 33) have been developed. Some of these developed sites are no longer in use or are maintained as alternate water supplies. Ten spring sites are currently being used as domestic water supplies serving about 16 private cabins. Two springs are developed as public water supplies for the towns of Cooke City (SPR13) and Silver Gate (SPR18). Based on information obtained from public water supply files maintained by the Montana Department of Environmental Quality (MDEQ), the distribution system for the Cooke City spring has 69 service connections serving a resident population of 75 people. The Silver Gate spring has a distribution system with 34 service connections and serves a resident population of 50 people. A cluster of springs to the northwest of Cooke City (SPR7) were developed historically to provide water to Cooke City but were abandoned as a public water supply due to low flows in the winter and early spring (MDEQ 1998). A spring emerging along the highway near Colter Pass (SPR1) was developed to serve the Cooke ranger station. The spring probably served as a drinking-water supply for the ranger station, but the cabin is now believed to be served by a well that serves the nearby Colter campground. The spring may still be used to provide stock water.

### Geologic Setting of Springs

The locations of most of the inventoried springs are controlled directly or indirectly by bedrock stratigraphy and/or structure. The five primary geologic settings and controls for the 23 springs are 1) Precambrian granitic and metamorphic bedrock with assumed structural control, 2) Paleozoic sedimentary bedrock with stratigraphic control, 3) thin Quaternary surficial deposits overlying Paleozoic sedimentary bedrock with stratigraphic or structural control, 4) Quaternary landslide deposits and thicker colluvial deposits with water table control, and 5) Quaternary surficial deposits with water table control.

Five of the springs discharge from Precambrian granitic and metamorphic bedrock in the headwaters

of the basin near Colter Pass (SPR1, SPR4, SPR5, and SPR23). The unique feature of these springs is their relatively high topographic position within the basin, near the divide between Soda Butte Creek and the West Fork of the Clark's Fork of the Yellowstone River. The best example of this type of occurrence is spring SPR1. This spring discharges along the edge of highway 212 at the base of a small knob of Precambrian metadolerite, and the discharge point is assumed to be controlled by fractures. A clustered area of spring discharge at location SPR23 is included in this category, but a thin mantle of glacial till covers the bedrock, which may be younger than Precambrian.

Springs that discharge directly from Paleozoic sedimentary bedrock and are controlled by stratigraphy, are mainly located along the south facing slope between Cooke City and Silver Gate (see plate 1). There are several intermittent springs and seeps in this area; however, only one perennial spring (SPR16) was inventoried that clearly falls into this category. This spring discharges from a small cave at a cliff base formed in the Pilgrim Limestone near the contact with the underlying Park Shale. The Paleozoic sedimentary rock in the area between Cooke City and Silver Gate dips gently southward and appear to control the locations of springs discharging from the contact between the Pilgrim Limestone and the underlying, relatively impermeable Park Shale. On the north side of the valley, the contact between the Pilgrim Limestone and Park Shale dips downward toward the valley. On the south side of the valley, this contact dips away from the valley. While evidence of small waterfalls and seeps were found along cliff bases formed in the Pilgrim Limestone along the south side of the valley, no perennial springs were found.

The majority of the inventoried springs occur in areas where Paleozoic sedimentary bedrock is covered with a thin layer of glacial till or colluvium. The springs northwest of Cooke City are probably controlled by the stratigraphic contact between the Pilgrim Limestone and Park Shale but discharge downslope from the mapped contact. It is believed that ground water discharges from the contact under the surficial deposits and migrates downslope until a change in slope or an area of exposed bedrock allows the water to reach the surface. A good example is the cluster of springs along an old roadcut on the Miller Mountain jeep trail (SPR 8, 9, 10, and 11). The roadcut exposes light green Park Shale. Springs and seeps occur along the upslope side. Spring SPR11 discharges above the road cut from a collapsed mine adit.

Table 11. Summary of inventoried springs

Spring ID	Flow (gpm)	SC (umhos)	Temp. (°C)	pH	Probable Geologic Source	Comments
SPR1	30-5	106	3.7	7.29	Precambrian metadolerite and/or granitic rocks	Developed for Cooke ranger station
SPR2	38-15	176	3.3	8.01	glacial till	Intermittent flow until mid-summer
SPR3	100	210	4.5	8.02	glacial outwash	Cooke City public water supply
SPR4	5-10	288	8.8	7.26	glacial till	Near basin divide
SPR5	1-5	144	4.6	7.59	Precambrian metadolerite and/or granitic rocks	Near basin divide
SPR6	100	306	4.7	6.15	Paleozoic bedrock	Developed for domestic use, clustered
SPR7	25-35	289	4.3	7.85	Pilgrim LS	Old Cooke City spring, clustered discharge
SPR8	2-10	316	4.7	7.98	Pilgrim LS	Developed for domestic use
SPR9	2-3	279	5.0	8.08	Pilgrim LS	Undeveloped clustered discharge
SPR10	5	276	4.5	8.05	Pilgrim LS	Undeveloped clustered discharge
SPR11	25-35	263	4.2	8.29	Pilgrim LS	Discharges at caved mine workings
SPR12	No Data				glacial till	Undeveloped
SPR13	5-20	266	6.5	7.91	alluvium	Developed for domestic use
SPR14	No Data					
SPR15	25	244	4.4	7.88	landslide deposit	Clustered spring discharge
SPR16	25	245	5.7	8.05	Pilgrim LS	Discharges from base of cliffs
SPR17	40-50	261	6.3	8.20	landslide deposit	Undeveloped
SPR18	75	186	6.9	8.32	landslide deposit	Silver Gate water supply, clustered springs
SPR19	4	302	7.6	7.95	landslide deposit	Developed for domestic use, status unknown
SPR20	1-3	429	3.5	8.11	colluvium	Developed for domestic use, inactive
SPR21	1-3	219	4.0	7.94	colluvium	Developed for domestic use, low flow
SPR22	2	236	8.5	5.87	glacial till	Undeveloped, may be intermittent
SPR23	+100	No Data			glacial till	Estimated cumulative discharge of numerous springs

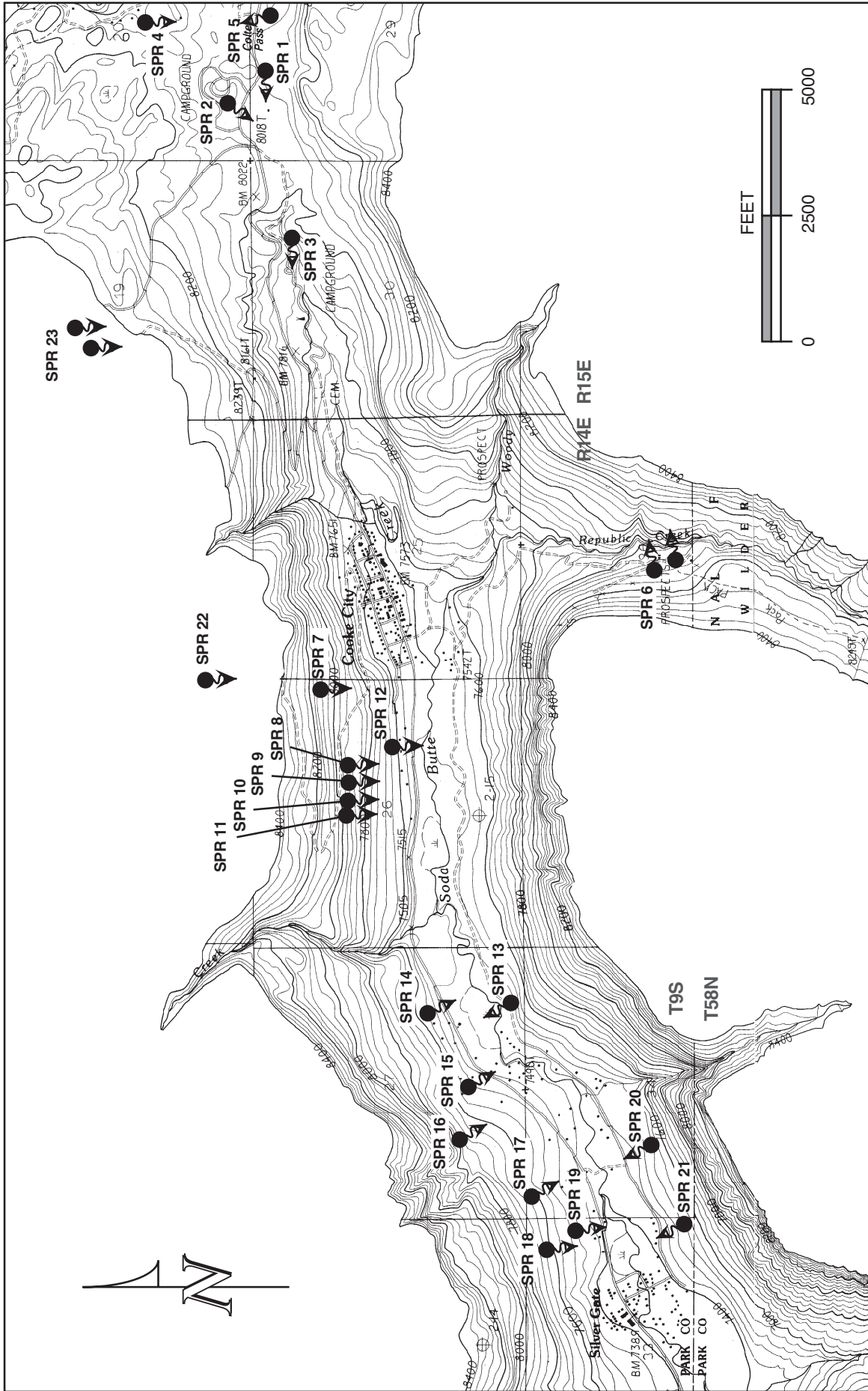


Figure 33. Most springs contributing sustained flow throughout the year are found on the north side of the valley, which is also the dip slope of the sedimentary formations.

The spring clusters in the Republic Creek drainage near the Irma mine are another example. Here, the springs emerge above the elevation of the mapped contact between the Pilgrim Limestone and Park Shale. The area is covered with colluvium, and ground water discharging from bedrock is probably controlled by structure. Two intersecting faults were mapped as projecting to a point just above the spring cluster by Elliott (1979). One of these structures may offset the Heart Mountain Detachment fault, which could also be the water source.

Five springs near Silver Gate discharge in areas covered with thick Quaternary surficial deposits (SPR 17, 18, 19, 20, and 21). The factors controlling the points of discharge for these springs appear to be more variable and include thinning of the surficial cover, changes in slope that cause the water table to intersect the surface, and possibly, impermeable layers of clay or silt within the surficial deposits. Spring SPR 17 and the spring cluster developed for Silver Gate (SPR18) are within landslide deposits. The land surface in this area is very hummocky and covered with large boulders of Eocene andesitic, volcanoclastic rock from the Lamar River and Cathedral Cliffs formations and limestone boulders from the Pilgrim Limestone. Springs SPR17 and SPR18 discharge from opposite flanks of a large area covered almost entirely with large blocks and boulders of Pilgrim Limestone. This limestone rubble area is surrounded on both sides by well-vegetated, hummocky topography covered mainly with volcanic boulders. The limestone rubble probably represents a younger landslide deposit on top of the older landslide deposits, and these springs may be related to the contact between the two landslides. Springs SPR20 and SPR21, on the south side of the valley near Silver Gate, also appear to discharge from an area covered with colluvium. At spring site SPR21, light green Park Shale is exposed, and the spring appears to be controlled by thinning of the colluvium. Spring SPR20 discharges at approximately the same elevation and in an area with a similar slope.

Finally, some springs discharge from Quaternary alluvium and glacial outwash, of which the Cooke City spring (SPR3) is a good example. This spring discharges at the base of a steep slope downgradient of a thick glacial outwash deposit, flows about 100 gpm, and is perennial. Spring SPR2 also discharges at the base of a slope below a glacial deposit that appeared to be till, and the spring is intermittent; during the spring months, it flows about 50 gpm. Spring SPR13 discharges from alluvium in a low spot along an old channel of Soda Butte Creek and is probably controlled by the water table elevation.

## Hydrology of Springs

The flow rate of the springs is highly variable for perennial and intermittent springs. There are no clear patterns in flow rates or geologic settings for perennial versus intermittent springs, but a few general observations can be made. The springs that discharge from bedrock tend to flow at low-to-moderate rates (2–50 gpm) with less fluctuation. A good example is spring SPR16, which discharges directly out of the Pilgrim Limestone. Intermittent springs may flow at very high rates (50–100 gpm) for short periods of time. A good example of this is spring SPR2 by the Colter campground, which may flow at rates in excess of 50 gpm in May but be dry by the end of July. Springs in areas covered with Quaternary surficial deposits tend to have low flows that often decrease to 1–2 gpm in the late fall. The original Cooke City spring (SPR7), which was abandoned because of low flow rates in the winter, and the springs along the Miller Mountain jeep trail are typical examples.

## Chemistry

### Ground-Water Chemistry

As with many other aspects of this investigation, ground-water sampling was restricted to available domestic wells. While this limits the ability to give a comprehensive ground-water quality description of the basin, a general characterization is certainly possible.

Of the 26 wells sampled (figure 34), most are completed in the valley-fill aquifer. Analytical results, which included cations, anions, and trace metals, revealed no discernible trends or plumes related to any particular constituent. However, the *type* of water is generally predictable. Waters from the valley-fill aquifer are all a calcium-bicarbonate type, while water types in the bedrock aquifers vary (figure 35). In the same respect, the total dissolved solids—the basis for the diameter of the circles in figure 35—distinguish the valley-fill ground water from bedrock ground water.

The water quality within the valley-fill aquifer is generally consistent regardless of depth or location within the valley (figure 36). Water from the aquifer at Silver Gate (*e.g.*, wells 152597, 06030) is nearly identical to water from the middle area of the drainage near Cooke City (*e.g.*, well 106004) and the upper drainage (*e.g.*, well 106075). The influence of bedrock water discharging into the valley-fill aquifer is seen in the sample collected from well 134028. This well is completed just above the

valley-fill bedrock aquifer contact, and the water has a noticeably higher concentration of magnesium.

Water from each of the sampled bedrock aquifers reflects the lithology of the rock (figure 36). Well 144533 is completed in a marine shale and produces a strongly sodium-sulfate water; marine shales typically produce sodic water. Well 106021 is completed in a different shale and produces a sodium bicarbonate water, which may be the product of oxidation potential reduction of a sodium-sulfate water. Well 106002 is completed in limestone and produces a calcium-sulfate water. Well 152503 is completed in the granite bedrock aquifer, which in this area, is overlain by glacial till. The water from this well is similar in type to that of the valley-fill aquifer, although it has a slightly higher sulfate concentration—probably a result of oxidizing sulfides known to be present in the area.

The consistency of the water type in the valley-fill aquifer, the large difference in type between the valley-fill aquifer, and most of the bedrock aquifers reflect the relative diversity of ground-water types in the basin. While the bedrock aquifers on the valley margins certainly discharge into the valley-fill aquifer, the quantity of this discharge is small compared to recharge from snowmelt and direct infiltration from precipitation. Concentrations of major cations, anions, and trace metals are presented in the appendix.

### Spring-Water Chemistry

Field parameter measurements for the inventoried springs (table 11) show that the spring sources exhibit differences in water quality. Springs with sources in the Precambrian granitic and metamorphic bedrock near Colter Pass tend to have low specific conductance (below 150 umhos/cm) and near neutral pH values from 7.2 to 7.5. The low specific conductances are attributed to the lack of highly soluble minerals in the bedrock. Quartz, feldspars, and the mafic minerals weather more slowly than the Paleozoic carbonate rock, such as the Pilgrim Limestone. The Precambrian rock also has not been exposed to weathering for very long (since the ice sheets retreated). Water temperatures recorded for these springs are more variable but are attributed to exposure of the water to ambient air at the measuring points. The actual spring water temperature for these springs is probably close to 4°C.

Springs that discharge directly or indirectly from the Paleozoic sedimentary rock show the effects of interaction with limestone and other carbonate sediments. These springs tend to have higher specific conductance values (200–300 umhos/cm),

pH values above eight and cold temperatures around 4°C. Concentrations of major cations, anions, and trace metals for those springs sampled are presented in appendix A.

## Computer Simulation of Soda Butte Creek

A computer-generated ground-water flow model is used to represent a simplified version of the ground-water/surface-water interaction near Soda Butte Creek. Information on real-world hydraulic conductivity, porosity, aquifer thickness, and ground-water flux or recharge are needed as input. Depending on the model type, the output from the simulation includes head or water level, ground-water flow direction, and ground-water flux. Three-dimensional, finite-difference models, such as MODFLOW (McDonald and Harbaugh 1988), can simulate ground water flow by establishing cells or cubes of various sizes in layers that are represented as a grid. Each cell in the grid contains the necessary hydrogeologic properties to calculate a value for head while taking into account the results of the same calculations in adjacent cells. The general approach, is to obtain as much information about the real system as practical, estimate or interpret the unknown, and then construct a model. The model can be used to fill in information gaps and increase understanding of the real system. One or more parameters are compared between the model and the real system, and adjustments to the model are made until a *best fit* is achieved. The most common comparison is between observed head and model-calculated head. However, using MODFLOW and the stream routing package by Prudic (1989), another comparison can be made between observed streamflow and calculated streamflow. Once a favorable comparison is achieved, the model can be used to evaluate a variety of conditions.

There are two types of ground-water flow simulations: steady state, where hydrogeologic conditions do not change with time, and transient, where conditions change with time. For example, pumping a well at a constant discharge will produce drawdown in the well and the surrounding aquifer. Consequently, the water level in the well will change as pumping continues, and water is taken out of aquifer storage. This may take days, months, or even years and is considered to be a transient condition. At some time, however, the system will reach a point, when the amount of ground water flowing to the well is in equilibrium with the pumping, and the amount of water being taken out

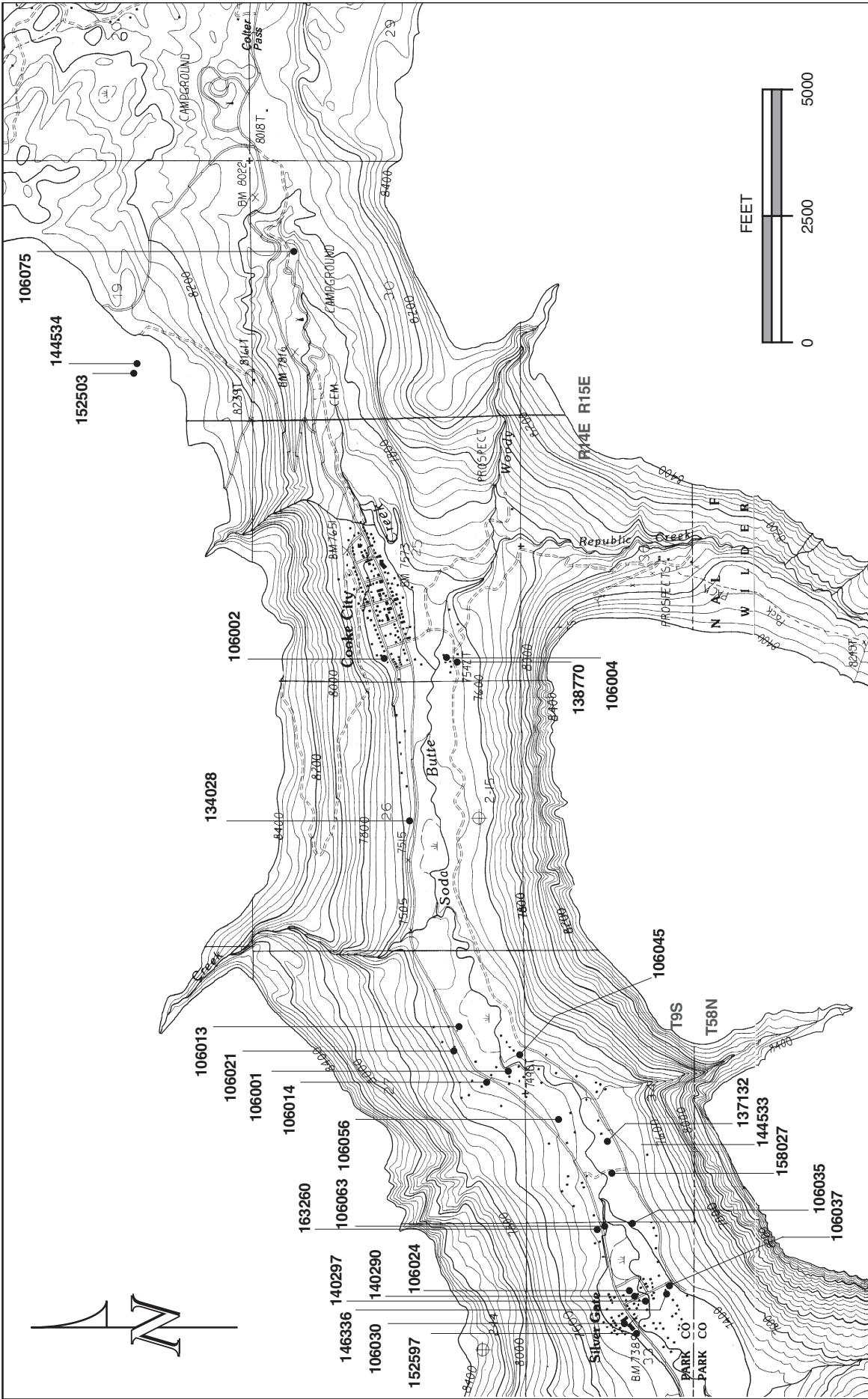


Figure 34. Twenty-six wells were sampled for complete water-quality analysis; some were sampled more than once.

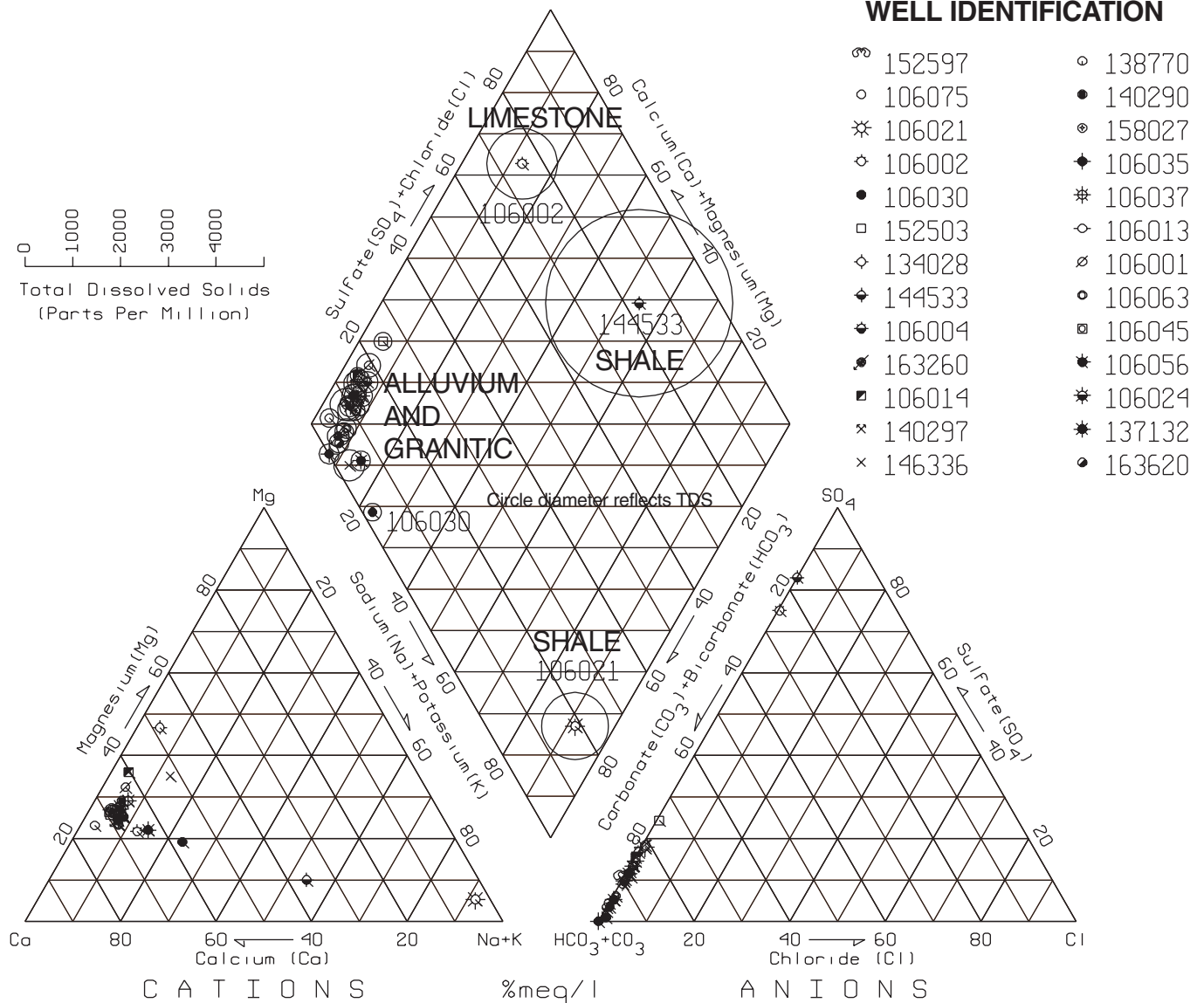


Figure 35. The majority of the ground water sampled was a calcium-bicarbonate type. Bedrock wells showed significantly different chemistry.

of aquifer storage is zero. The water level will no longer change, and the system is considered to be *steady state*.

### Modeling Procedure

In the manner described above, a ground-water flow model was constructed using MODFLOW (McDonald and Harbaugh 1988) to evaluate the streamflow response to pumping ground water from the adjacent aquifer. The stream routing package by Prudic (1989) was particularly useful in simulating Soda Butte Creek and evaluating the ground-water/surface-water interaction. The model area (~9,000 x 4,000 ft; figure 37) includes the valley bottom and margins and extends from the downstream end of the study area near the Northeast Entrance of the park to the wetland area upstream of Silver Gate.

Water-level and streamflow data were available for September and were used as the real world conditions to calibrate the model. September was chosen as the best month; the number of wells being pumped would be high and streamflow low.

The model consisted of 91 columns, 32 rows, and 4 layers, which translates to 11,648 cells. The grid-spacing along columns was held at 100 ft, while the grid-spacing along rows varied from 200 ft on the north and south edge to 50 ft near the stream. The top layer of the model was used to simulate near-surface, unconfined conditions in the aquifer and contained all of the stream cells. The layer thickness was about 50 ft but varied, based on surface topography. The second layer was used to simulate the lower hydraulic conductivity material between 50 and 100 ft deep; the third layer was

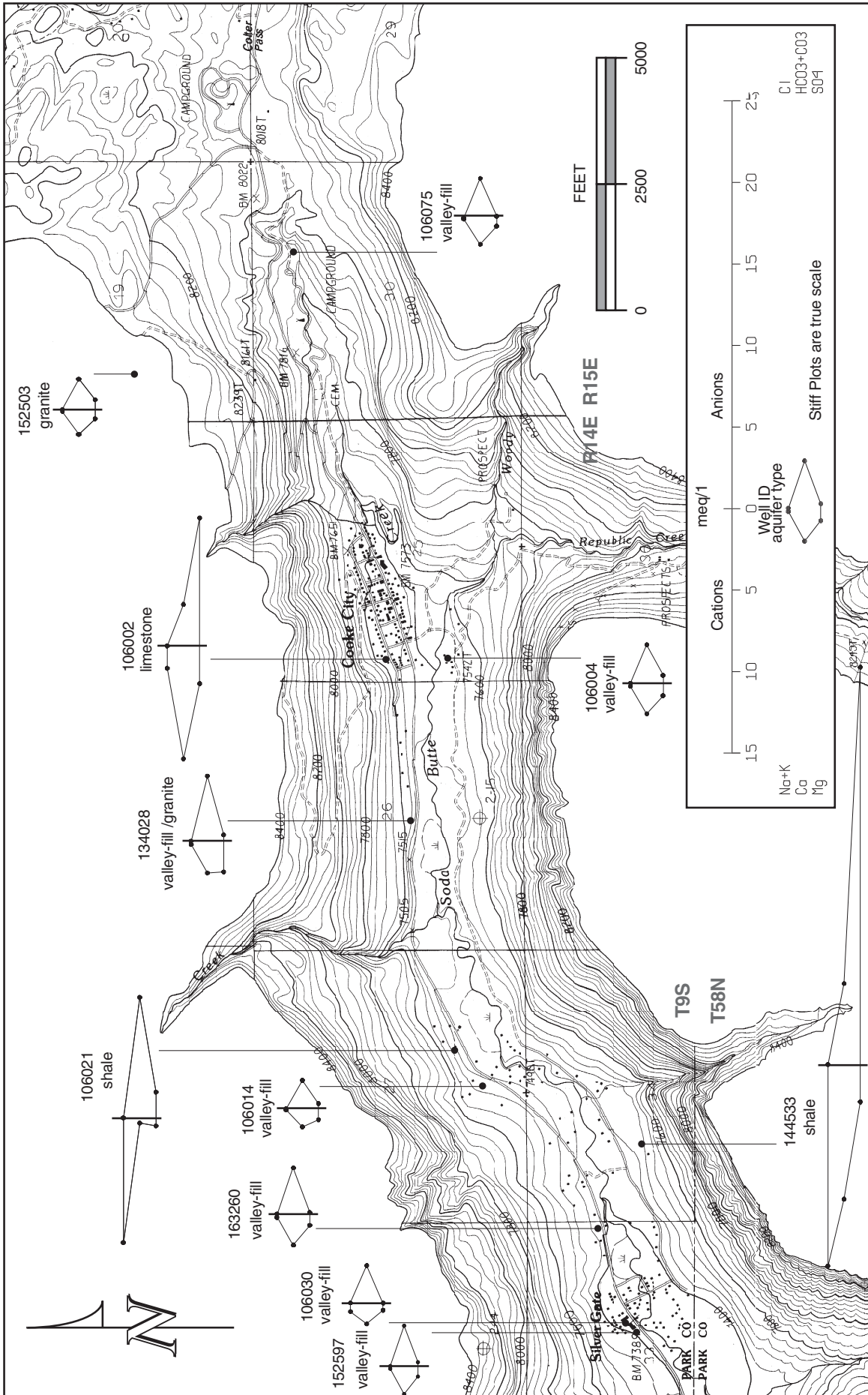


Figure 36. Waters in the valley-fill aquifer show little quality difference across the basin. Waters in bedrock aquifers show a variety of types.

used to simulate higher hydraulic conductivity material between 100 and 150 ft deep; and the bottom layer was used to simulate the bedrock aquifer. The first two of five simulations were run under steady-state conditions, and the last three simulations were run under transient conditions.

The initial value and distribution of the hydraulic conductivity in each model layer and of the stream bed was based on the surficial geology, lithologic logs from domestic wells, field observations, and results from the aquifer test. Ground-water flow into the model from upstream and from the valley margins was simulated with injection wells. The initial amount of recharge from the wells was based on hydraulic conductivity, gradient, and cross-sectional area of the alluvial material. Initial head values were unneeded for the first simulation.

Initial stream conditions were based on field observations of flow, stage, stream-bed slope, channel roughness, and channel width. On the inflow (upstream) end of the model, Soda Butte Creek was discharging 12 cfs in the first cell; streamflow and stage for each stream cell downstream were calculated by the model.

The first steady-state model did not include pumping by domestic wells. The model was run, and the results compared to observed (nonpumping) water levels in the Silver Gate area for September. Streamflow was compared to measurements made during the same period. Ground-water recharge rates, hydraulic conductivity, and stream-bed conductance were varied for each model run, until the model data and the observed data were comparable. As noted in earlier discussions, the aquifer test of the well in Silver Gate indicated a transmissivity on the order of 10,000 ft<sup>2</sup>/d; with an aquifer thickness of 150 ft, this translates to a hydraulic conductivity of about 66 ft/d. The final values and distribution of hydraulic conductivities needed to calibrate the model differed little. For the model, near-stream hydraulic conductivity was 30 to 50 ft/d, while the material on the margins of the valley were 10 to 20 ft/d. The lower hydraulic conductivity units in layer two of the model had values ranging from 10 to 30 ft/d. Steady-state models do not utilize storativity information. The largest head difference between the modeled and the observed data was about one foot in the Silver Gate area; the modeled streamflow of Soda Butte Creek below Silver Gate was about 14.5 cfs compared to the 15 cfs measured at that station.

## Modeling Results

The final head values from the first steady-state simulation with no pumping were used as starting

heads for the second steady-state simulation so that drawdown from pumping could be calculated. There are about 30 domestic wells in the Silver Gate area. Although the actual pumping capacity varies, a 5–10 gpm capacity was assumed, or a total well capacity of 150–300 gpm. Several simulations were run using an increasing number of wells and increasing discharge for each well, until a measurable reduction of streamflow could be seen. It is important to note that the term *measurable* in the context of modeling does not necessarily imply that the difference could be measured in the field, where a 5–10% error is generally assumed. A flow reduction of 0.75–1.5 cfs is the lower practical detection limit for field measurement in a stream flowing at 15 cfs. However, the model is capable of calculating a measurable flow reduction, as low as 0.01 cfs. For the purposes of these simulations, a measurable flow reduction was considered to be 0.1 cfs or more.

A 0.13 cfs streamflow reduction was achieved when 16 wells, eight in the shallow alluvium next to the stream plus eight more in the deep alluvium near the stream were pumped at five gpm each for a total of 80 gpm, or 15,402 cfd. Doubling discharge from each well to 10 gpm, for a total of 160 gpm, resulted in a streamflow reduction of about 0.3 cfs. As noted, steady-state conditions assume constant pumping, no fluctuation in recharge from ground water or surface water, and no aquifer storage. Thus, the steady-state model only provides information based on the extreme case of perpetually pumping, while the streamflow into the area remains constant.

A transient model provides a means of evaluating more realistic conditions. Here the pumping time could be varied, and aquifer storage could be taken into account. The storativity values were 0.15 for the unconfined, top layer, 0.001 for the *clay* layer, 0.002 for the confined, deeper alluvium, and 0.002 for the underlying bedrock. All other input parameters were the same. Several configurations of pumping rate, well depth, and distance from the stream were simulated at varying time periods. A measurable flow reduction (0.2 cfs) was established with 16 wells within 150 ft of the stream (shallow and deep) and a constant pumping rate of 5 gpm for 60 days. Doubling the discharge of each well to 10 gpm produced an additional 0.1 cfs reduction. Five additional wells, 300 ft or more from the stream, had no measurable effect on streamflow. Figure 38 presents the streamflow reduction in the Silver Gate area for various pumping configurations compared to the steady state model with no pumping. Figure 39 shows the drawdown in the valley-fill aquifer as a result of 16 wells pumping 10 gpm for 60 days.

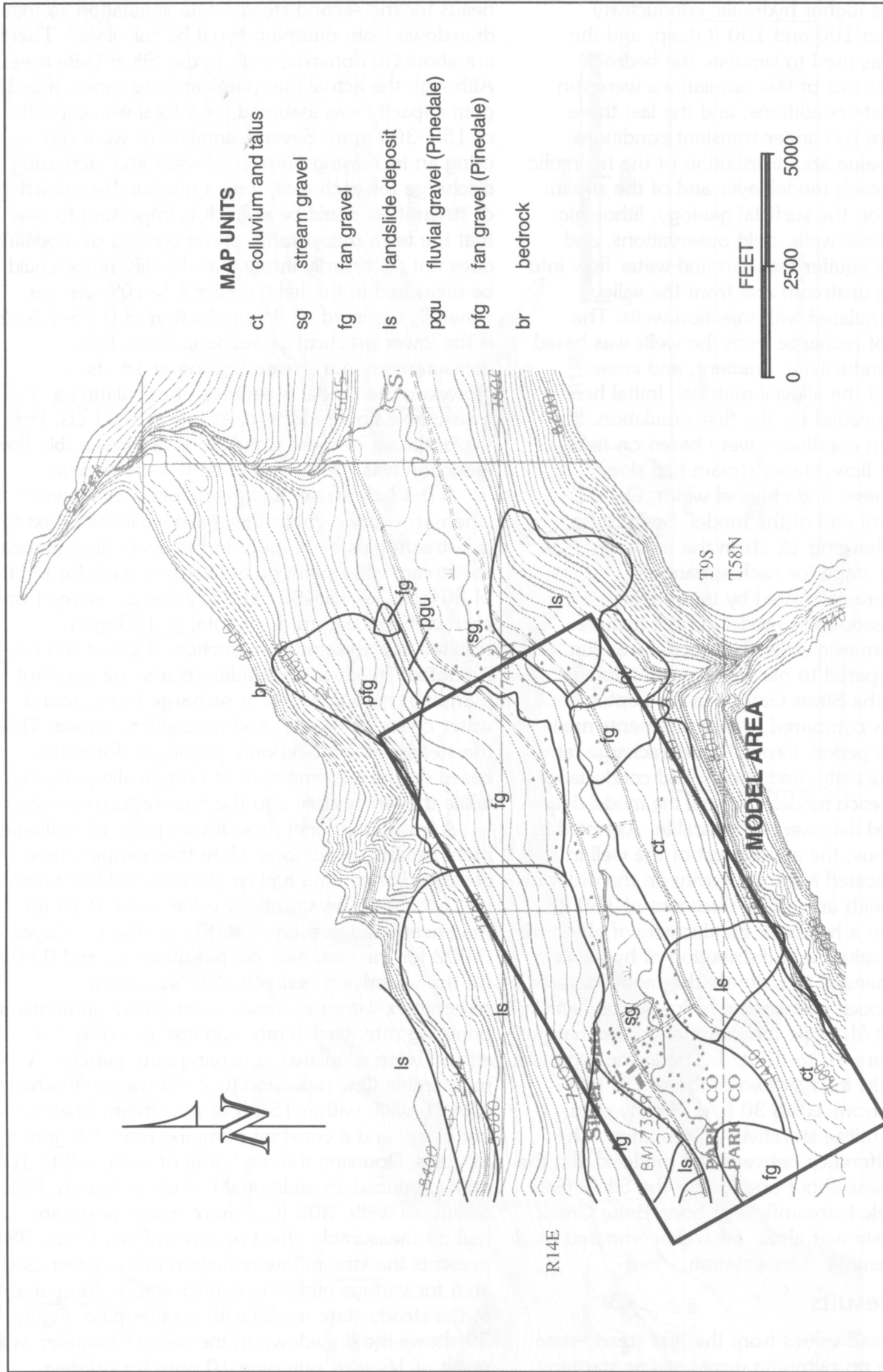


Figure 37. The Silver Gate area was chosen as the focus of the ground-water flow model area because it has the highest density of wells in the basin.

The intent of the modeling effort was to push the limits of domestic pumping until an impact on Soda Butte Creek could be observed. In this regard, it is unlikely that wells will ever be pumped continuously until steady-state conditions develop, nor is continuous pumping for 60 days a realistic expectation. Furthermore, not all water pumped would be consumed—a portion of the water is returned via septic systems. Based solely on the generalized hydrogeologic conditions of the model, under these extreme conditions, the reduction of streamflow in Soda Butte Creek would not be measurable in the field.

## Tritium-Helium Age-Dating of Ground Water

All ground water originates from one of three sources: juvenile water, which has never circulated as part of the hydrologic cycle and may include magmatic water; connate water, which has been out of contact with the atmosphere and the hydrologic cycle for an extended period of geologic time; and water that originated as surface water, whether it be from lakes and streams, or from precipitation. Most ground water, especially that accessible to most domestic wells, originated as surface water. The *age* of a given volume of ground water is the time that has elapsed since the water infiltrated the ground surface to become part of the ground-water flow system. The age further depends on how far and how deep the water has traveled. Thus, determining the age of a given volume of ground water, along with the hydraulic characteristics of the aquifer, will provide a means of *locating* the source of recharge for that ground water.

Tritium ( $^3\text{H}$ ) 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 in water on the planet is a result of above-ground nuclear weapons testing that began in the 1950s. Background, *prebomb*, atmospheric tritium levels measured in rain water have been estimated to be 5–10 tritium units (TU). The level increased to over 1,000 TU in the United States during the peak of testing in 1963 and has since declined to less than 100 TU. Tritium is unaffected by chemical reactions, and sources other than nuclear weapons are rare; the decay process continues as tritiated water leaves the atmosphere and enters the ground water. These qualities make tritium particularly useful in determining ground-water age by comparing the tritium concentration in a ground-water sample to the historical tritium concentrations in rain water.

Using tritium as a tracer, the ground-water age can be estimated with a precision of a few years.

One of the decay products of tritium is helium-3 ( $^3\text{He}$ ), a stable, inert isotope. In the atmosphere,  $^3\text{He}$  escapes and does not accumulate; however, in ground water,  $^3\text{He}$  accumulates and is referred to as excess  $^3\text{He}$ . The ratio of tritium and the excess  $^3\text{He}$  can be used to determine the time elapsed since the ground water was in contact with the atmosphere (Poreda *et al.* 1988). This method provides a precision of a few weeks to a few months. This is particularly useful in determining the ground-water age in shallow flow systems.

As described earlier, the upper Soda Butte Creek drainage has three principal aquifers: the bedrock aquifers, granitic intrusives and Paleozoic sedimentary rock; the stream-laid sediment of the valley bottom; and the hillslope and periglacial deposits on the valley margins. To assess their relative contribution to the ground-water/surface-water flow system of the drainage, selected domestic wells were sampled to determine the  $^3\text{H}/^3\text{He}$  concentrations from which the ground-water age could be estimated.

Well 106030: Completed at 51 ft deep in what are probably stream gravels and sands just north of Highway 212 in Silver Gate, this well was chosen to represent a typical, shallow domestic well. Based on the potentiometric maps (figures 27, 28, and 29) and the ground-water flow model, ground water in this area is recharged from up-valley with some influence from the valley margin.

Well 140290: This well is completed at 123 ft deep in sands and gravels below a layer of *blue clay* that is reported in well logs throughout the Silver Gate area and upstream. Like several others completed below the clay layer, this is a flowing well through the spring and early summer months and was chosen to assess whether the ground-water source for deeper sands and gravels in this area are from upstream or from a significant bedrock contribution.

Well 144633: At 189 ft deep, this well is completed in shale on the south valley margin. The sample from this well was intended to represent deep, old ground water. Information collected during sampling confirmed the low transmissivity suggested by the lithology and supported by the ground-water flow model.

Well 134028: This well is 80 ft deep and is completed in decomposed granite on the north valley margin between Silver Gate and Cooke City. Area water-level data suggest an upward gradient from the granitic bedrock to the overlying sands and gravels. This well was chosen to assess the relative

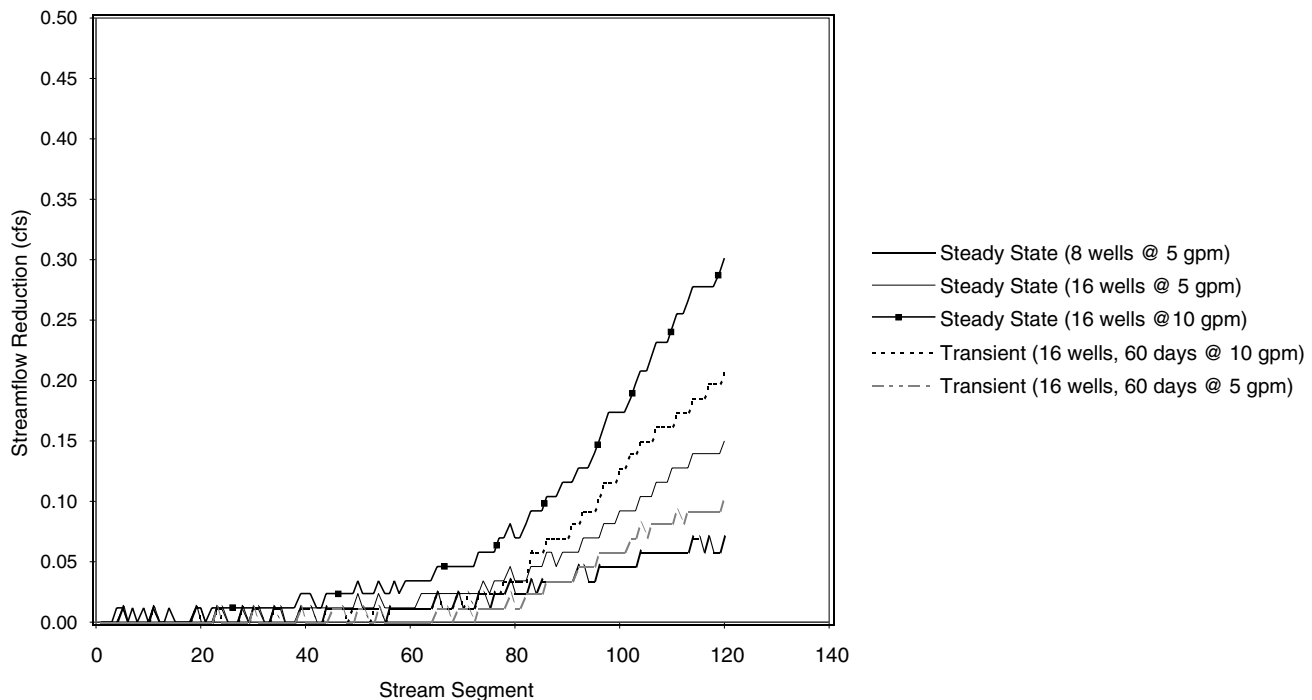


Figure 38. Increasing the number of wells and the pumping rate of each well increased the effect on streamflow. Note the difference between steady-state and transient conditions.

contribution of ground water from the bedrock to the alluvial valley aquifer.

Well 152503: The area known locally as Pilot's Roost is near the drainage divide between Soda Butte Creek and the Clark's Fork River. The area is overlain by 4–10 ft of glacial till. This well was chosen to represent ground water within what was considered to be a ground-water recharge area.

Figure 40 presents the sample locations and ages calculated from the  $^3\text{H}/^3\text{He}$  analysis results; complete analyses are presented in appendix A. Ages range from less than two years for the shallow well in Silver Gate to more than 55 years in the deep shale well. Mixing ground water of two different ages can change the apparent age. Combining old (prebomb) water, which is assumed to have no  $^3\text{H}$  or  $^3\text{He}$ , with younger (postbomb) water will not change the ratio of  $^3\text{H}$  to  $^3\text{He}$ ; the calculated age will reflect only the younger water. However, mixing two postbomb waters will result in a younger or older apparent age, depending on the relative quantities of each water. These age values, therefore, are considered to be the *mean residence time* of the dominant ground water in that area.

### Travel-Path Estimates

Using the mean residence time or  $^3\text{H}/^3\text{He}$ -age of the water near each well, estimates of the ground-

water seepage velocity, based on hydraulic conductivity, effective porosity, and the ground-water gradient, can be used to calculate the length of the ground-water travel-path (table 12). In table 12, hydraulic conductivity (K) and effective porosity were estimated based on pumping-test data and the ground-water flow model or on lithology; the ground-water gradient was based on the topographic gradient and, where available, water-level data.

The  $^3\text{H}/^3\text{He}$ -age calculations and the resulting travel-path calculations generally produced reasonable results, but are best described as approximations. More precise values of aquifer parameters, along with more  $^3\text{H}/^3\text{He}$ -age values along each flow path, would allow detailed mapping of each aquifer. Even with these limitations, however, the data provide a reliable means for describing the general ground-water flow in the watershed.

The young age (about 1.6 years) obtained from the shallow well in Silver Gate (well 106030), along with a fairly transmissive aquifer, suggest that recharge to the valley-fill material is from a short distance away, either from precipitation and snowmelt (directly or from nearby surficial deposits) or surface-water flow. Variations in the flow directions as shown with the potentiometric maps would probably result in younger and older water flowing to this well.

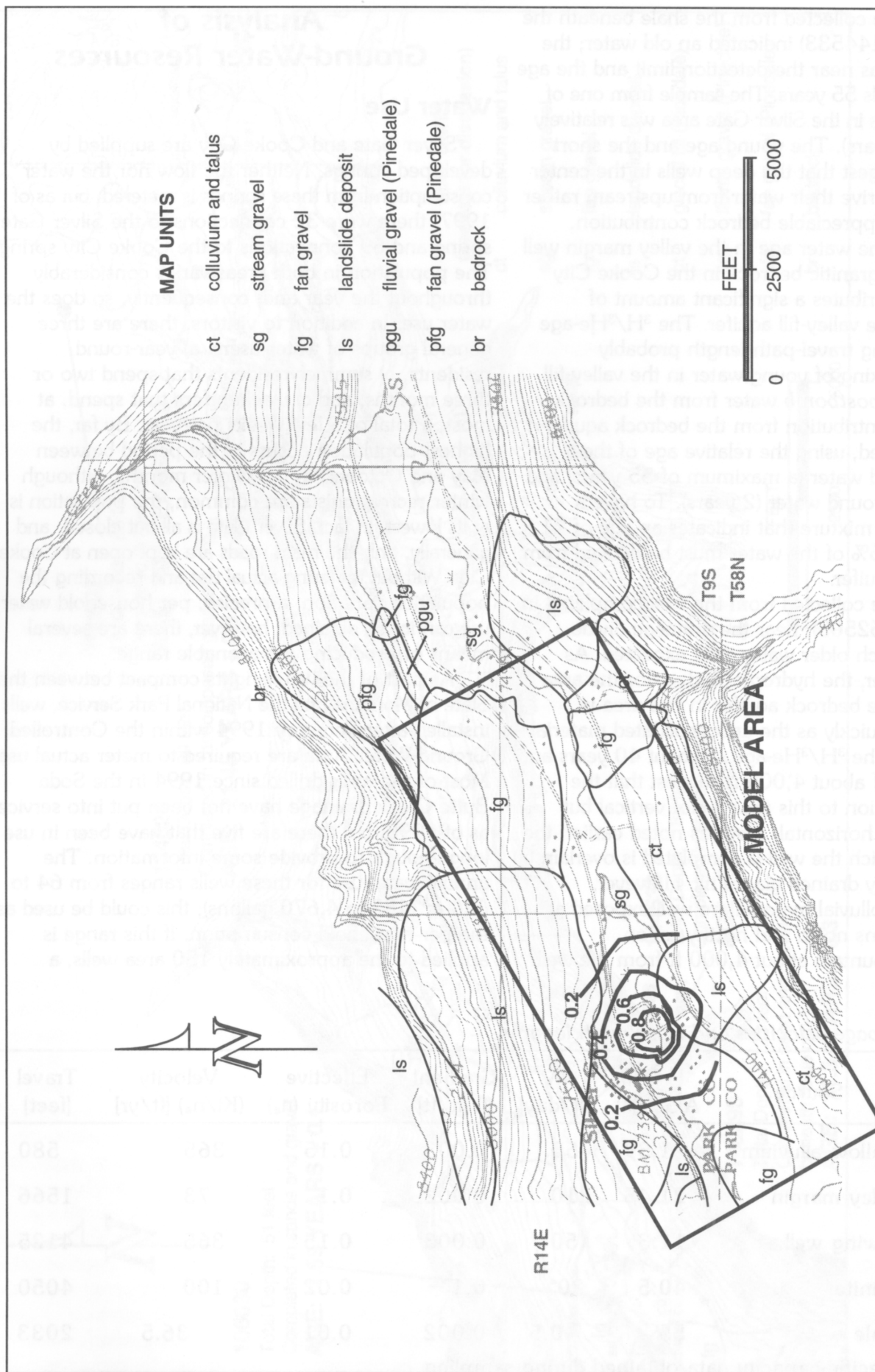


Figure 39. Sixteen wells pumping 10 gpm for 60 days produced a drawdown cone with a maximum drawdown of about 0.8 ft.

## Analysis of Ground-Water Resources

The sample collected from the shale beneath the valley fill (well 144533) indicated an old water; the tritium value was near the detection limit and the age probably exceeds 55 years. The sample from one of the flowing wells in the Silver Gate area was relatively young (11.3 years). The young age and the short travel path suggest that the deep wells in the center of the valley derive their water from upstream rather than from an appreciable bedrock contribution.

Based on the water age in the valley margin well (134028), the granitic bedrock in the Cooke City area likely contributes a significant amount of discharge to the valley-fill aquifer. The  $^3\text{H}/^3\text{He}$ -age and the resulting travel-path length probably represent a mixing of young water in the valley-fill and older, but *postbomb* water from the bedrock. The relative contribution from the bedrock aquifer can be estimated, using the relative age of the bedrock ground water (a maximum of 55 years) and the valley-fill ground water (2 years). To have a resulting water mixture that indicates an age of 21 years, about 35% of the water must be derived from the bedrock aquifer.

The sample collected from the well completed in granite (well 152503), near the drainage divide, indicated a much older water than expected. As discussed earlier, the hydrograph data for the area suggest that the bedrock aquifer in this area is recharged as quickly as the unconsolidated material in the valley. The  $^3\text{H}/^3\text{He}$ -age of about 40 years and a travel path of about 4,000 ft suggest that the recharge direction to this area is not vertical but predominantly horizontal. Also, as noted earlier, the area within which the well is completed is overlain by 4–6 ft of poorly drained glacial till. However, bedrock and colluvial material are well exposed at higher elevations north and northwest on Henderson Mountain about 4,000 ft from the well.

### Water Use

Silver Gate and Cooke City are supplied by developed springs. Neither the flow nor the water consumption from these springs is metered, but as of 1997, there were 32 connections to the Silver Gate spring and 69 connections to the Cooke City spring. The population in both areas varies considerably throughout the year and, consequently, so does the water use. In addition to visitors, there are three general groups of water users: a) year-round residents, b) summer residents that spend two or three months, and c) *weekenders* that spend, at most, a total of a few weeks per year. By far, the highest population occurs in the period between May and October; in the winter months, although winter recreationists are common, the population is at its lowest. In fact, Silver Gate is all but closed, and generally, only the main roads are kept open at Cooke City. Without metering actual use and recording the population variation, a precise, per household water use cannot be obtained; however, there are several means of producing a reasonable range.

As part of the water-rights compact between the State of Montana and the National Park Service, wells installed after February 1994 within the Controlled Ground-Water Area are required to meter actual use. Most of the wells drilled since 1994 in the Soda Butte Creek drainage have not been put into service as of 1998, but there are five that have been in use long enough to provide some information. The annual water-use for these wells ranges from 64 to 624 ft<sup>3</sup> (482 to 4,670 gallons); this could be used as the per household consumption. If this range is applied to the approximately 150 area wells, a

Table 12. Seepage velocities and travel-path lengths.

Sample	Source	$^3\text{H}-^3\text{He}$ AGE [Y]	K [ft/day]	Gradient (i) [ft/ft]	Effective Porosity ( $n_e$ )	Velocity ( $K_i/n_e$ ) [ft/yr]	Travel [feet]
1E+05	shallow alluvium	1.59	50	0.003	0.15	365	580
1E+05	valley margin	21.45	10	0.002	0.1	73	1566
1E+05	flowing well	11.3	50	0.003	0.15	365	4125
2E+05	granite	40.5	20*	0.1	0.02	100	4050
1E+05	shale	55	0.5	0.002	0.01	36.5	2033

\*Based on specific-capacity data obtained during sampling

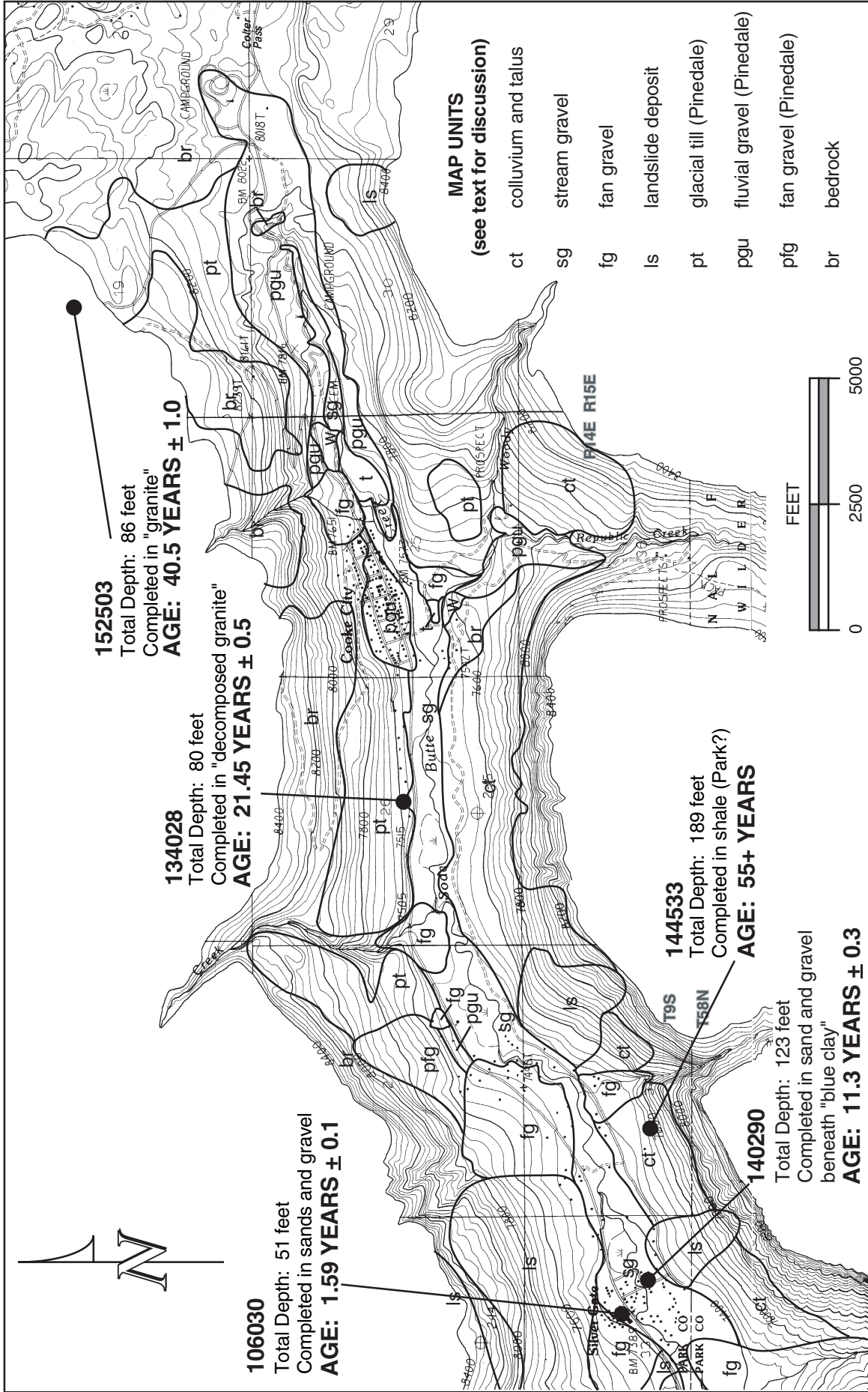


Figure 40. Isotope (helium/tritium) samples were collected from strategic wells throughout the drainage. The apparent age of the sampled water is shown for each.

conservative annual ground-water removal for the basin would range from 9,600 to 94,000 ft<sup>3</sup> (72,300 to 700,500 gallons).

Bioeconomics (1995) estimated a water use for the Clark Fork River Basin, Montana, of 30,000 cfd (224,400 gallons) per household, based on metered use for municipal water supplies. Another usage estimate is based on septic system requirements. Septic systems are required to be designed to accommodate up to 27 cfd (200 gallons) or 9,800 cfd (73,000 gallons). Applying these two estimates to 150 homes yields a total water demand of 1.5–4.5 million cfd (11–34 million gallons) for the basin.

For these estimates, it is important to note that these are values for gross use, or the total amount of water intercepted for use; some portion of the gross use is available for reuse after purification. If water obtained from a well is used for normal household activities, most of that water is returned to the aquifer through the septic system. Only a portion of the total amount of water pumped from the well is consumed by evaporation or other means.

Consumptive use is that portion of the water that cannot be reused or returned to the surface water or ground water. Dunne and Leopold (1978) give an estimate of 22% consumptive use for municipal water supplies. In the upper Soda Butte Creek basin, no water is exported by means other than the creek or ground water, and other gross consumption by industry or agriculture is insignificant.

## Water Balance

Table 13 presents a summary of the estimated annual water budget for the upper Soda Butte Creek drainage. The basis for the estimates of precipitation, runoff, and evapotranspiration (ET) were discussed in preceding sections. The baseflow estimate is derived from streamflow measurements, collected under low flow conditions when runoff is negligible. This generally occurs in late winter when the ground is frozen and snowmelt has not begun; the assumption is that all water flowing in the creek at this time is ground water. This corresponds with the amount of discharge required to balance and calibrate the ground-water flow model and a flow-net analysis, using fall water levels in the Silver Gate area. Consumptive use is based on 22% of the maximum estimated water use (gross use).

The inflow and outflow estimates on an annual basis balance to within 0.5%. Water withdrawal for consumptive use effects a change in the balance by about 0.1%. This change is much smaller than the error associated with the estimates that make up the balance and could probably be considered negligible.

Table 13. Water balance components and estimates.

	Annual volume (cubic feet per year)	Percent
<b>Total in</b> (precipitation)	4.14E+09	
Runoff	2.07E+09	49.7
ET	1.99E+09	47.8
Baseflow	9.46E+07	2.3
Consumptive use (max)	4500000	0.1
<b>Total out</b> (including use)	4.16E+09	
Difference (%)	-0.46	
<b>Total out</b> (w/o use)	4.15E+09	
Difference (%)	-0.35	

## Aquifer Storage

Over a long period of time (decades), barring any major changes to the watershed, the water balance is normally consistent and the net change in the amount of water stored as surface water or ground water is zero. Throughout a given year, changes in ground-water levels reflect the amount of water going into storage, which results in rising ground-water levels, or out of storage, which results in falling ground-water levels. The storativity reflects the amount of water absorbed or expelled by the aquifer as the head or water level rises or falls. Typically the storativity for sand and gravel aquifers ranges from 0.1 to 0.2 (equivalent to the effective porosity of the material) for unconfined conditions and 0.01 to 0.0001 for confined conditions. In the portions of the aquifer near Silver Gate, the deeper, confined aquifer has a potential water level that is well above the top of the aquifer and, in the case of flowing wells, the potential water level is above the land surface. In this case, a change of the potential water level, whether seasonal or by pumping, results in a very small change in the amount of water going into or out of storage. Conversely, the portions of the same aquifer near Silver Gate that are unconfined exhibit the greatest amount of water going into or out of storage as the water level changes.

Over the two-year period during which water levels were monitored, the four wells in the valley fill

aquifer changed by an average of about 16 ft the first year and 12 ft the second year. Using an approximate area for the aquifer between Silver Gate and the Cooke City area (19.5 million ft<sup>2</sup>) and a porosity of 15%, a 12-ft water-level change in the unconfined portion of the aquifer means 35 million ft<sup>3</sup> of water is going into storage in the spring and out of storage during the rest of the year. If ground-water withdrawal is assumed to be part of the annual storage change, the maximum consumptive use (4.5 million ft<sup>3</sup>) would amount to 13%. In the same respect, the maximum consumptive use would amount to about 1% of the total aquifer storage, assuming a 150 ft average aquifer thickness. This represents extreme conditions because it assumes that there is no additional recharge from summer storms, from the bedrock aquifers, or from recharge induced by drawdown caused by pumping.

### Summary: Conceptual Model

The hydrologic balance of the upper Soda Butte Creek drainage is dominated by runoff and evapotranspiration (figure 41). The timing and magnitude of runoff is controlled by precipitation, which, like most of the mountainous northwestern United States, is snow dominated and temperate. The cycle of ground-water recharge reflects the surface-water cycle: the rate of recharge is greatest in the spring and early summer and declines for the remainder of the year. In the areas above Cooke City that are covered by glacial till, infiltration is slow, and most of the water remains in the till rather than passing through to the underlying bedrock aquifer.

Numerous bogs, springs, and small streams, fed by shallow ground-water flow through the till, remain active throughout the summer and late fall. Meanwhile, the older tritium-helium age along with the obvious seasonal response suggest that recharge to the bedrock aquifer above Cooke City comes from higher elevations that are barren of soil and till. The till or other overlying material receives water from the bedrock in the lower part of the valley. Springs develop along the dip slope of the sedimentary rocks where a change in slope, lithology, or other conditions allows water to discharge to the surface; however, as suggested by the ground-water flow model, the material on the valley margin near Silver Gate does contribute directly to ground water in the main valley. The sedimentary bedrock beneath Silver Gate probably acts as an impediment to flow and contributes little to ground water in the overlying sand and gravel. This is evidenced by the older tritium-helium age of

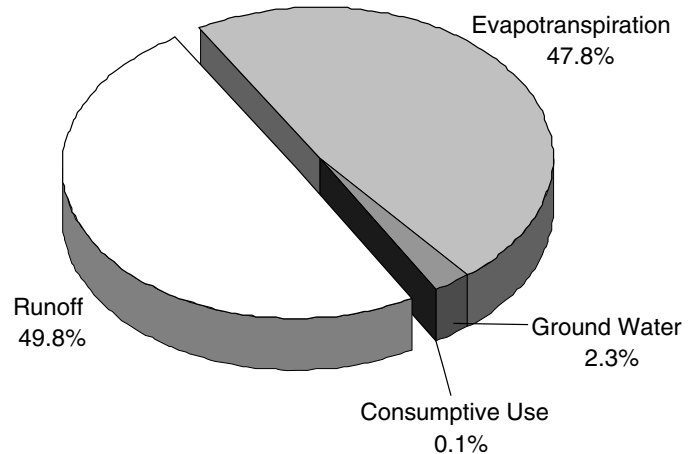


Figure 41. The water balance for the upper Soda Butte Creek drainage is dominated by runoff and evapotranspiration (ET).

the ground water and the low transmissivity of the shale underlying the area.

Ground water in the main valley is recharged by direct infiltration of snowmelt and high tributary streamflow in the spring and early summer. This is evidenced by the young tritium-helium ages and the rapid response of the hydrograph, and facilitated by the moderate transmissivity of the aquifer material. As the summer progresses, streamflow and ground-water levels in the main drainage decline as the snow pack declines and evapotranspiration increases. Although the evapotranspiration rate is at a minimum in the late fall and winter months, streamflow and ground-water levels continue to decline as freezing temperatures and the buildup of the snow pack prevent runoff and infiltration. The lowest streamflows and the lowest ground-water levels occur in late winter.

### Recommendations for Additional Work

The greatest limitation in any investigation of ground-water resources is the availability of ground-water sampling and monitoring points—wells. In the most thorough investigation, multiple wells are installed to investigate each aquifer with respect to lithology, horizontal and vertical hydraulic gradients, the aquifer's hydrogeologic properties, and water quality. Additional information is needed for surface-water characteristics, such as discharge and stage, water quality, storm and snowmelt response, and its loss/gain with respect to ground water.

In this investigation of the upper Soda Butte Creek watershed, the ground-water investigation was limited to domestic wells. Several areas of the valley bottom and most of the higher elevation areas did not have wells. Domestic wells are most often completed at depths sufficient to provide quality

drinking water for the owner throughout the year; thus, wells completed in the very shallow aquifers and the bedrock underlying the valley are rare. Similarly, stream discharge measurements had to be restricted to seasonal, discrete events. Measurements were also restricted to the main stem of the drainage.

Although the populations of Silver Gate and Cooke City are not expected to grow dramatically over the next few years, some growth will likely occur. Consequently, additional wells will be drilled and the demand for ground water will increase as will the likelihood of wells inducing drawdown in nearby wells. The information collected for this investigation can be used as a baseline for evaluating the impacts of additional ground-water use on streamflow and ground-water levels. Year-round (continuous recorder) monitoring of selected wells along with a set of annual baseflow or lowflow stream discharge measurements would serve as the best evaluation of streamflow impacts by ground-water withdrawal. These data would document any downward trends not attributable to climatic changes. Similarly, annual sampling of selected wells and streams for water-quality parameters would provide the means to detect any loading induced by human activity, such as septic systems and spills, or natural processes, such as debris flows.

## References

- Alley, W. M. and Burns, A. W., 1983, Mixed-station extension of monthly streamflow records: American Society of Civil Engineers, *Journal of Hydraulic Engineering*, 109(10), p. 1272–1284.
- Bioeconomics, Inc., 1995, Literature review and estimation of municipal and agricultural values of ground water use in the upper Clark Fork River drainage, Report to the Natural Resource Damage Program, Montana Department of Justice, Bioeconomics, Inc., Missoula, Montana, January, 1995, 33 p.
- Cary, L. E. and Parrett, C., 1996, Synthesis of natural flows at selected sites in the upper Missouri River basin, Montana, 1928–1989: U.S. Geological Survey Water-Resources Investigations Report 95-4261, 109 p.
- Dunne, T. and Leopold, L. B., 1978, *Water in Environmental Planning*, New York: W. H. Freeman and Company, 818 p.
- Elliott, J. E., 1979, Geologic map of the southwest part of the Cooke City quadrangle, Montana and Wyoming: U.S. Geological Survey Miscellaneous Investigations Map I-1084, scale 1:24,000.
- Hirsch, R. M., 1982, A comparison of four streamflow record extension techniques: *Water Resources Research*, 18(4), p. 1081–1088.
- Kirk, A.R., 1995, Bedrock structure and hydrogeology, New World project, Park County, Montana, prepared for Montana Department of State Lands, 33 p.
- Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H., 1986, *Hydrology for engineers* (3rd ed.): New York, McGraw-Hill Series in Water Resources and Environmental Engineering, 508 p.
- Maxim Technologies, Inc., 1995, Results of phase 2 aquifer testing in the Miller Creek drainage, New World project, Cooke City, Montana, prepared for Crown Butte Mines, Inc., September, 1995, 28 p.
- McDonald, M. G. and Harbaugh, A. W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.
- Meyer, G. A., Anderson, J. R., Bingham, M. K., O'Hara, P. M., Simpson, E. D., and Pierce, K. L., 1995a, Road Log, Chief Joseph campground to Lamar ranger station, Yellowstone National Park via Highway 212: Friends of the Pleistocene, Rocky Mountain Cell Field Conference Guidebook, August 25–27, 1995, p. 11–55.
- Meyer, G. A., Wells, S. G., and Jull, A. J. T., 1995b, Fire and alluvial chronology in Yellowstone National Park: Climatic and intrinsic controls on Holocene geomorphic processes: Friends of the Pleistocene, Rocky Mountain Cell Field Conference Guidebook, August 25–27, 1995, p. 1–26.
- Montana Department of Environmental Quality, 1995, Montana numeric water quality standards: Helena, Montana, Water Quality Division Circular WQB-7, 39 p.
- Montana Department of Environmental Quality, 1998, Unpublished data from public water supply files maintained by the Montana Department of Environmental Quality (MDEQ), Helena, Montana.
- National Oceanic and Atmospheric Administration, 1992, Monthly normals of temperature, precipitation, and heating and cooling degree days, 1961–1990, Montana: Asheville, North Carolina, *Climatology of the United States* no. 81, unpagged.
- Natural Resources Conservation Service, 1996, Montana annual data summary–water year 1995: Bozeman, Montana, p. 27–29 and 39–40.
- Nyberg, E. E., 1996, A geophysical characterization of the Soda Butte Creek drainage, Yellowstone National Park, July 15, 1996, report submitted to Mary Hektner, National Park Service, Mammoth, Wyoming, 18 p.

- 
- Pierce, W. G., 1957, Heart Mountain and South Fork Detachment thrusts of Wyoming, American Association of Petroleum Geologists Bulletin, v. 41, no. 4, p 591–626.
- Pierce, K. L., 1974, Surficial geologic map of the Abiather Peak and parts of adjacent quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-646, scale 1:62,500.
- Pierce, K. L., 1979, History and dynamics of glaciation in the northern Yellowstone National Park area: U.S. Geological Survey Professional Paper 729-F, 90 p.
- Poreda, R. J., Cerling, T. E., and Solomon, D. K., 1988, Tritium and Helium Isotopes as Hydrologic Tracers in a Shallow Unconfined Aquifer, Journal of Hydrology, 1988, vol. 103, p. 1–9.
- Prudic, D. E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.
- Sonderegger, J. L., Wallace, J. J., and Higgins, G. L., 1975, Acid mine drainage control feasibility study, Cooke City, Montana, Final Report submitted to Montana Department of Natural Resources and Conservation, December, 1975, 197 p.
- U.S. Environmental Protection Agency, 1986, Quality criteria for water 1986: Washington D.C., Office of Water Regulation and Standards, EPA 440/5-86-001, unpagged.
- Ward, J. C., 1996, Written communication.
-

**Appendix A. Inorganic Chemistry  
for Wells and Springs;  
Isotope Chemistry for Wells**

---

SAMPLE	"SOURCE"	HELIUM (1E-8 cc/g)	NEON (1E-8 cc/g)	$\Delta$ Ne (%)	He corr. (1E-8 cc/g)	$\Delta$ <sup>4</sup> He (%)	R(3/4) in Ra	TRITIUM (TU)	ERROR (TU)	<sup>3</sup> H/ <sup>3</sup> He AGE (Y)	ERROR (Y)
106030	Silver Gate	6.36	26.41	23.80	4.90	1.4	1.017	14.2	0.5	1.59	0.1
134028	valley margin	8.82	34.98	64.58	4.86	0.9	3.773	32.9	1.1	21.45	0.5
140290	flowing well	7.34	28.48	35.47	5.19	8.1	1.345	14.4	0.5	11.3	0.3
152503	granite	24.61	48.66	130.60	16.67	247	2.749	26.8	0.9	40.5	1.0
144533	shale	100.6	26.24	24.10	99.2	1962	0.164	3.02	0.12	55.7	1.5

## NOTES:

HELIUM: observed total helium  
 NEON: observed total neon  
 Ne: neon excess above solubility equilibrium  
 He corr.: air corrected total helium  
<sup>4</sup>He: corrected *helium excess above solubility equilibrium*  
 R(3/4): <sup>3</sup>He/<sup>4</sup>He isotopic ratio in units of the same for air  
 TRITIUM: tritium concentration in tritium units  
 ERROR: analytical uncertainty in tritium measurement  
<sup>3</sup>H - <sup>3</sup>He AGE: the tritium-helium age of the sample in years  
 ERROR: uncertainty of the <sup>3</sup>H/<sup>3</sup>He age determination

Tritium was measured with electrolytic enrichment. Sample 144533 required three distillations.

SURFACE WATER

Site ID	Laboratory ID	Location	Agency	Sample Date	Lab pH	Lab SC	Calcium (Ca)	Magnesium (Mg)	Lab Chloride (Cl)	Carbonate (CO3)	Fluoride (F)	Iron (Fe)	Bicarbonate (HCO3)	Potassium (K)	Manganese (Mn)	NO3 as N	Sodium (Na)	Phosphate (P as PbO4)	Silica (SiO2)	Sulfate
158925	1997Q0686 09S	14E 27	USGS	3/27/1997	8.30	265	40.7	9.5	<.5	0.0	<.003	145.2	.671	<.002	.19	2.4	<.25	10.1	14.0	
158922	1997Q0687 09S	14E 26	USGS	3/27/1997	8.30	219	32.0	9.5	<.5	0.0	<.003	121.8	.379	<.002	.11	1.9	<.25	7.9	10.2	
158926	1997Q0684 09S	14E 33	USGS	3/27/1997	8.30	259	37.1	8.7	<.5	0.0	.007	135.7	.304	.003	.16	4.7	<.25	12.2	11.4	
169046	1999Q0363 09S	14E 27	CACD	10/31/1998	7.46	250	28.7	12.1	<.5	0.0	.06	.054	136.6	.556	<.001	>.109	1.68	<.05	5.2	22.227
169047	1999Q0364 09S	14E 33	DAAD	10/31/1998	7.64	227	29.3	6.3	.769	0.0	.097	.027	140.1	.339	<.001	.203	9.591	.058	10.948	6.494
158923	1997Q0688 09S	14E 26	USGS	3/27/1997	8.40	332	53.2	12.0	<.5	0.0	<.003	146.1	.453	.003	.14	3.1	<.25	12.4	18.5	
158927	1997Q0685 09S	14E 33	USGS	3/27/1997	8.30	257	39.3	8.8	<.5	0.0	.01	138.4	.517	<.002	.16	3.6	<.25	10.7	13.2	
167710	1999Q0135 09S	15E 29	BABA	8/6/1998	7.04	130	15.5	3.7	<.5	0.0	<.05	<.005	74.5	.463	<.001	<.05	1.627	<.05	12.4	3.695
158924	1997Q0689 09S	14E 26	USGS	3/27/1997	7.80	174	22.0	6.4	<.5	0.0	.012	90.8	<.1	<.002	.06	5.3	<.25	12.8	6.3	
158927	1999Q0594 09S	14E 33	USGS	3/18/1999	8.03	268	36.5	7.7	.326	0.0	<.05	<.005	145.4	.459	.002	.073	2.99	<.05	8.43	13.10
168730	1999Q0319 09S	14E 26	CBBD	10/8/1998	7.85	181	20.1	6.1	<.5	0.0	<.05	<.005	99.3	.357	<.001	<.05	1.82	<.05	5.40	6.957
168731	1999Q0320 09S	14E 26	CCBA	10/8/1998	7.74	189	22.1	5.8	.517	0.0	.06	.018	106.4	.477	.003	<.05	3.93	<.05	9.62	8.998
168732	1999Q0321 09S	14E 34	BADD	10/7/1998	8.19	210	28.2	6.6	.513	0.0	.06	.009	122.4	.586	.002	<.05	3.53	<.05	9.03	10.811
168733	1999Q0322 09S	14E 34	BADD	10/8/1998	7.52	81	5.4	1.9	<.5	0.0	.06	.288	43.4	.312	.003	<.05	8.10	<.05	14.1	4.334
168734	1999Q0323 09S	14E 34	BADC	10/8/1998	8.15	19	26.8	6.3	<.5	0.0	.06	.001	118.1	.529	.002	<.05	3.723	<.05	9.19	10.319
168735	1999Q0324 09S	14E 33	CAAA	10/7/1998	7.98	218	26.5	6.0	.597	0.0	.06	.007	124.0	.556	.003	<.05	3.87	<.05	9.3	10.336

Concentrations are milligrams per liter

Site ID	Silver (Ag)	Aluminum (Al)	Arsenic (As)	Boron (B)	Barium (Ba)	Bromide (Br)	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Lithium (Li)	Nickel (Ni)	Lead (Pb)	Antimony (Sb)	Selenium (Se)	Strontium (Sr)	Titanium (Ti)	Vanadium (V)	Zinc (Zn)	Zirconium (Zr)
158925	<.1	<.30	<.1	<.30	29.8	<100	<.2	<.2	<.2	<.6	4.0	<.2	<.2	<.1	142	<10	<.5	2.1	<.20
158922	<.1	<.30	<.1	<.30	21.1	<100	<.2	<.2	<.2	<.6	3.2	<.2	<.2	<.1	120	<10	<.5	<.2	<.20
158926	<.1	<.30	<.1	<.30	18.5	<100	<.2	<.2	<.2	<.6	3.8	<.2	<.2	<.1	141	<10	<.5	3.0	<.20
169046	<.1	<.30	<.1	<.80	16.6	<25	<.2	<.2	<.2	<.50	6.9	<.2	<.2	<.1	162	<10	<.5	<.2	<.5
169047	<.1	<.30	<.1	<.80	28.6	<25	<.2	<.2	<.2	<.50	6.9	<.2	<.2	<.1	113	12.9	7.15	<.2	<.5
158923	<.1	<.30	<.1	<.30	28.6	<100	<.2	<.2	<.2	<.6	5.0	<.2	<.2	<.1	142	<10	<.5	2.5	<.20
158927	<.1	<.30	<.1	<.30	20.7	<100	<.2	<.2	<.2	<.6	4.0	<.2	<.2	<.1	141	<10	<.5	4.4	<.20
167710	<.1	<.15	<.1	<.30	27.9	<.25	<.2	<.2	<.2	<.10	<.2	<.2	<.1	<.10	<.5	<.2	<.2	<.10	
158924	<.1	<.30	1.2	<.30	15.4	<100	<.2	<.2	<.2	<.6	2.5	<.2	<.2	<.1	109	<10	<.5	4.1	<.20
158927	<.1	<.30	<.1	<.30	27.1	<50	<.2	3.31	<.2	<.50	<.2	<.2	<.2	<.1	131	<10	<.5	5.10	<.5
168730	<.1	<.30	<.1	<.80	22.3	<25	<.2	<.2	<.2	<.50	4.9	<.2	<.2	<.1	95	<10	<.5	<.2	<.5
168731	<.1	<.30	<.1	<.80	27.0	<25	<.2	<.2	<.2	<.50	5.6	<.2	<.2	<.1	92	<10	<.5	3.80	5
168732	<.1	<.30	<.1	<.80	31.6	<25	<.2	<.2	<.2	<.50	6.6	<.2	<.2	<.1	107	<10	<.5	4.67	<.5
168733	<.1	1.15	<.1	<.80	35.4	<25	<.2	<.2	<.2	<.50	<.2	<.2	<.2	<.1	47	14.2	6.53	7.63	<.5
168734	<.1	<.30	<.1	<.80	28.2	<25	<.2	<.2	<.2	<.50	6.4	<.2	<.2	<.1	107	<10	<.5	<.2	<.5
168735	<.1	<.30	<.1	<.80	29.7	<25	<.2	<.2	<.2	<.50	6.5	<.2	<.2	<.1	116	<10	<.5	<.2	<.5

Concentrations are micrograms per liter

Analyses by the Montana Bureau of Mines and Geology