Prepared in cooperation with
RIO BLANCO COUNTY

Baseline Characterization of Water Quality and Mass Loading in Piceance Creek, Rio Blanco County, Colorado, December 2000

Water-Resources Investigations Report 02–4134

Cover Photograph:

Piceance Creek looking downstream from transport site 2.
Field team retrieving tracer samples from automatic sampler.
(Photograph by Sheryl A. Ferguson, U.S. Geological Survey)

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By Roderick F. Ortiz

U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

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TABLES

CONVERSION FACTORS, ABBREVIATED UNITS, AND ACRONYMS

Multiply	By	To obtain
gram	0.03527	ounce
kilogram	2.205	pound
ton (metric)	1.102	ton (short)
micrometer	0.0000394	inch
millimeter	0.0394	inch
meter	3.281	feet
kilometer	0.6214	mile
milliliter	0.0339	ounce
liter	0.2642	gallon
square kilometer	0.3861	square mile
cubic meter	0.000811	acre-foot
liter per second	0.03531	cubic feet per second
milliliter per minute	0.0339	ounce per minute
kilogram per day	0.0011	ton per day

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$$°F = 9/5°C + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

ABBREVIATED UNITS USED IN THIS REPORT

L/s   liter per second

s.u.   standard units

pCi/L   picocurie per liter

ACRONYMS USED IN THIS REPORT

BLM   Bureau of Land Management

USGS   U.S. Geological Survey

RPR   Relative percent difference

NWQL   National Water Quality Laboratory

NaBr   Sodium Bromide

LiBr   Lithium Bromide

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ABSTRACT

Data collected by the U.S. Geological Survey provided a baseline characterization of the water quality in Piceance Creek and quantified the mass load for selected chemical constituents in Piceance Creek during base-flow conditions. Tracer-dilution techniques and instantaneous measurements were used to determine streamflow in Piceance Creek. Synoptic-sampling techniques were used to determine baseline concentrations for selected constituents. Load profiles along subreaches of the creek were generated by combining tracer-dilution and synoptic-sampling techniques.

Data collected as part of this study provide an updated characterization of the water quality in Piceance Creek along the 28-kilometer study reach. In 1987, bicarbonate, sulfate, and sodium were reported as the principal dissolved constituents in Piceance Creek. The principal dissolved constituents remained the same in December 2000. High concentrations of bicarbonate and sodium result from the contact of ground water with evaporite minerals in the Green River Formation. Sulfate is commonly found in high concentrations in the ground water of the overlying Uinta Formation. Concentrations of barium, boron, lithium, and strontium also were elevated in Piceance Creek. No significant load input to Piceance Creek was detected along the reach adjacent to the boundary of the Yankee Gulch Lease (primary study reach). Although the area near Alkali Flat contributed substantially to the increase in constituent concentration in Piceance Creek, losses in streamflow resulted in relatively small increases in load downstream to the end of the study reach.

INTRODUCTION

The Piceance Creek Basin is a downwarped, depositional region located in northwestern Colorado (fig. 1). The structural basin was formed during the Laramide orogeny, a mountain-building process of thrusting, faulting, and folding that lasted at least 10 million years from Late Cretaceous to Eocene time (Maclachlan, 1987). About 48 million years ago, an ancient lake (Lake Uinta) covered thousands of square kilometers of Colorado, Utah, and Wyoming. At its maximum size, Lake Uinta covered about 57,000 square kilometers, including the Piceance structural basin. Vast quantities of oil shale accumulated as organic-rich marls in the deeper part of the lake. Evaporite minerals such as sodium, bicarbonate, and chloride also precipitated in the oil-rich marlstones as brine concentrations exceeded the solubility limits of these minerals. When downwarping ceased, the basin filled with sediments and Lake Uinta disappeared (Dyni, 1987).

The marlstone of the Green River Formation in the Piceance Basin is a repository for one of the largest energy reserves in the world (Donnell, 1987). For nearly a century, the area has been known for its rich oil-shale deposits. From 1950 to 1990, concentrated efforts were made by the federal government and the oil industry to locate and develop the oil-shale reserves as alternative energy sources. These efforts were never fully realized.

Other potentially valuable minerals also are abundant in the oil-shale deposits. Nahcolite, a sodium bicarbonate mineral; dawsonite, a sodium aluminum carbonate mineral; and halite, sodium chloride, are interspersed through the lower part of the oil-shale deposits. In recent years, the emphasis of resource development in the Piceance Creek Basin has turned to

108°30'

108°

40°

39°30'

09306222

White

Meeker

64

Yellow Creek

Dry Fork

River

Gulch

09306200

Ryan

13

Piceance Creek

5

RIO
BLANCO

139

Rio
Blanco

Parachute Creek

Rifle

70

Colorado River

GARFIELD

Roan Creek

MESA

Hydrology modified by Denver Water Board 1998
from U.S. Geological Survey Digital Line Graphs 1:100,000, 1981-82.
Albers Equal-Area projection
Standard parallels 37°30'N and 40°30'N
Central Meridian 105°30'W

0   5   10   15   20 KILOMETERS

0   5   10   15   20 MILES

COLORADO

Meeker

Denver

Grand
Junction   Piceance Creek
Basin

EXPLANATION

APPROXIMATE EXTENT OF STUDY AREA

APPROXIMATE BOUNDARY OF YANKEE GULCH LEASE

BASIN BOUNDARY

▲ 09306200   U.S. GEOLOGICAL SURVEY GAGING STATIONS–Number
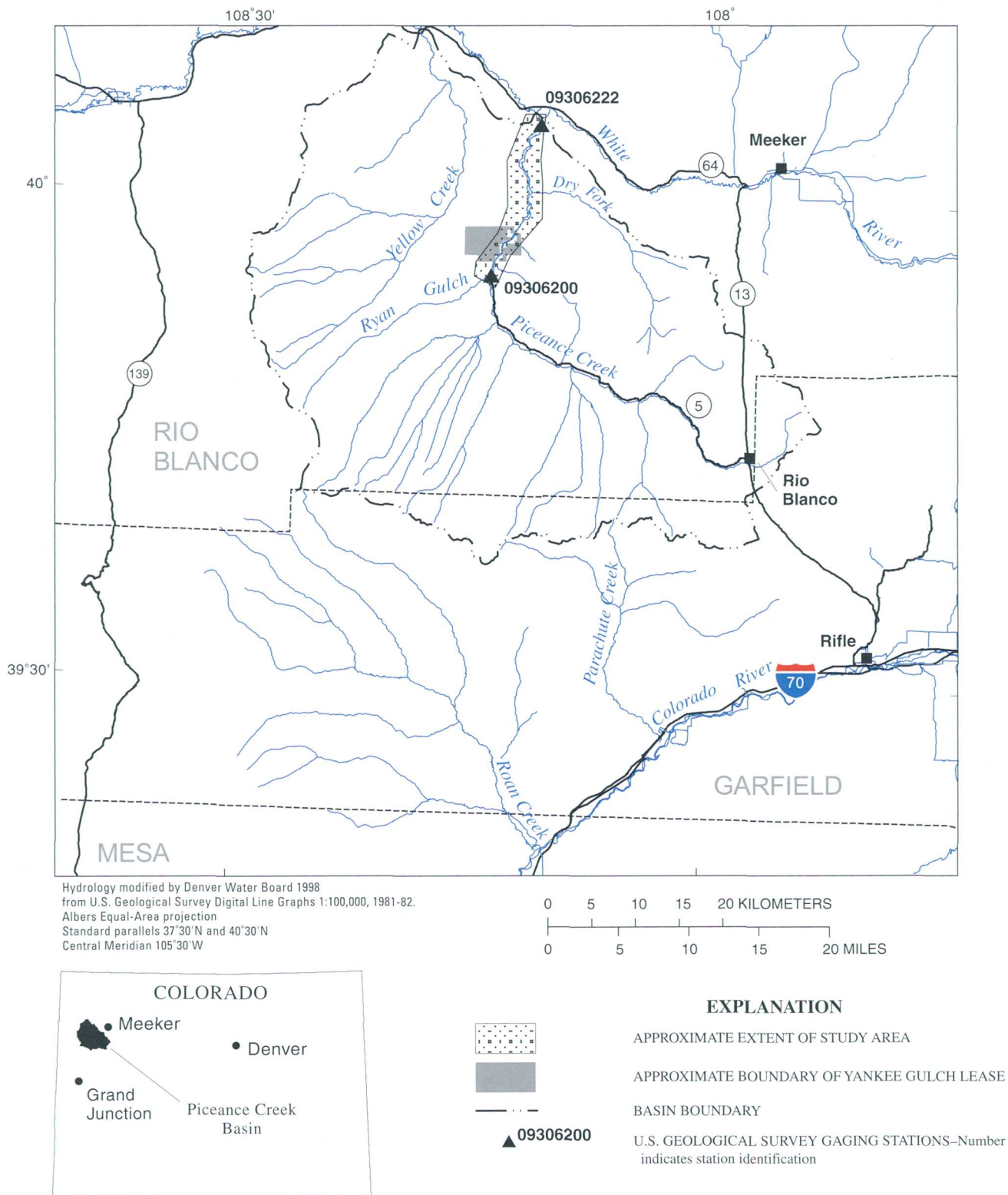indicates station identification

Figure 1. Location of the Piceance Basin and the study area, Rio Blanco County, Colorado.

commercial nahcolite solution mining for sodium bicarbonate (baking soda) and sodium carbonate (soda ash). The Piceance Basin is reported to have the largest and most economically significant nahcolite resources in the world (Beard and others, 1974). Conservative estimates of in-place nahcolite have been reported at 26 billion metric tons.

In 1999, the U.S. Bureau of Land Management (BLM) issued a Draft Environmental Impact Statement that evaluated the effects of a commercial nahcolite solution mining operation on the Yankee Gulch Joint-Venture Lease (fig. 1) within the BLM's White River Resource Area (U.S. Bureau of Land Management, 1999). The Yankee Gulch Sodium Minerals Project (Yankee Gulch Project) would occur at this site about 37 kilometers southwest of Meeker, Colorado (fig. 1). As part of the permitting and regulatory requirements, the mine operators were required to submit a monitoring plan that, in part, would characterize the baseline water quality in the adjacent Piceance Creek (Agapito Associates, Inc., 1999). The primary objective of the baseline characterization, of which this study is a part, is to provide the baseline data needed to assess possible changes in the water quality of Piceance Creek due to continued mining operations. The U.S. Geological Survey (USGS) provided this characterization in cooperation with Rio Blanco County, Colorado.

Purpose and Scope

The purpose of this report is to (1) provide a baseline characterization of the water quality in Piceance Creek, and (2) quantify the mass load for selected chemical constituents in Piceance Creek during base-flow conditions. Physical and chemical data were collected during the week of December 3–8, 2000, at 47 main-stem sites and 4 inflow sites (table 1). Several quality-assurance samples also were collected. The study reach extended about 28 kilometers between the USGS streamflow-gaging stations 09306200 (Ryan Gulch station, PC0) and 09306222 (White River station, PC28,348) on Piceance Creek (fig. 1). The primary focus of the study was along the approximately 11.5 kilometers of the study area adjacent to the lease boundary for the Yankee Gulch Project (primary study reach).

Table 1. Site locations for tracer-dilution and synoptic-sampling study in Piceance Creek, December 4–7, 2000

[s.u., standard units; μS/cm, microsiemens per centimeter; °C, degrees Celsius; USGS, U.S. Geological Survey; Y, yes; N, no; NA, not applicable; e, estimated; LiBr, lithium bromide; NaBr, sodium bromide]

Site number	Distance from streamflow-gaging station 09306200 (meters)	Sample collection Date	Sample collection Time	pH (s.u.)	Specific conductance (μS/cm at 25 °C)	Back-ground bromide sample collected	Site type designation
				Main-stem Piceance Creek sites			
PC0	0	12–07–00	1040	8.0	1,540	NA	Background, USGS streamflow-gaging station 09306200, LiBr injection site
PC180	180	12–07–00	1035	8.0	1,590	N	Routine, transport site T1
PC420	420	12–07–00	1030	8.0	1,590	Y	Routine
PC660	660	12–07–00	1020	8.0	1,600	N	Routine
PC1,080	1,080	12–07–00	1015	8.1	1,610	N	Routine
PC1,320	1,320	12–07–00	1005	8.1	1,610	N	Routine
PC1,560	1,560	12–07–00	0955	8.1	1,610	Y	Routine
PC1,960	1,960	12–07–00	0945	8.1	1,610	N	Routine
PC2,205	2,205	12–07–00	0935	8.1	1,600	Y	Indicator, transport site T2, quality control
PC2,445	2,445	12–07–00	0925	8.1	1,610	N	Routine
PC2,685	2,685	12–07–00	0920	8.0	1,620	N	Routine
PC2,925	2,925	12–07–00	0910.	8.0	1,630	N	Routine
PC3,105	3,105	12–07–00	0900	8.0	1,630	Y	Routine

Table 1. Site locations for tracer-dilution and synoptic-sampling study in Piceance Creek, December 4–7, 2000—Continued

[s.u., standard units; μS/cm, microsiemens per centimeter; °C, degrees Celsius; USGS, U.S. Geological Survey; Y, yes; N, no; NA, not applicable; e, estimated; LiBr, lithium bromide; NaBr, sodium bromide]

Site number	Distance from streamflow-gaging station 09306200 (meters)	Sample collection Date	Time	pH (s.u.)	Specific conductance (μS/cm at 25 °C)	Back-ground bromide sample collected	Site type designation
				Main-stem Piceance Creek sites—Continued			
PC3,278	3,278	12–07–00	0845	8.0	1,630	N	Routine
PC3,505	3,505	12–07–00	0835	8.0	1,640	Y	Routine, quality control
PC3,735	3,735	12–07–00	0825	8.1	1,650	N	Routine
PC3,935	3,935	12–07–00	0815	8.1	1,640	Y	Routine
PC4,180	4,180	12–07–00	0800	8.0	1,630	Y	Indicator, transport site T3
PC4,420	4,420	12–07–00	0755	8.0	1,630	N	Routine
PC4,660	4,660	12–07–00	0745	8.0	1,630	Y	Routine
PC4,900	4,900	12–07–00	0735	8.0	1,640	N	Routine
PC5,040	5,040	12–07–00	0727	8.1	1,630	N	Routine
PC5,280	5,280	12–07–00	0700	8.0	1,590	N	Indicator, transport site T4
PC6,625	6,625	12–05–00	1040	8.0	1,680	Y	Background, NaBr injection site
		12–07–00	1147	8.1	1,690	N	Quality assurance
PC6,813	6,813	12–05–00	1020	8.0	1,690	Y	Routine, transport site T5
PC7,028	7,028	12–05–00	1010	8.0	1,690	Y	Routine
PC7,248	7,248	12–05–00	0955	8.0	1,700	Y	Routine
PC7,498	7,498	12–05–00	0945	8.0	1,680	N	Routine
PC7,738	7,738	12–05–00	0935	8.0	1,690	Y	Routine
PC7,978	7,978	12–05–00	0930	8.0	1,710	N	Routine
PC8,098	8,098	12–05–00	0915	8.1	1,700	Y	Indicator, transport site T6, quality control
PC8,448	8,448	12–05–00	0905	8.0	1,720	Y	Routine, quality control
PC8,688	8,688	12–05–00	0855	8.0	1,730	Y	Routine
PC8,938	8,938	12–05–00	0850	8.0	1,720	Y	Routine
PC9,298	9,298	12–05–00	0825	8.0	1,720	Y	Routine
PC9,608	9,608	12–05–00	0815	8.0	1,700	Y	Routine
PC9,938	9,938	12–05–00	0805	8.0	1,740	Y	Routine, transport site T7
PC10,328	10,328	12–05–00	0800	8.0	1,730	Y	Routine
PC10,748	10,748	12–05–00	0745	8.0	1,730	Y	Routine
PC11,483	11,483	12–05–00	0730	8.1	1,720	Y	Indicator, transport site T8
PC14,789	14,789	12–06–00	1005	8.0	1,780	NA	Routine
PC16,210	16,210	12–06–00	0910	8.0	1,770	NA	Routine
PC17,860	17,860	12–06–00	0805	8.1	1,710	NA	Indicator
PC20,708	20,708	12–06–00	1030	8.0	1,730	NA	Routine
PC23,721	23,721	12–06–00	0945	8.0	1,980	NA	Indicator
PC24,787	24,787	12–06–00	0900	7.9	1,950	NA	Routine
PC28,348	28,348	12–06–00	0745	8.0	1,980	NA	Routine, USGS station 09306222
				Inflows and springs			
RGS	e200	12–04–00	0900	7.8	3,060	NA	Ryan Gulch spring
HGS	e1,625	12–07–00	1220	8.0	3,510	NA	Spring contact near Hatch Gulch
PT16,225	e16,225	12–06–00	0925	8.0	1,150	NA	Dry Fork
AFS	e21,288	12–04–00	1225	7.8	12,700	NA	Alkali Flat spring contacts

Tracer-dilution techniques were used to develop a spatial streamflow profile along the primary study reach. This reach is close to the Yankee Gulch Project, a nahcolite-solution mining operation that could possibly affect the water quality of the creek. A less detailed streamflow profile was developed along the lower two-thirds of the study reach (secondary study reach) by using standard USGS streamflow-measurement techniques (Rantz and others, 1982). Synoptic water-quality samples were collected along both study reaches to establish baseline constituent concentrations and to calculate mass loading in Piceance Creek.

Description of Study Area

The study area described in this report extends between the Ryan Gulch streamflow-gaging station (PC0) and the White River streamflow-gaging station (PC28,348) (fig. 2). Sites were identified by a downstream distance in meters from the PC0. The study area encompasses about 235 square kilometers of drainage area (Crowfoot and others, 2001). Stream-channel elevations range from 1,850 to 1,746 meters above sea level. The highest elevation in the study area is nearly 2,400 meters. Generally, streamflow increases downstream during base-flow conditions from October to April; streamflows are more similar during the irrigation season (fig. 3). Tobin (1987), however, identified a subreach downstream from Dry Fork where streamflow decreased. An estimated 80 percent of the annual runoff in the watershed occurs during base-flow conditions, and springs are an important contributor to streamflow during this period (Robson and Saulnier, 1981). Most of the tributaries to Piceance Creek are ephemeral; Dry Fork was the only surface-water inflow to Piceance Creek measured during the December 2000 field activities (fig. 2). Because of the large number of sites sampled as part of this study, only sample sites specifically addressed in this report are shown in figure 2.

Piceance Creek is characterized by a meandering stream channel incised into the floodplain with deep bank carving that is prone to sloughing. As such, sediment loads to the stream can be considerable during high runoff (Norman, 1987). The streambed is composed of silt, sand, gravel, and occasional cobbles. Pockets of fine material are deposited where slow stream velocity occurs. Although lakes and reservoirs are not abundant in the Piceance Creek Basin, a small

irrigation/wildlife impoundment is located in the study reach (fig. 2). Typically, impoundments such as these are less than 4.5 meters in depth and are prone to siltation (U.S. Bureau of Land Management, 1984). The gentle slope of the stream valley provides an area well suited for sub-irrigated or flood-irrigated agricultural production. Irrigation is prevalent from May through mid-October in the relatively narrow (300 to 380 meters wide) alluvial valley. The predominant crops are alfalfa and grass hay for livestock (U.S. Bureau of Land Management, 1984). The climate in the area is characterized by low humidity, sunny days, clear nights, little precipitation, extreme evaporation, and large diurnal temperature changes (U.S. Bureau of Land Management, 1984). The mean daily air temperature during December 2000 at Rifle, Colorado (fig. 1), ranged from –8 to 2 degrees Celsius (Colorado Climate Center, 2001). Stream temperatures during the field activities were routinely near freezing, and ice was observed along much of the streambank of Piceance Creek.

The valleys of the White River (fig. 2) and its tributaries are partly filled with alluvium and fan deposits consisting of sand and gravel. However, test holes drilled downstream from Ryan Gulch (fig. 1) penetrated about 21 meters of clay interbedded with sand and gravel, which indicates deposition in a lake environment (Welder, 1987). The frequency of occurrence of such clay beds is unknown. Downstream water movement in these less permeable aquifers is restricted, which forces the water to discharge as springs. Springs that maintain the streamflow throughout the year are found along the upper reaches of Piceance Creek including Ryan Gulch, where water-bearing marlstones of the Green River Formation intersect the valley of Piceance Creek (Saulnier and Ford, 1977). Springs in the area also may be supplied directly by water discharging from the bedrock aquifers through fractures (Welder, 1987). The complex fracture system in the Piceance Creek Basin has been extensively studied and is the primary conduit through which ground water flows through the bedrock aquifers of the basin (Grout and Verbeek, 1985; Verbeek and Grout, 1983a, 1983b, and 1987).

Acknowledgments
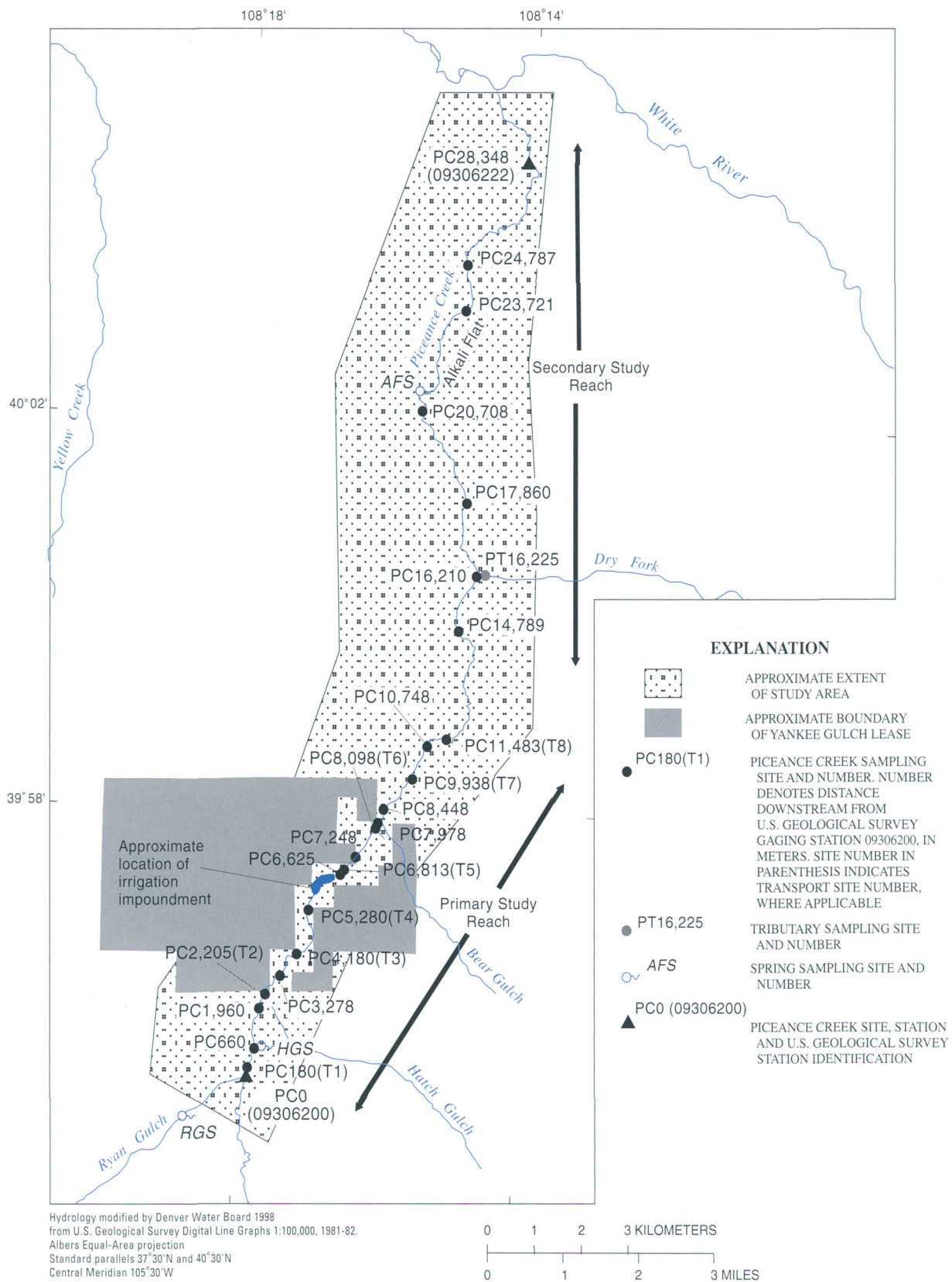
Figure 2. Location of injection and selected sampling sites in Piceance Creek and inflow sites to Piceance Creek, December 4–7, 2000.
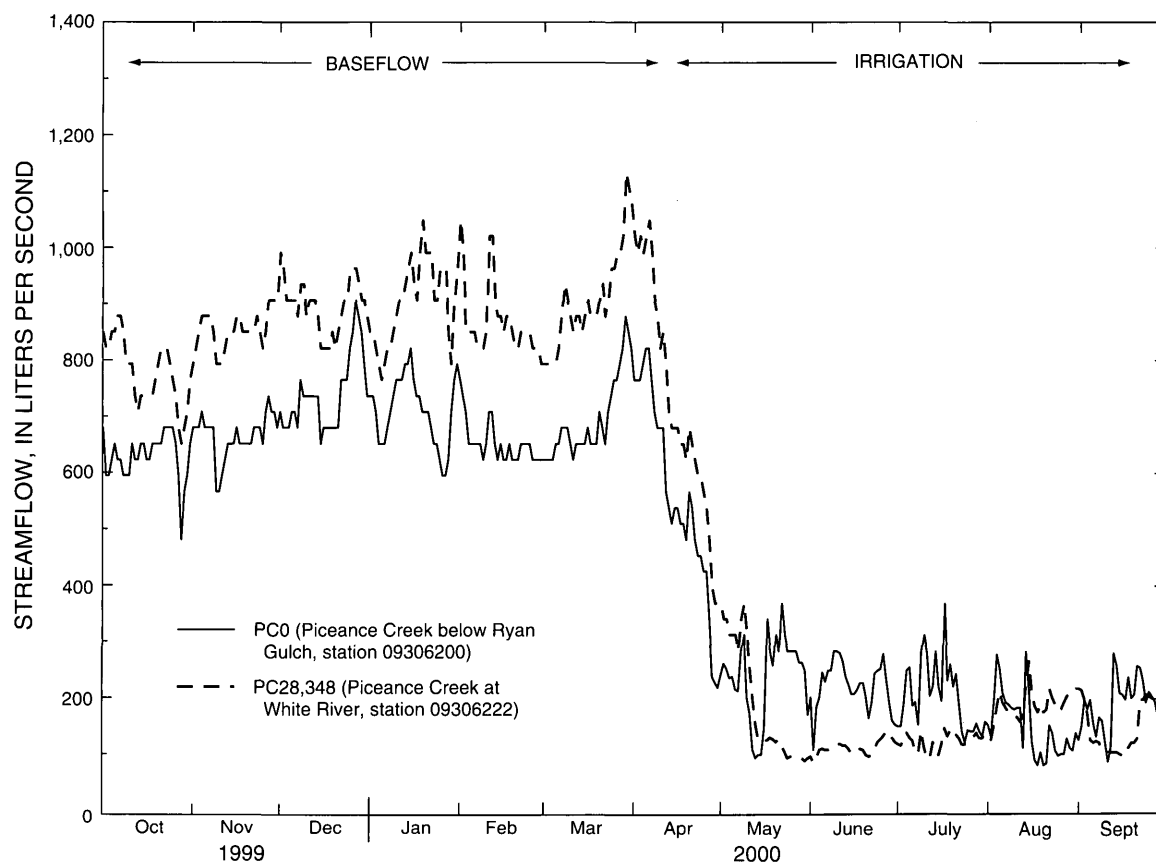
Figure 3. Annual hydrograph at USGS streamflow-gaging stations 09306200 and 09306222 for water year 2000.

extended to George J. Saulnier, Jr., of Duke Engineering and Celina Akin of American Soda, LLP, for sharing their insight and knowledge of the study area. Individuals assisting in the collection of water-quality, hydrologic, or geologic data are acknowledged and include: Tom Young and Willard Phillips of American Soda, LLP and volunteer Mary Leib. The author also would like to acknowledge the contributions of Daniel L. Brendle, Russell G. Dash, Joseph R. Dungan, Sheryl A. Ferguson, Kenneth J. Leib, Robert L. Runkel, Robert W. Stogner, Sr., Kenneth R. Watts, and Douglas B. Yager of the USGS.

METHODS OF DATA COLLECTION

This study was designed to determine streamflow and baseline-chemical quality at numerous mainstem sites in Piceance Creek. Tracer-dilution tech-

niques and instantaneous streamflow measurements were used to determine streamflow. Synoptic-sampling techniques were used to determine concentrations for selected constituents in Piceance Creek. Load profiles along subreaches of the creek were generated by combining tracer-dilution and synoptic-sampling techniques (Kimball, 1997).

A general overview of the field activities is described here. A more detailed account can be found in table 2 and in the following sections of this report. The study area was divided into two areas of investigation. The upper one-third of the study area (primary study reach) was investigated by using tracer-dilution and synoptic-sampling techniques. About 85 percent of the total sites were located along the primary study reach to provide a detailed understanding of the baseline concentrations near the Yankee Gulch Project. The primary study reach was divided further into two separate tracer-dilution experiments for logistical

Table 2. Sequence of events during tracer-dilution and synoptic-sampling study, September 12–14, 2000, and December 3–7, 2000

[NA, not applicable; NaBr, sodium bromide; LiBr, lithium bromide]

Start date	Approximate start time	Activity
9–12–00 to 9–14–00	NA	Reconnaissance to determine location of injection sites and stream sampling sites.
12–03–00	0800	Collection of background bromide samples between PC6,625 and PC11,483.
	0830	Estimation of traveltimes between PC6,625 and PC11,483.
	1200	Preparation of NaBr solution.
	1400	Installation of automatic samplers at designated transport sites.
12–04–00	0800	Start of NaBr injection and automatic samplers downstream from PC6,625. Collection of background bromide samples between PC0 and PC5,280.
	0830	Estimation of traveltimes between PC0 and PC5,280.
	1000	Collection and processing of water-quality samples collected at inflow sites.
12–05–00	0730	Collection and processing of synoptic water-quality samples from PC11,483 to PC6,625. Collection of bromide samples by hand in response to difficulties with automatic samplers. Start of instantaneous streamflow measurements along reach.
	1100	End of synoptic water-quality sampling and NaBr injection. Relocation of injection equipment to upper injection site.
	1200	Preparation of LiBr solution. End of instantaneous streamflow measurements along reach.
	1830	End of bromide sampling at furthest downstream transport site in reach (PC11,483).
12–06–00	0730	Collection and processing of synoptic water-quality samples and instantaneous streamflow measurements from PC28,348 (USGS 09306222) to PC20,708 (team 1). Collection and processing of synoptic water-quality samples and instantaneous streamflow measurements from PC17,860 to PC14,789 (team 2).
	0800	Start of LiBr injection downstream from PC0. Collection of bromide samples by hand in response to difficulties with automatic samplers.
	1030	End of water-quality sampling along secondary study reach by all teams.
	1800	Initialization of automatic samplers for limited sample collection during night.
12–07–00	0730	Collection and processing of synoptic water-quality samples from PC5,280 to PC0. Collection of bromide samples by hand in response to difficulties with automatic samplers Start of instantaneous streamflow measurements along reach.
	1100	End of synoptic water-quality sampling and LiBr injection.
	1200	End of instantaneous streamflow measurements along reach.
	1630	End of bromide sampling at furthest downstream transport site in reach (PC5,280).

reasons. The lower two-thirds of the study area (secondary study reach) was investigated by using conventional current-meter techniques and synoptic water-quality sampling. Several instantaneous stream-flow measurements were made at selected sites as a quality-control measure. These data provided a measure of the stability of the streamflow over the several days of field activities and during the actual synoptic sampling. These data also provided a measure of the reasonableness of the streamflow estimates using tracer-dilution techniques. Synoptic sampling along the primary and secondary reaches was done on three separate days. In each case, synoptic sampling was scheduled to be done as early in the day as possible to avoid potential input from melting ice along the banks of Piceance Creek. Sampling was done in an upstream order to avoid potential contamination.

Tracer Injection

A reconnaissance of the study area in September 2000 indicated that two tracer injections were needed along the primary study reach because of the length of the reach, the low streamflow velocity, and the presence of a small irrigation impoundment between PC5,280 and PC6,625. Bromide was chosen as the tracer because of the low concentrations in samples collected during the reconnaissance (James W. Ball, USGS, written commun., 2000). The median bromide concentration was 0.09 milligram per liter in 25 background samples collected. The first injection began at 0800 on December 4, 2000, at PC6,625 and was continuous for 28 hours (table 2). A concentrated solution of sodium bromide (NaBr) was injected using a positive-displacement metering pump system. The stream reach extended from just downstream from PC6,625 to PC11,483 (fig. 2). Four samples of the injectate were collected periodically to confirm steady-state injection parameters. The samples were subsequently analyzed by the USGS National Research Program in Boulder, Colorado, to determine injection rates and bromide concentrations (James W. Ball, USGS, written commun., 2001). The injection rate varied by less than 3 percent and ranged from 325 to 335 milliliters per minute (fig. 4); the average rate of 332 milliliters per minute was used to calculate streamflow. The bromide concentration ranged from 176.4 to 177.2 grams per liter (fig. 4); the average concentration of 176.7 grams per liter was used to calculate streamflow.

The second injection began at 0800 on December 6, 2000, and continued for 27 hours (table 2). A concentrated solution of lithium bromide (LiBr) was injected along the stream reach from just downstream from the Ryan Gulch streamflow-gaging station (PC0) to PC5,280 (fig. 2). Seven injectate samples were collected and subsequently analyzed to determine injection rates and bromide concentrations (James W. Ball, USGS, written commun., 2001). The variability in the bromide concentrations for this injection was larger than expected. Concentrations in three samples collected the day before the synoptic sampling were statistically different from the four collected the day of sampling (James W. Ball, USGS, written commun., 2001). As such, only the samples collected on the day of the synoptic sampling were used to calculate streamflow. The injection rate for these four samples varied by 1 percent and ranged

from 318.6 to 321.2 milliliters per minute (fig. 4); the average rate of 320 milliliters per minute was used to calculate streamflow. The bromide concentration ranged from 165.1 to 173.5 grams per liter (fig. 4); the average concentration of 168.9 grams per liter was used to calculate streamflow.

Multiple bromide samples were collected at eight transport sites (table 1 and fig. 2) in Piceance Creek during the two tracer injections. Transport sites are sampling locations where numerous tracer samples are collected to determine if steady-state injection parameters have been established prior to synoptic sampling. Transport sites T5 to T8 were associated with the NaBr injection from PC6,625 to PC11,483 on December 4 and 5, 2000 (fig. 5). Transport sites T1 to T4 were associated with the LiBr injection from PC0 to PC5,280 on December 6 and 7, 2000 (fig. 6). Data collected at the transport sites are used to determine if tracer concentrations in the stream have reached a plateau concentration, which indicates that stable injection parameters have been attained. Also, the decrease in plateau concentrations at subsequent downstream transport sites can be used as a measure of the increase in streamflow at these locations (Kimball, 1997). Tracer samples collected at these sites generally are collected manually as the tracer arrives at each site. Thereafter, it is common to use automatic samplers programmed to collect samples at pre-determined times and/or intervals; automatic samplers provide the temporal coverage that cannot be easily maintained by manual sampling.

The automatic samplers were only marginally successful during the NaBr injection on December 4 and 5 because of cold temperatures in the study area. Intake lines became restricted with ice or froze entirely as water was pumped from the creek. Manual sampling procedures were implemented at 0730 on December 5 when it became apparent that the samplers had not functioned as anticipated (table 2). No plateau concentrations were calculated at T5, T6, T7, and T8 because of the limited number of samples and the concern that the samples might not accurately represent the bromide concentration in the creek (fig 5). It was assumed, however, that steady-state injection conditions were in effect and that the injection had proceeded long enough to reach plateau concentrations. Time of travel estimates using a fluorescent dye injection the previous day indicated that sufficient time had elapsed for the bromide tracer to come to a plateau in Piceance Creek. Therefore,
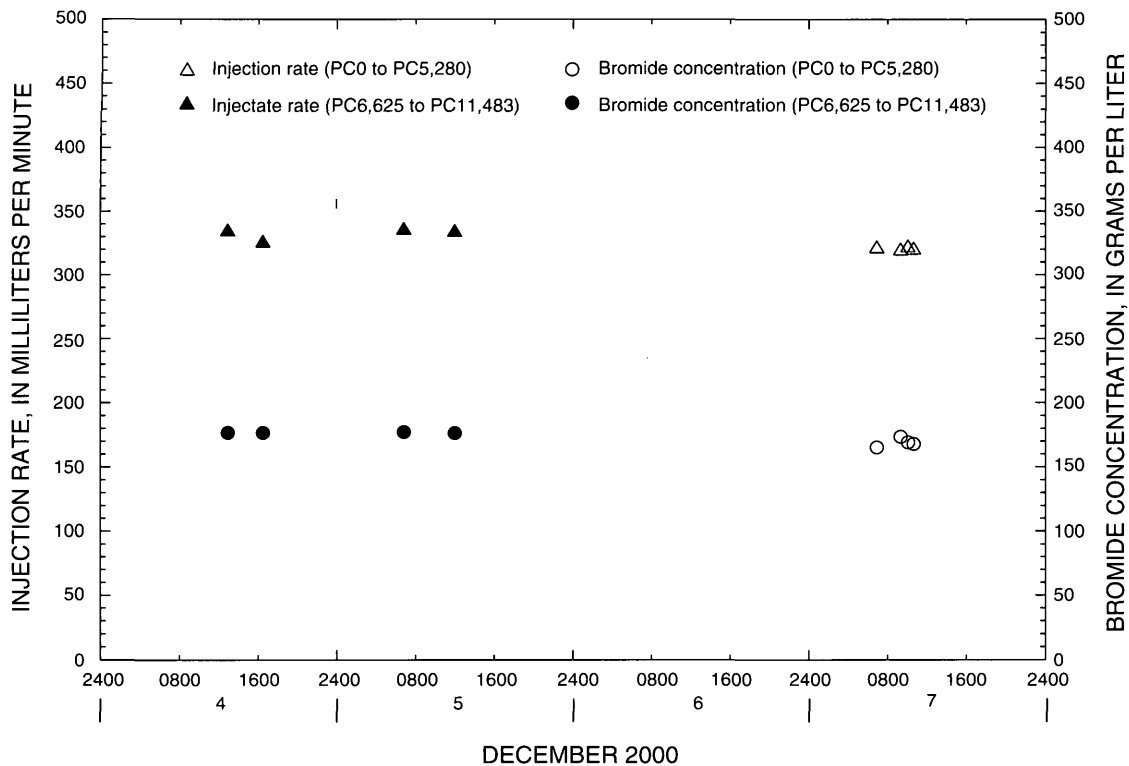
Figure 4. Injection rates and bromide concentrations from injectate samples collected during tracer-injection study in Piceance Creek, December 4 and 5, 2000, and December 7, 2000.

bromide samples collected manually at about the same time as the synoptic water-quality sample were used to represent plateau bromide concentrations at T5, T6, T7, and T8.

The majority of LiBr samples collected December 6 and 7 were collected manually because of the limitations encountered earlier with the automatic samplers. However, the intake tubing to the automatic samplers was modified so at least one or two samples could be collected early on December 7. These data points were important in determining if tracer concentrations in the stream had reached plateau concentrations. Sufficient data were collected to calculate plateau concentrations at T1, T2, T3, and T4 (fig. 6). The synoptic-bromide concentrations at T1, T3, and T4 compare favorably with the calculated bromide plateaus at each site, whereas, the synoptic concentration at T2 was somewhat higher than the plateau concentration. It appears that a change in pump parameters increased the bromide concentration in the steam. A more complete description of this event is forthcoming. Samples collected at the rise and fall of the

bromide injection were not used to calculate plateau concentrations.

Supplemental Instantaneous Streamflow Measurements

Instantaneous streamflow measurements using standard techniques (Rantz and others, 1982) were made at selected sites along the primary and secondary study reaches. These data were used to determine if streamflow conditions remained constant throughout the study period, particularly during synoptic sampling. In addition, the measurements help determine the reasonableness of the tracer-dilution streamflow estimates. The data, however, were not intended as a check of the accuracy of the tracer-dilution streamflow estimates because standard techniques do not measure the flow in the hyporheic zone (Zellweger and others, 1988). In high-gradient mountain streams with rock and cobble streambeds, tracer-dilution techniques have been reported to account for about 30 percent more water than instantaneous streamflow measurements (Kimball and others, 1998). Overall,
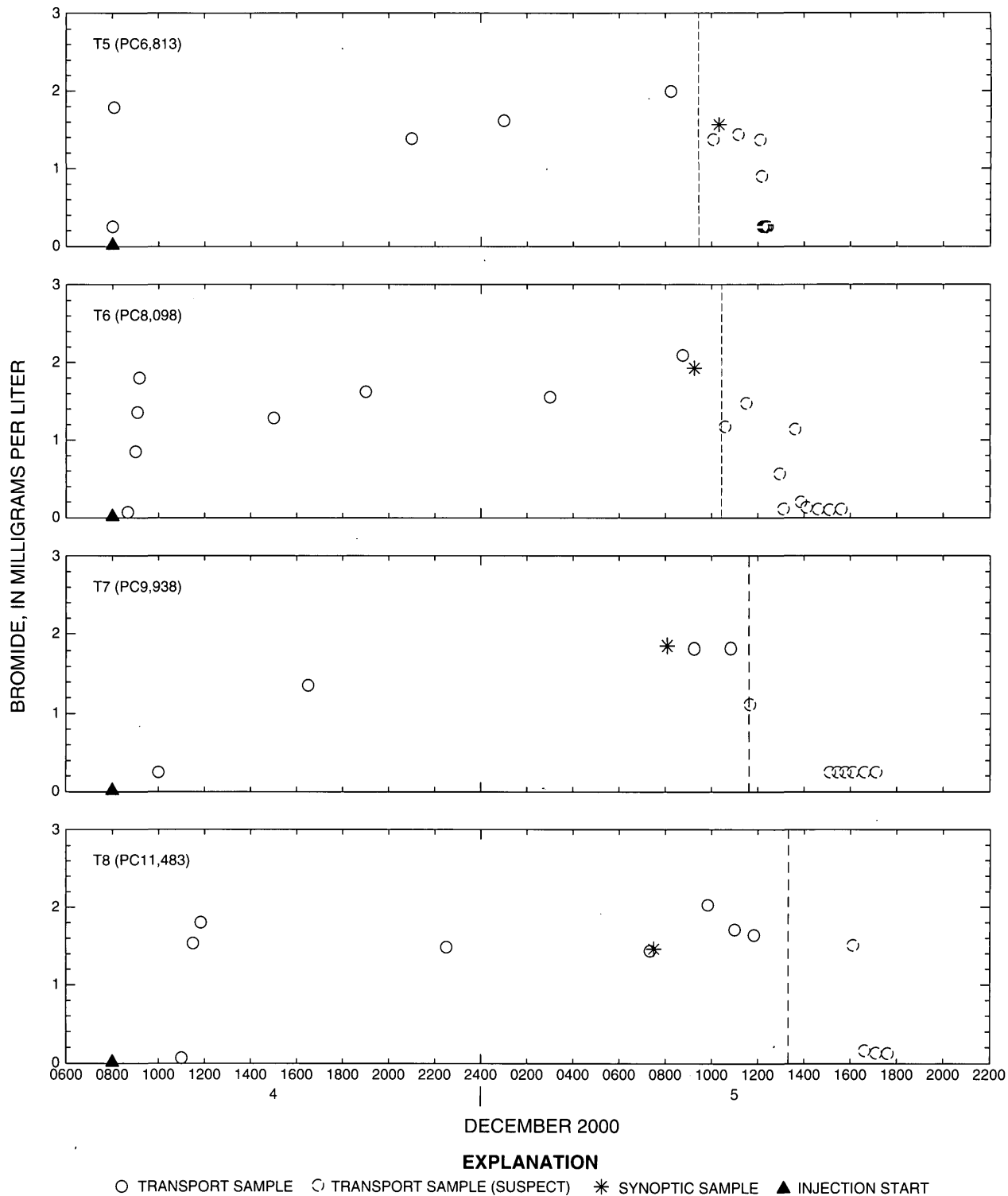
Figure 5. Bromide concentrations at transport sites T5 to T8 in Piceance Creek, December 4 and 5, 2000.
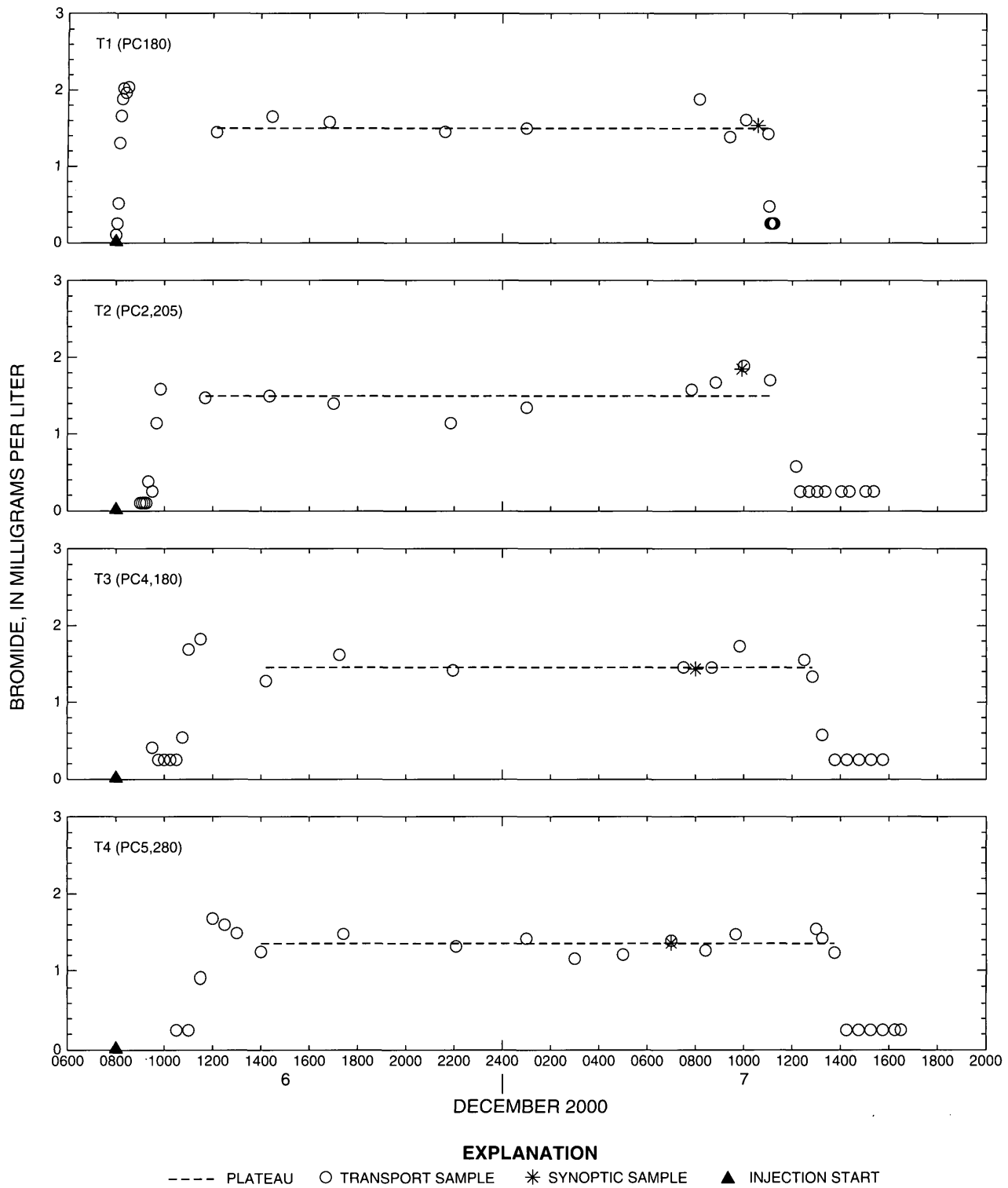
Figure 6. Bromide concentrations at transport sites T1 to T4 in Piceance Creek, December 6 and 7, 2000.

the error associated with the instantaneous streamflow measurements made during this study was estimated to be about 15 percent.

Streamflow measurements made at PC0 (December 4 at 0740 and December 7 at 0800) and PC11,483 (December 3 at 0945 and December 5 at 1000) were used to determine if base-flow conditions remained constant during the study period (table 3). Instantaneous measurements were needed because the two streamflow-gaging stations in the study area were not operational at the time because of freezing temperatures. The relative percent difference (RPD) of the two sets of measurements was about 6 percent at PC0 and 9 percent at PC11,483. RPD is calculated by dividing the absolute value of the streamflow difference by the mean of the streamflow; the result is shown as a percentage. These data indicated that baseline streamflow conditions were relatively stable during the study period.

Streamflow measurements also were done to determine if streamflow conditions remained constant during synoptic water-quality sampling on December 5 and December 7, 2000. Measurements made on December 5 at PC6,625 (at 0900) and PC11,483 (at 1000) indicated that streamflow probably was stable at 0900 hours (table 3); synoptic sampling had proceeded in an upstream order to PC8,448 by this time (table 1). However, less than 2 hours later, streamflow at PC6,625 had increased nearly twofold (960 liters/second; table 3) as water was released from the upstream impoundment. It appears that an ice dam across the outlet works of the impoundment gave way releasing a large amount of water. Analysis of specific conductance and pH data indicated that the water was native to the stream (table 1) and, as such, no change in chemical concentrations was expected. All synoptic samples collected downstream to PC7,978 exhibited lower than expected bromide concentrations, which indicated that dilution of the injectate solution had occurred. The implications of the change in streamflow on the synoptic bromide concentrations and subsequent estimates of streamflow downstream will be discussed in a later section. On December 7, instantaneous measurements at PC0; PC2,205; and PC5,280 and gage-height measurements at PC0 indicated that streamflow was relatively stable throughout the synoptic sampling on that date (table 3).

Synoptic Sampling

Synoptic sampling provides a spatially detailed description of the water quality in a stream and is accomplished by sampling numerous sites in a relatively short time. In addition, synoptic samples provide both the tracer-concentration data needed to estimate streamflow and the concentration data needed to compute loads. Synoptic sampling along each subreach of Piceance Creek was conducted early in the morning and as quickly as possible to avoid changes in streamflow due to diurnal variation. Samples were collected in an upstream order near the centroid of the stream in clean, 4-liter plastic containers. The samples were transported to a centrally located staging area and processed as soon as possible. A list of the sites, sampling dates, and sampling times are in table 1. Field values of pH and specific conductance were determined on an unfiltered aliquot of each sample (table 1). The remaining sample volume was filtered through a 0.45-millimeter capsule filter and preserved as described by Horowitz and others (1994). All synoptic samples were submitted for analysis to the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado.

All synoptic water-quality samples were analyzed for a base list of constituents that was consistent with the standard list of analytes in the ground-water monitoring program for the Yankee Gulch Project (Agapito Associates, Inc., 1999). The analytes included dissolved major ions, selected trace constituents, alkalinity, and residue on evaporation. These constituents are possible indicators of fluid migration away from the production solution-mining zone (Douglas B. Yager, U.S. Geological Survey, written commun., 2000). In addition, samples collected at seven spatially dispersed sites (designated as indicator sites in table 1) were analyzed for additional dissolved constituents consistent with the USGS water-quality monitoring program at the Ryan Gulch (09306200) and White River (09306222) streamflow-gaging stations (Crowfoot and others, 2001) and the comprehensive list of parameters for the ground-water monitoring program at the Yankee Gulch site (Agapito Associates, Inc., 1999). This expanded list included additional trace constituents, dissolved organic carbon, nitrogen and phosphorus compounds, and gross alpha and beta radioactivity. Specific chemical data for all sites are listed in table 5 in the Data Section at the back of the report.

Table 3. Summary of instantaneous streamflow measurements made along the primary study reach of Piceance Creek, December 3–7, 2000

[L/s, liters per second; --, no data; 09306200 denotes U.S. Geological Survey streamflow-gaging-station number]

Site name	Date	Time	Streamflow[1] (L/s)	Outside gage height[2] (feet)	Remarks
PC11,483	12–3–00	0945	509	--	Prior to injection. Needed to determine injection parameters.
PC0	12–4–00	0740	448	--	Prior to injection along reach.
PC6,625	12–5–00	0900	500	--	Above injection site. Sampling started at 0730 at PC11,483.
PC11,483	12–5–00	1000	466	--	Downstream end of subreach. Soft bottom with ice throughout. Slow velocities. Measurement likely underestimated streamflow.
PC6,625	12–5–00	1040	960	--	Rise in stage noted. Abrupt change in streamflow due to release of water from impoundment. Last synoptic sample collected at 1040 at PC6,625.
PC8,098	12–5–00	1120	952	--	Streamflow increased in response to release of water from impoundment.
PC11,483	12–5–00	1200	764	--	Streamflow increasing in response to release of water from impoundment.
PC0	12–7–00	0700	--	3.58	At 09306200 (Ryan Gulch streamflow-gaging station). Outside gage height only. Sampling started at 0700 at PC5,280.
PC5,280	12–7–00	0720	451	--	At downstream end of subreach.
PC0	12–7–00	0800	421	3.58	At 09306200. Approximately 20 percent shore ice.
PC0	12–7–00	0840	--	3.58	At 09306200. Outside gage height only.
PC2,205	12–7–00	0850	434	--	At Horse Draw bridge to mine site.
PC0	12–7–00	0915	--	3.62	At 09306200. Outside gage height only.
PC5,280	12–7–00	0930	438	--	At downstream end of subreach.
PC0	12–7–00	1010	--	3.61	At 09306200. Outside gage height only.
PC0	12–7–00	1100	--	3.58	At 09306200. Outside gage height only. Last synoptic sample collected at 1040 at 09306200.
PC6,625	12–7–00	1130	730	--	Measurement made after last synoptic sampling along upper reach.

[1] Measurements were rated as fair to poor with an estimated error of 15 percent.
[2] Reading taken from wire weight with an estimated error of plus or minus 0.02 foot.

Quality Assurance

Data-collection and analytical procedures used in this study incorporated practices designed to control, verify, and assess the quality of the sample data. Methods and associated quality control for collection and field processing of water-quality samples are described by Ward and Harr (1990), Horowitz and others (1994), and Wilde and others (1998). The quality of analytical results for water-quality samples can be evaluated with data from quality-control samples submitted from the field and analyzed concurrently in the laboratory with routine samples. In addition, internal quality-assurance practices at the NWQL were performed systematically to provide quality control of the analytical procedures (Pritt and Raese, 1995).

Four duplicate samples were collected to provide quantitative information on the precision and bias of the overall field and laboratory process. Selected analytical results for the field duplicates are presented in table 6 in the Data Section at the back of the report. The RPD among the duplicate concentrations generally was less than 10 percent, which indicates acceptable precision for analytical results.

Two field blanks were analyzed to identify the presence and magnitude of contamination that potentially could bias analytical results. Certified deionized water was used to produce a field blank that was subjected to the same processing and analysis as

an environmental sample. Analytical results for field blanks are presented in table 7 in the Data Section at the back of the report. For the most part, the concentrations in the blanks were at or below the method reporting limits, which indicates that the synoptic samples were free of significant or systematic bias from contamination. However, dissolved aluminum and zinc concentrations in the blank collected on December 7, 2000, were five to six times higher than the method reporting level. Further analysis determined that a systematic aluminum contamination had occurred in all synoptic samples collected that day. It is unclear if the contamination was associated the with field-processing procedures or the laboratory analysis. Nevertheless, the contamination was substantial enough to require removal of all aluminum data for samples collected on December 7, 2000. This was not the case with the elevated zinc concentration in the same blank sample. The contamination was not shown to be systematic in any other water-quality sample, and the data were retained.

BASELINE CHARACTERIZATION OF WATER QUALITY

Routine water-quality data have been collected at the Ryan Gulch (09306200; PC0) and White River (09306222; PC28,348) streamflow-gaging stations since 1970 (Crowfoot and others, 2001). Physical and chemical data collected from 1977 to 1981 for streams in the Piceance Creek Basin have been summarized (Tobin and others, 1985). A spatially comprehensive data-collection effort in Piceance Creek during steady-flow conditions in March 1981 indicated that major dissolved constituents in Piceance Creek generally increased in the downstream direction as ground water discharged to springs, streams, and valley-fill alluvial aquifers in various reaches of Piceance Creek (Tobin, 1987). The exact location and extent of hydrologic connections between aquifers and streams are not well known although bedrock and fracture-controlled springs are observed along Piceance Creek. A substantial change in water quality was observed as ground water discharged upward through an extensive northwest-southeast fracture zone that crosses Piceance Creek in the area known as Alkali Flat (Tobin, 1987) (fig. 2). Salts precipitated on the land surface by evaporation of the shallow ground water are visible during base-flow conditions. Data collected as part of

this study provide (1) an updated characterization of the water quality in Piceance Creek between the two USGS streamflow-gaging stations and (2) a baseline characterization of the water quality in Piceance Creek before full-scale nahcolite solution mining begins at the Yankee Gulch Project.

Physical Properties

In December 2000, pH values in Piceance Creek were stable throughout the study reach (fig. 7). The pH values ranged from 7.9 to 8.1 (table 1) with a median value of 8.0 standard units. Specific conductance increased steadily along the upper two-thirds of the study reach to PC17,860 at a rate of about 10 microsiemens per centimeter per kilometer (fig. 7). Along the reach that included the Alkali Flat area (PC20,708 to PC23,721), the rate increased to nearly 1,000 microsiemens per centimeter per kilometer, which equated to a 14-percent increase in less than 3,000 meters. Specific conductance at a spring contact in the area (site AFS) was measured at 12,700 microsiemens per centimeter (table 1). Specific conductance remained elevated downstream to PC28,348. Overall, specific conductance in Piceance Creek ranged from 1,540 to 1,980 microsiemens per centimeter. The profile for dissolved-solids concentrations was similar to that described for specific conductance (fig. 7). Specific conductance was shown to be a good predictor of dissolved solids in Piceance Creek including the stream reach downstream from Alkali Flat (table 4).

Major-Ion Concentrations

Tobin (1987) reported the principal dissolved constituents in water from Piceance Creek as bicarbonate, sulfate, and sodium. In December 2000, the principal dissolved constituents in the study area remained the same. The median bicarbonate concentration was 610 milligrams per liter (table 5). The median sulfate concentration was 420 milligrams per liter. The median sodium concentration was 170 milligrams per liter. Ground-water dissolution of evaporite minerals of nahcolite and halite (Green River Formation), and oxidation of pyrite and hydrogen-sulfide gas (Uinta Formation) are most likely sources

| DECEMBER 7 | DECEMBER 5 | DECEMBER 6 |
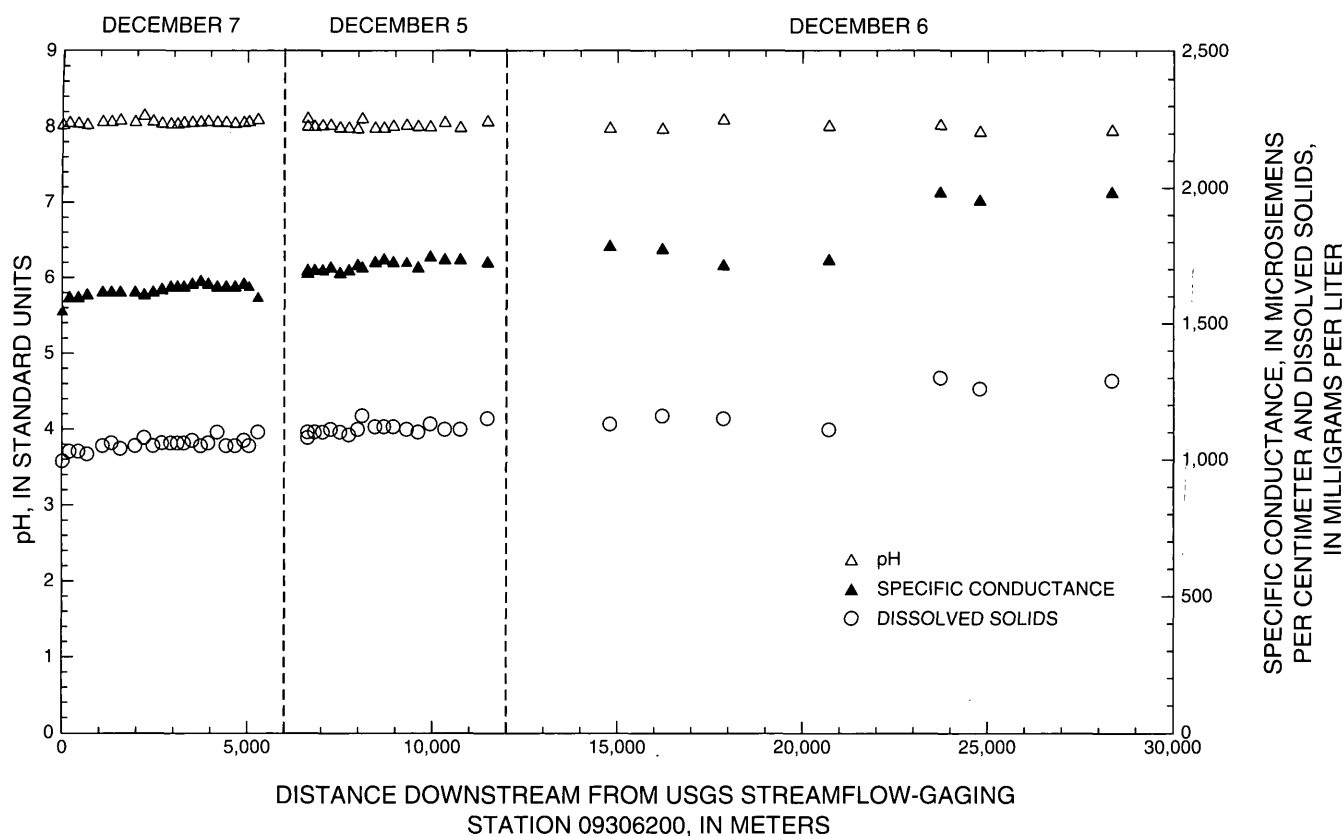
Figure 7. Values of pH, specific conductance, and dissolved solids in Piceance Creek, December 5–7, 2000.

of these ions (George J. Saulnier, Jr., Duke Engineering, written commun., 2001).

Table 4. Linear regression statistics for predicting dissolved solids and selected ion concentrations in Piceance Creek from specific-conductance data, December 2000

Constituent (in milligram per liter)	Slope	y intercept	R^2
Dissolved solids	0.633	31.4	0.91
Sodium	.298	−319.0	.96
Bicarbonate	.693	−530.8	.85
Chloride	.047	−60.2	.85

Sodium, bicarbonate, and chloride concentrations increased gradually downstream from PC0 to PC20,708 as ground water discharged to the stream valley (table 5 and figs. 8 and 9). Overall, the increase along this 21-kilometer reach was from 25 to 35 percent; no sodium data were available from PC6,813 to PC11,483 because sodium bromide was used as the

tracer along this reach. In contrast, a sharp increase in sodium (35 percent), bicarbonate (19 percent), and chloride (89 percent) concentrations was measured along a 3-kilometer reach between PC20,708 and PC23,721. This short reach of Piceance Creek flows across the area known as Alkali Flat (PC20,708 to PC23,721). Sulfate, calcium, magnesium, potassium, silica, and fluoride concentrations remained relatively constant throughout the study area including Alkali Flat. The relation of specific conductance to bicarbonate, sodium, and chloride concentrations in Piceance Creek is listed in table 4.

Trace-Constituent Concentrations

Characteristic trace constituents in the two major bedrock aquifers of the Piceance Creek Basin were identified as strontium in the Uinta Formation and barium, boron, and lithium in the Green River Formation (Tobin, 1987). Concentrations of barium, boron, lithium, and strontium also were elevated in
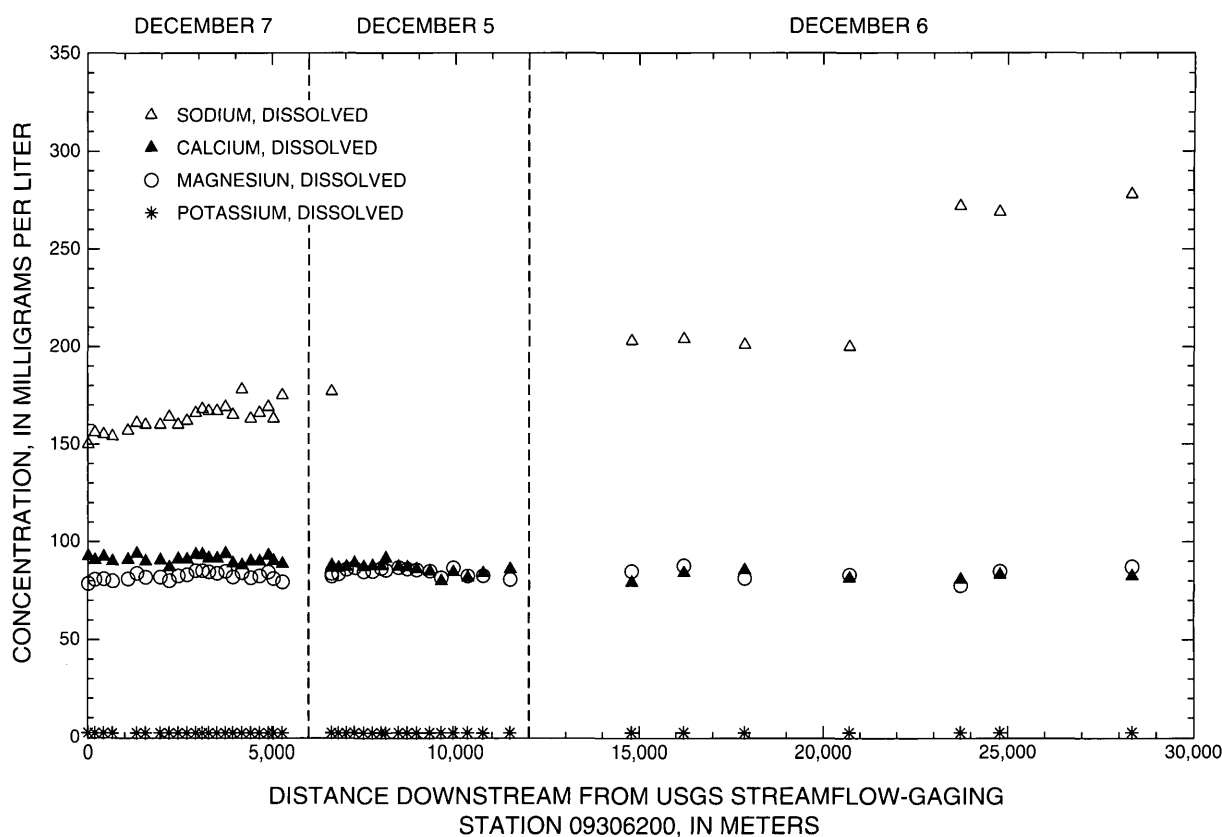
Figure 8. Selected dissolved-cation concentrations in Piceance Creek, December 5–7, 2000.

surface-water samples collected in Piceance Creek in December 2000 (table 5 and fig. 10). Strontium concentrations ranged from 2,810 to 3,390 micrograms per liter and were the highest of the trace constituents. However, concentrations remained relatively stable (median value about 2,990 micrograms per liter) throughout Piceance Creek including the reach along Alkali Flat. Barium concentrations (median value 75 micrograms per liter) and boron concentrations (median value 180 micrograms per liter) increased by about 50 to 65 percent from upstream to downstream. The largest increase in barium and boron concentrations occurred in the area of Alkali Flat. Although lithium was not analyzed for at all sites, a 70-percent increase in concentration was measured between PC17,860 and PC23,721. This reach includes the Alkali Flat area. Most other trace-constituent concentrations were at or near method reporting limits and little or no downstream increases were measured (table 5 and fig. 10).

TRACER-INJECTION RESULTS

Tracer-injection methods are used to determine streamflow at numerous sites in a relatively short time. This determination is accomplished by continuously injecting a known mass of a conservative tracer into the stream and measuring the concentration of the tracer at each downstream location. Using the principle of conservation of mass, a decrease in tracer concentration downstream (dilution) is a measure of an increase in streamflow. Variations in streamflow, injection flux (mass per unit time), and analytical precision can affect the measured tracer concentration at each site. An understanding of these variables is needed when interpreting the bromide profiles generated as part of these tracer injections. This understanding is particularly important in a stream such as Piceance Creek where downstream increases in streamflow were relatively small.

DECEMBER 7   DECEMBER 5   DECEMBER 6
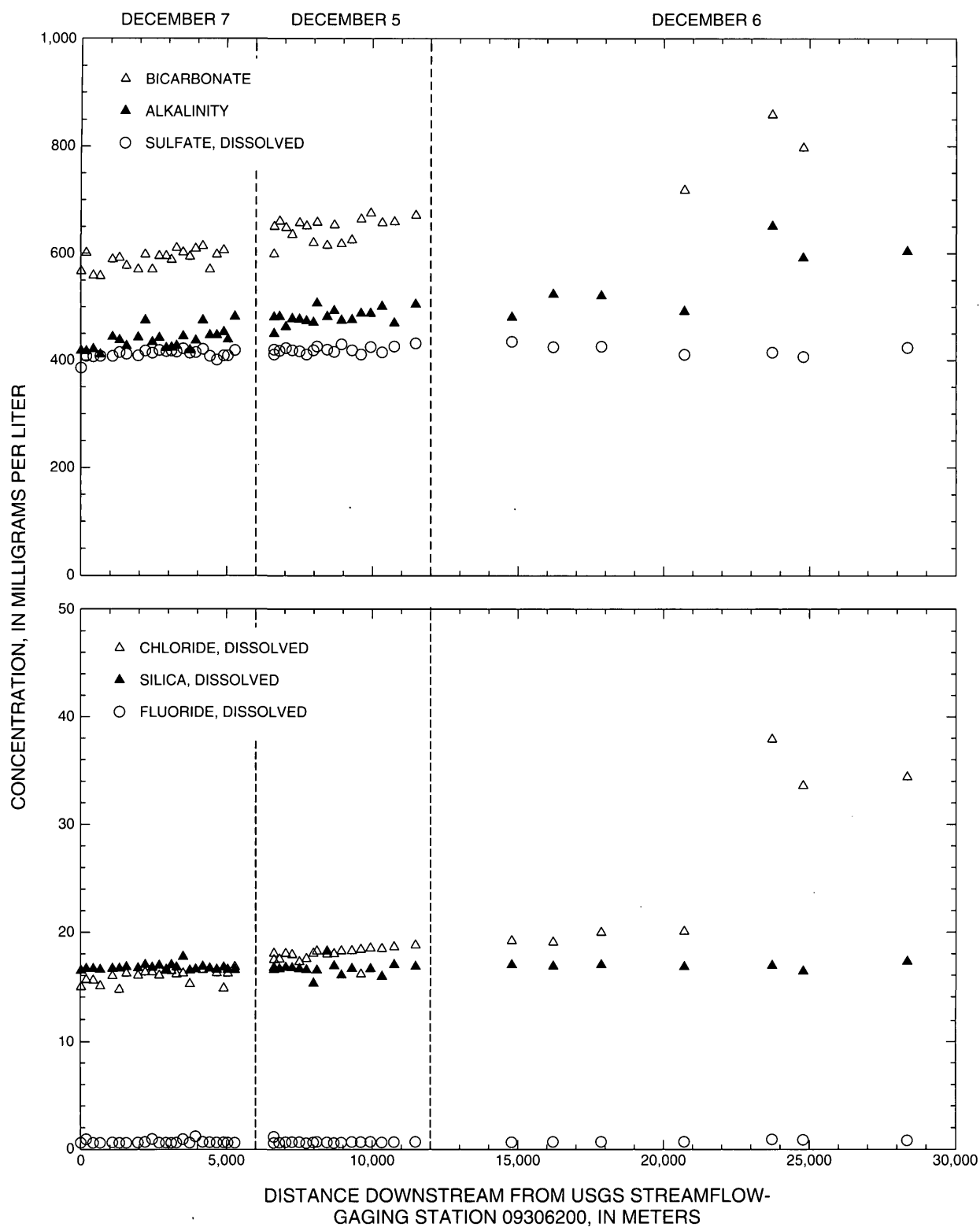
Figure 9. Selected dissolved-anion concentrations in Piceance Creek, December 5–7, 2000.
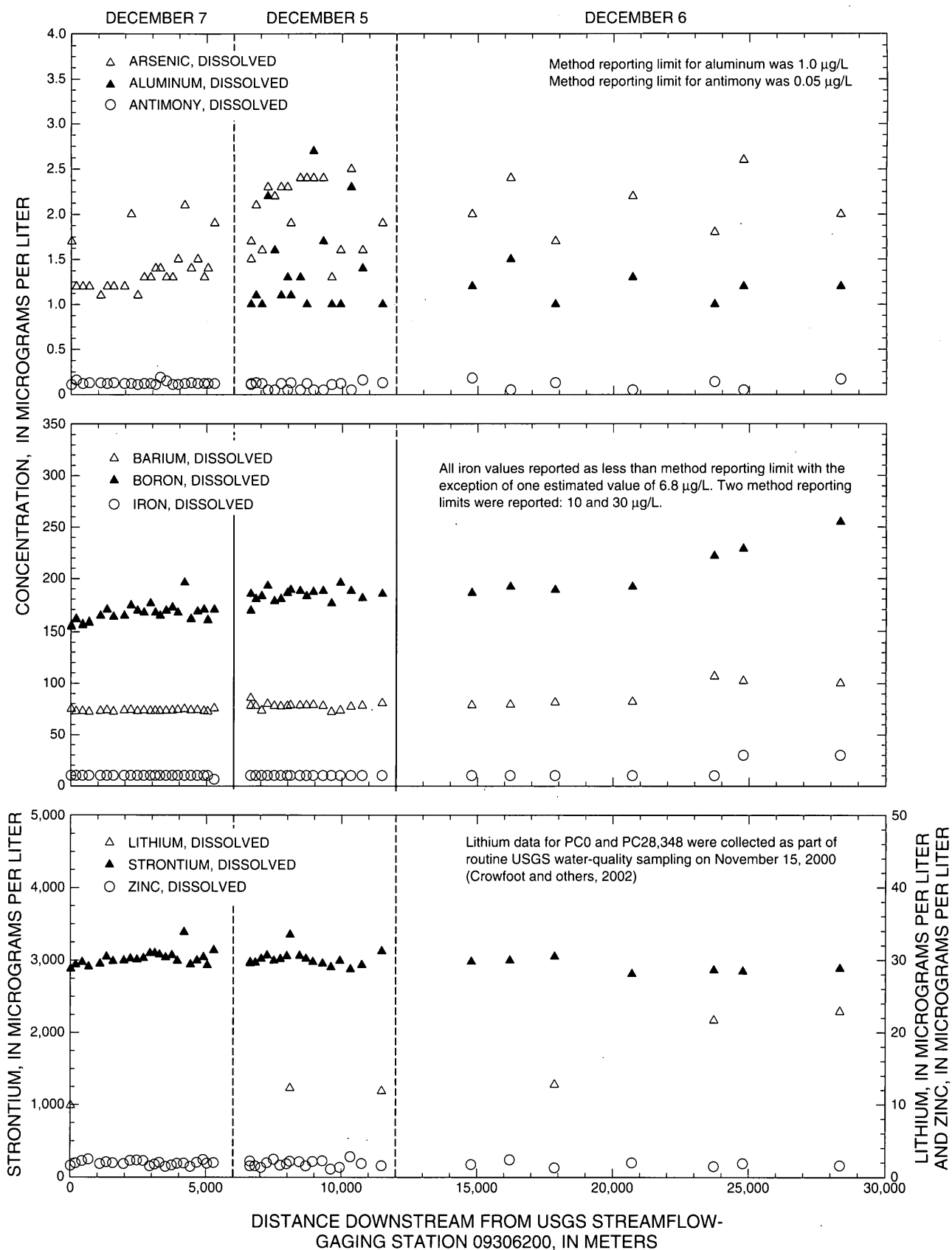
Figure 10. Selected dissolved-trace-constituent concentrations in Piceance Creek, December 5–7, 2000.

Synoptic Bromide Concentrations

The first synoptic sampling event began at 0730 on December 5, 2000, along the primary study reach from PC6,625 to PC11,483 (fig. 2). Injectate-bromide concentrations in Piceance Creek were assumed to be at plateau concentrations because nearly 24 hours had elapsed since the start of the NaBr injection. Sampling began at the downstream site and proceeded upstream under stable streamflow conditions. However, a rapid increase in streamflow part way through the sampling diluted the synoptic-bromide concentrations in the stream upstream from PC8,098 (fig. 5); samples collected downstream from PC8,098 were unaffected by the increase because the samples had already been collected. As a result, synoptic bromide concentrations upstream from PC8,098 did not represent steady-state streamflow conditions (fig. 11). For the purpose of defining a bromide profile along the affected reach, the last bromide concentration collected at PC6,813 as part of the transport data (at 0815 hours) was substituted for the suspect synoptic concentration at this site (fig. 5). Intermediate bromide concentrations were estimated using a linear interpolation between PC6,813 and PC8,098. Bromide concentrations generally decreased downstream from PC8,098 along the reach unaffected by the sudden increase in streamflow. A smoothed line was drawn for these remaining bromide concentrations. The bromide concentrations from the smoothed line were used to develop an estimated streamflow profile for this reach. An error of plus or minus 3 percent was assumed for all bromide determinations.

The second synoptic sampling began at 0730 on December 7, 2000, along the upper section of the primary study reach from PC0 to PC5,280 (fig. 2). Synoptic sampling was done in an upstream order nearly 24 hours after the start of the LiBr injection. Supplemental streamflow measurements and stage data indicated that the streamflow was stable during the sampling (table 3). Synoptic bromide concentrations at PC180 (T1), PC4,180 (T3), and PC5,280 (T4) compared well with plateau bromide concentrations (fig. 6), which indicates that the synoptic concentrations were representative of stable injection conditions. However, the synoptic bromide concentration at PC2,205 (T2) was higher than the plateau concentration at this transport site (fig. 6). Analysis of injectate bromide samples collected at 0655 (882 milligrams per second) and 0920 (922 milligrams per second)

indicated that a 4.5-percent increase in bromide flux to the stream occurred during this 2.5-hour period. Traveltimes from the injection site to PC2,205 (T2) support the hypothesis that elevated synoptic bromide concentrations observed between PC660 and PC4,180 were the result of increased bromide flux to the stream. For the purpose of defining a bromide profile for this reach, the plateau bromide concentration at PC2,205 (T2) was used in place of the synoptic bromide concentration. A linear interpolation then was used between PC2,205 and PC660 and between PC2,205 and PC4,180 to define intermediate concentrations (fig. 12). Synoptic-bromide concentrations generally decreased downstream from PC4,180.

A smoothed line was drawn between PC4,180 and PC5,280 (fig. 12).The bromide concentrations from the smoothed line were used to develop an estimated streamflow profile for the entire reach. An error of plus or minus 3 percent was assumed for all bromide determinations.

Estimation of Streamflow

Streamflow can be calculated at any site downstream from the tracer-injection site by using the concentration of the tracer in the stream, the background tracer concentration, the concentration of the injection solution, and the rate of injection. Streamflow profiles for each of the subreaches along the primary study reach of Piceance Creek (figs. 11 and 12) were developed by using the following equation (modified from Ortiz and Bencala, 2001):

$$Q = Q_{INJ}C_{INJ}/(C - C_p) \qquad (1)$$

where

Q is streamflow, in liters per second;

Q_{INJ} is the rate of the tracer injection into the stream, in liters per second;

C_{INJ} is the tracer concentration in the injection solution, in milligrams per liter;

C is the tracer concentration from the smoothed tracer profile, in milligrams per liter; and

C_P is the tracer concentration in the background sample, in milligrams per liter.

The instream tracer concentration was determined at each synoptic sampling site from a smoothed
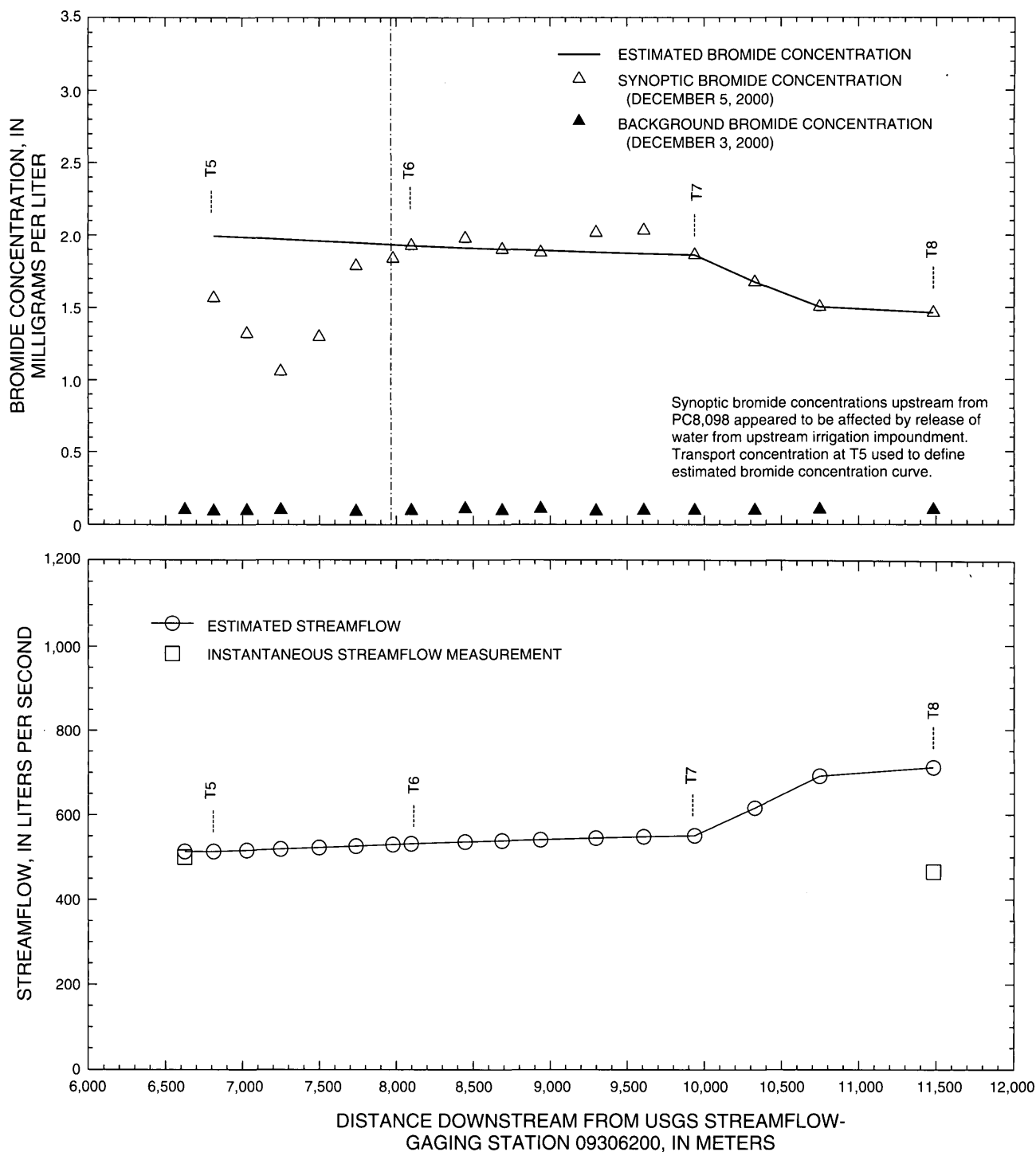
Figure 11. Bromide concentrations and estimated streamflow at synoptic sampling sites in Piceance Creek, December 5, 2000.
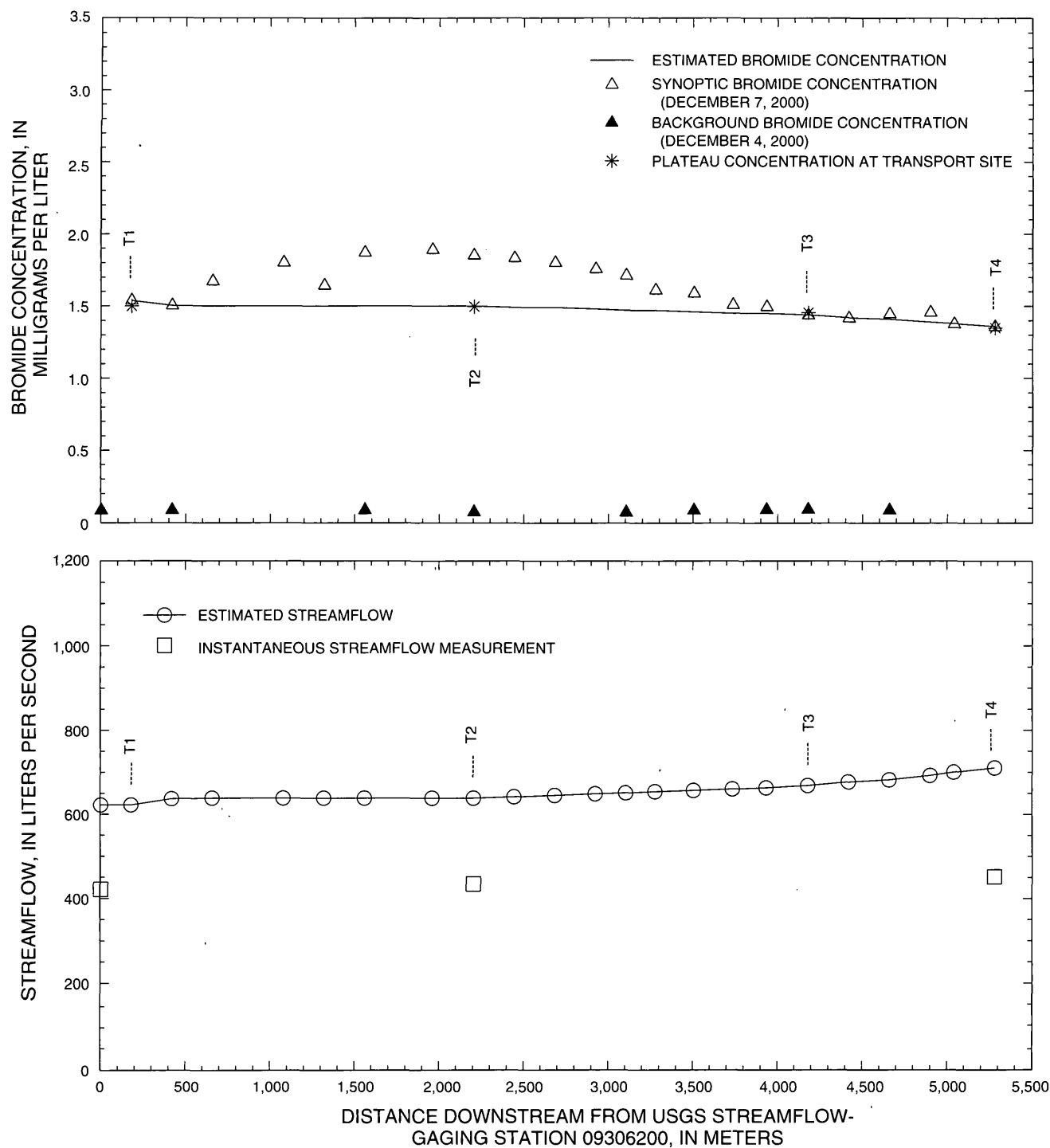
Figure 12: Bromide concentrations and estimated streamflow at synoptic sampling sites in Piceance Creek, December 7, 2000.

profile of bromide concentrations (figs. 11 and 12). The median background bromide concentration was 0.09 milligram per liter in 25 stream samples collected prior to the injection. The average bromide concentration in the NaBr injection solution was 176,700 milligrams per liter; the average injection rate was 0.00553 liter per second. The average bromide concentration in the LiBr injection solution was 168,900 milligrams per liter; the average injection rate was 0.00533 liter per second. Analytical uncertainty associated with these determinations was estimated at plus or minus 2 percent for the NaBr injection and 4 percent for the LiBr injection (James W. Ball, U.S. Geological Survey, written commun., 2000).

The profiles show the increase in estimated streamflow along specific reaches of Piceance Creek. Streamflow increased by 14 percent or about 16 liters per second per 1,000 meters along the reach from PC0 to PC5,280 (fig. 12). A similar increase (12 liters per second per 1,000 meters) was measured between

PC6,625 and PC9,938 (fig. 11). Even though the same general streamflow pattern appears to exist along the entire reach from PC0 to PC9,939, the streamflow data derived from the two tracer injections should not be compared directly. Differences in sampling dates, injections solutions, injection parameters, and anomalies specific to each stream reach do not warrant the direct comparison of the streamflow estimates between the two reaches. Streamflow increased by 25 percent downstream from PC9,938 as the valley floor narrowed and, presumably, ground-water inputs increased (fig. 2).

In addition, seven instantaneous streamflow measurements were done in the secondary study reach in conjunction with synoptic sampling on December 6, 2000 (fig. 13). Streamflow generally increased downstream to PC17,860 and PC20,708. A substantial decrease in streamflow occurred between PC20,708 and PC23,721 along the Alkali Flat area; the area is known to be a region of extensive fracturing. Stream-
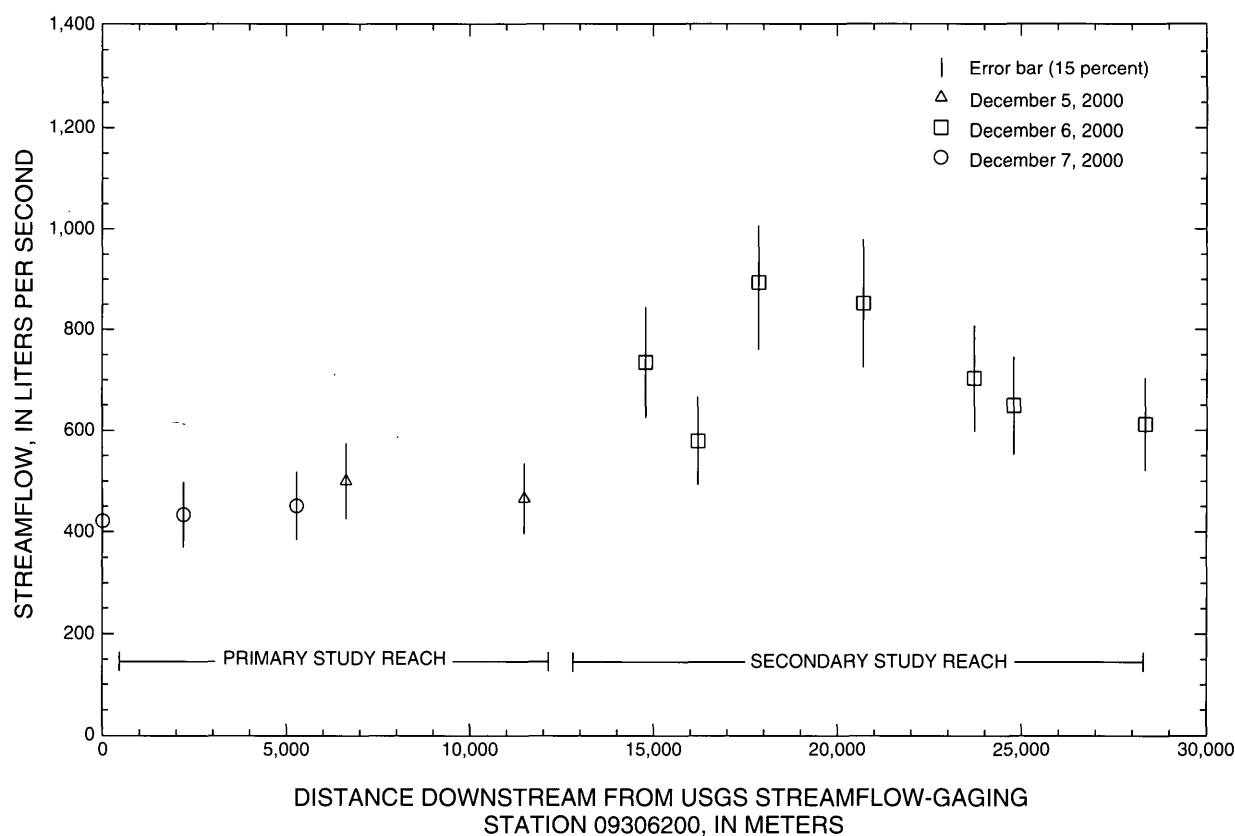
Figure 13. Instantaneous streamflow measurements along the primary and secondary study reaches in Piceance Creek, December 5–7, 2000.

flow profiles presented by Tobin (1987) show a similar decrease in streamflow near this reach, but additional streamflow data are needed to better quantify these findings. These streamflow data were used to calculate loads along this lower reach of the study area. Instantaneous streamflow data along the secondary study reach should not be compared directly with streamflow estimates derived from the tracer injections (figs. 11 and 12) because tracer-dilution techniques can account for about 30 percent more water (Kimball and others, 1998).

MASS LOADS

Downstream load profiles can be used to illustrate graphically the spatial distribution of mass loads at many locations along a main stem and can be used to identify sources and sinks that affect the constituent load. The downstream mass load profiles for this study represent the instantaneous loads at each main-stem sampling site for each of the two tracer-injection reaches in the primary study reach and along the secondary study reach. The three stream reaches are presented separately because, as stated previously, streamflow profiles used to compute loads were not continuous between study reaches. No significant load input to Piceance Creek was detected along the primary study reach. Although substantial increases in constituent concentration were observed near Alkali Flat, apparent losses in streamflow along the secondary study reach resulted in relatively small increases in load downstream to the end of the study reach.

Major Ions

Load profiles for dissolved cations (fig. 14) and anions (fig. 15) from PC0 to PC11,483 were similar to streamflow profiles in Piceance Creek for these same reaches (figs. 11 and 12). Overall, the loads increased gradually along the primary study reach, and the only substantial increase in load occurred between PC9,938 and PC10,748. Increased loading along this short reach was more closely related to increased streamflow than to any large increase in concentration.

Presumably, ground-water inputs to the stream increased as the alluvial cross section constricted in the narrow valley.

Along the secondary study reach, the large increases in ion concentration that were observed in December 2000 (figs. 8 and 9) were offset by decreased streamflow along much of the reach (fig. 13). The resulting load profiles for most dissolved cations and anions downstream from PC11,483 showed little or no increase (figs. 14 and 15). The only constituent load that increased appreciably along this reach was chloride, which increased nearly 50 percent. Additional investigation along the secondary study reach is needed to substantiate these findings.

Trace Constituents

Selected dissolved metal loading (fig. 16) from PC0 to PC11,483 also was similar to streamflow profiles in Piceance Creek for these same reaches (figs. 11 and 12). Overall, the loads increased gradually along the primary study reach and the only substantial increase in load occurred between PC9,938 and PC10,748 where, presumably, ground-water inputs to the stream increased as the alluvial valley narrowed. Barium, boron, and strontium loads were the only trace constituents readily quantifiable in the study area and, as such, are the only ones shown in figure 16. Most of the other concentrations were reported as near or below the method reporting levels.

Along the secondary study reach, load profiles for dissolved-trace constituents downstream from PC11,483 showed little or no increase (fig. 16). Because strontium concentrations (fig. 10) were unchanged throughout the secondary study reach, the resulting load profile indicated a loss of strontium mass downstream to PC28,348. Strontium is generally associated with the ground water of the Uinta Formation so increased ground water from the Green River Formation could reduce the proportion of strontium in this area (George J. Saulnier, Jr., Duke Engineering, written commun., 2001). Additional investigation along the secondary reach is needed to substantiate these findings.

Study reach from PC0 to PC5,280 on December 7

Hatch Gulch

Study reach from PC6,625 to PC11,483 on December 5   Note: Sodium loads downstream of PC6,625

Bear Gulch

Study reach from PC14,789 to PC28,348 on December 6

Dry Fork

Alkali Flat

White River

20,000

15,000

10,000

5,000

0

CONSTITUENT LOAD, IN KILOGRAMS PER DAY

DISTANCE DOWNSTREAM FROM USGS STREAMFLOW-
GAGING STATION 09306200, IN METERS

EXPLANATION

△ DISSOLVED CALCIUM LOAD   ▲ DISSOLVED MAGNESIUM LOAD   ○ DISSOLVED SODIUM LOAD

Figure 14. Dissolved calcium, magnesium, and sodium loads in Piceance Creek, December 5–7, 2000.
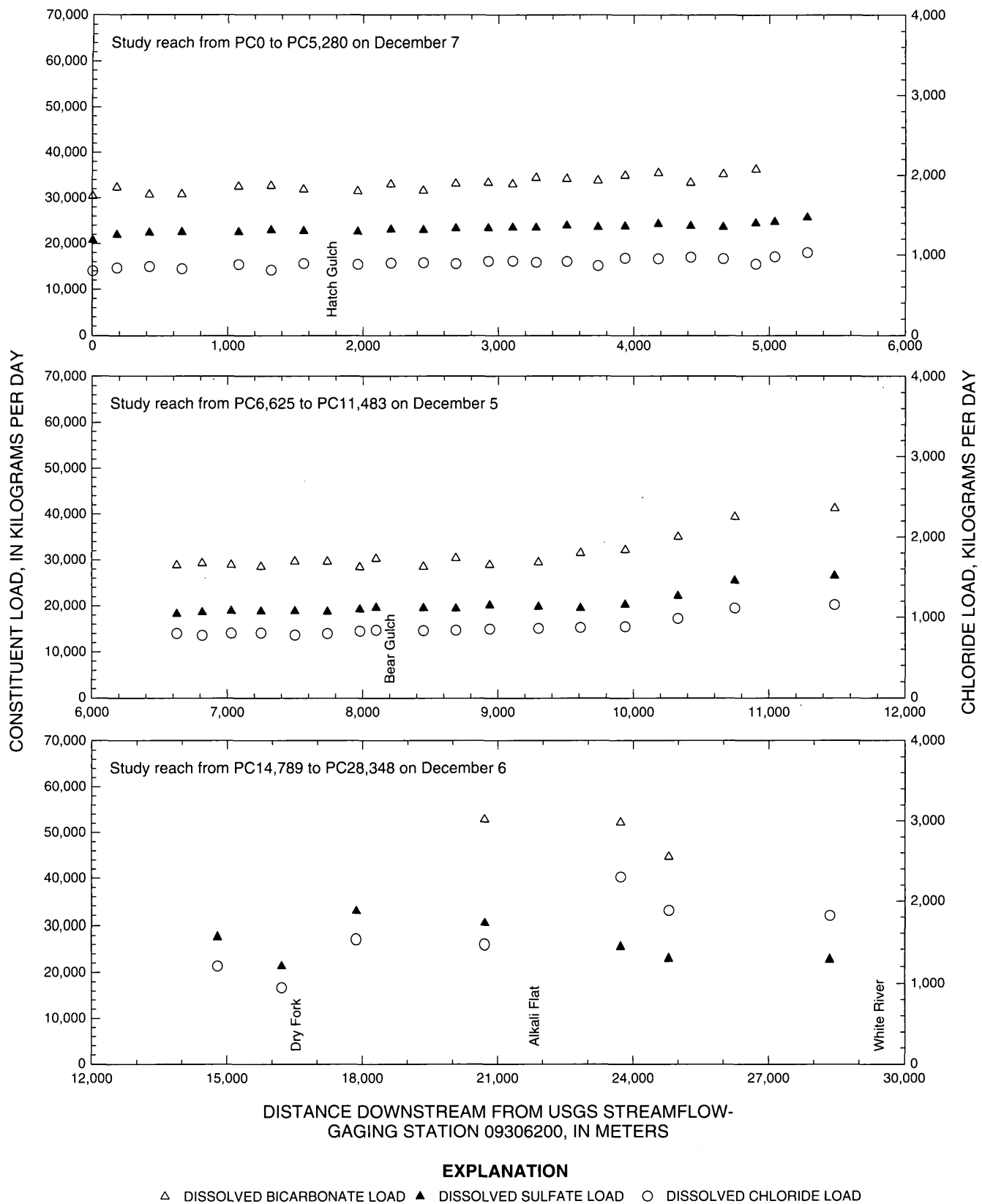
Figure 15. Dissolved bicarbonate, sulfate, and chloride loads in Piceance Creek, December 5–7, 2000.
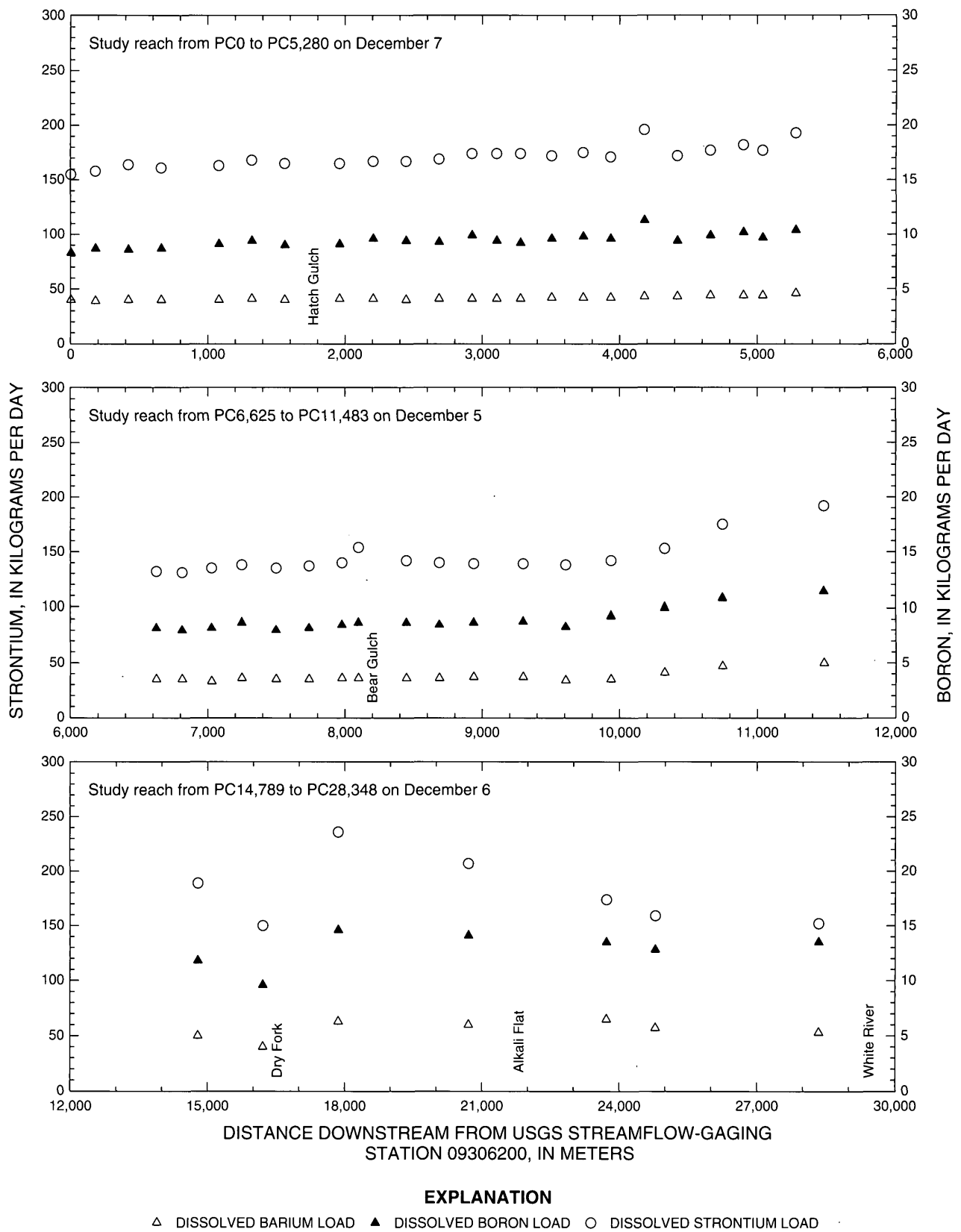
Figure 16. Dissolved barium, boron, and strontium loads in Piceance Creek, December 5–7, 2000.

SUMMARY

In recent years, the emphasis of resource development in the Piceance Basin has turned to commercial nahcolite solution mining for sodium bicarbonate (baking soda) and sodium carbonate (soda ash). The Yankee Gulch Sodium Minerals Project was required to submit a monitoring plan that, in part, would characterize the baseline water quality in the adjacent Piceance Creek. The U.S. Geological Survey (USGS) provided this characterization in cooperation with Rio Blanco County, Colorado. The purpose of this report is to provide a baseline characterization of the water quality in Piceance Creek and to quantify the mass load for selected chemical constituents in Piceance Creek during base-flow conditions. Physical and chemical data were collected during December 2000 at 47 main-stem sites and 4 inflow sites. The study area extended about 28 kilometers along Piceance Creek between the USGS streamflow-gaging stations 09306200 (PC0) and 09306222 (PC28,348). The primary study reach was along the approximately 11.5 kilometers of the study area adjacent to the lease boundary for the Yankee Gulch Sodium Minerals Project.

Tracer-dilution techniques and instantaneous measurements were used to determine streamflow in Piceance Creek. Synoptic-sampling techniques were used to determine baseline concentrations for selected constituents in Piceance Creek. Synoptic water-quality samples were analyzed for a base list of constituents that was consistent with the ground-water monitoring program for the mine. The constituents are possible indicators of fluid migration away from the solution-mining zone. Load profiles along subreaches of the creek were generated by combining tracer-dilution and synoptic-sampling techniques.

Data collected as part of this study provide an updated characterization of the water quality in Piceance Creek between the two USGS streamflow-gaging stations 09306200 and 09306222. In March 1981, a spatially comprehensive data-collection effort in Piceance Creek indicated increases in major dissolved constituents in the downstream direction as ground water discharged to springs, streams, and valley-fill alluvial aquifers. Additionally, a substantial change in water quality was observed as ground water discharged upward through an extensive northwest-southeast trending fracture zone that crosses Piceance Creek in the area known as Alkali Flat.

In December 2000, pH values in Piceance Creek were stable throughout the study area and ranged from 7.9 to 8.1 standard units. Specific conductance increased steadily along the upper two-thirds of the study reach. The rate increased by nearly 14 percent along the reach that included Alkali Flat (PC20,708 to PC23,721). Specific conductance was shown to be a good predictor of dissolved solids in Piceance Creek. In 1987, bicarbonate, sulfate, and sodium were reported as the principal dissolved constituents in Piceance Creek. The principal dissolved constituents remained the same in December 2000. High concentrations of bicarbonate and sodium result from the contact of ground water with evaporite minerals nahcolite and halite in the Green River Formation. Sulfate is commonly high in the ground water of the overlying Uinta Formation. Sodium, bicarbonate, and chloride concentrations increased gradually (25 to 35 percent) downstream to PC20,708 as water discharged to the stream valley. A substantial increase in bicarbonate (19 percent), sodium (35 percent), and chloride (89 percent) occurred in the Alkali Flat area of Piceance Creek. Sulfate, calcium, magnesium, potassium, silica, and fluoride concentrations remained relatively constant throughout the study area.

Concentrations of barium, boron, lithium, and strontium were elevated in Piceance Creek. Strontium concentrations were the highest but remained relatively constant throughout Piceance Creek. Barium and boron concentrations increased from 50 to 65 percent from upstream to downstream. The largest increase in barium and boron concentrations occurred in the area of Alkali Flat. Lithium also increased substantially between PC17,860 and PC23,721, which includes the Alkali Flat area. Concentrations of most of the other trace constituents were at or near method reporting limits, and little or no downstream increases were observed.

No significant load input to Piceance Creek was detected along the primary study reach. Although the area near Alkali Flat contributed substantially to the increase in constituent concentration in Piceance Creek, losses in streamflow along the secondary study reach resulted in relatively small increases in load downstream to the end of the study reach. Load profiles for dissolved cations, anions, and trace constituents from PC0 to PC11,483 were similar to streamflow profiles in Piceance Creek for this same reach. Overall, the loads increased gradually along the primary study reach, and the only substantial increase

in load occurred between PC9,938 and PC10,748. Presumably, increased ground-water inputs to the stream resulted in a gradual increase in streamflow as the alluvial valley narrows. Along the secondary study reach, the increases in ion concentration that were observed were offset by decreased streamflow along much of the reach. The resulting load profiles for dissolved cations, anions, and trace constituents downstream from PC11,483 showed little or no increase. Additional investigation along the secondary study reach is needed to substantiate these findings.

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DATA SECTION

Table 5. Chemical data for synoptic samples collected in Piceance Creek Basin, December 4–7, 2000

[mg/L, milligrams per liter; HCO_3, bicarbonate; $CaCO_3$, calcium carbonate; nd, no data; mv, missing value; e, estimated; <, less than; μg/L, microgram per liter; pCi/L, picocurie per liter]

Site name	Sample collection Date	Time	Calcium, dissolved (mg/L)	Mag-nesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potas-sium, dissolved (mg/L)	Bicar-bonate (mg/L as HCO_3)	Alk-alinity (mg/L as total $CaCO_3$)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)
					Main-stem sites					
PC0	12-07-00	1040	93	79	150	2.4	570	420	390	14.9
PC180	12-07-00	1035	91	81	160	2.4	600	420	410	15.6
PC420	12-07-00	1030	92	81	160	2.4	560	420	410	15.5
PC660	12-07-00	1020	90	80	150	2.4	560	410	410	15.0
PC1,080	12-07-00	1015	91	81	160	mv	590	440	410	15.9
PC1,320	12-07-00	1005	94	84	160	2.5	590	440	420	14.7
PC1,560	12-07-00	0955	90	82	.160	2.4	580	430	410	16.2
PC1,960	12-07-00	0945	91	82	160	2.4	570	440	410	16.0
PC2,205	12-07-00	0935	87	80	160	2.5	600	470	420	16.3
PC2,445	12-07-00	0925	91	83	160	2.5	570	430	410	16.3
PC2,685	12-07-00	0920	91	83	160	2.4	590	440	420	16.0
PC2,925	12-07-00	0910	94	85	170	2.4	600	420	420	16.4
PC3,105	12-07-00	0900	93	85	170	2.4	590	420	420	16.4
PC3,278	12-07-00	0845	92	85	170	2.5	610	430	420	16.1
PC3,505	12-07-00	0835	92	84	170	2.4	600	440	420	16.2
PC3,735	12-07-00	0825	94	85	170	2.4	590	420	410	15.2
PC3,935	12-07-00	0815	89	82	170	2.5	610	440	420	16.8
PC4,180	12-07-00	0800	88	84	180	2.4	610	470	420	16.5
PC4,420	12-07-00	0755	90	82	160	2.4	570	450	410	16.6
PC4,660	12-07-00	0745	90	82	170	2.4	600	450	400	16.2
PC4,900	12-07-00	0735	93	84	170	2.4	610	450	410	14.8
PC5,040	12-07-00	0727	90	81	160	2.4	mv	440	410	16.2
PC5,280	12-07-00	0700	89	79	170	2.4	mv	480	420	16.8
PC6,625	12-07-00	1147	88	82	180	2.5	600	450	420	17.5
PC6,625	12-05-00	1040	87	84	180	2.5	650	480	410	18.1
PC6,813	12-05-00	1020	87	84	mv	2.3	660	480	420	17.5
PC7,028	12-05-00	1010	87	86	mv	2.4	650	460	420	18.0
PC7,248	12-05-00	0955	89	87	mv	2.5	640	480	420	17.9
PC7,498	12-05-00	0945	87	85	mv	2.4	660	480	420	17.3
PC7,738	12-05-00	0935	88	85	mv	2.3	650	470	410	17.6
PC7,978	12-05-00	0930	88	86	mv	2.5	620	470	420	18.0
PC8,098	12-05-00	0915	92	86	mv	2.4	660	510	430	18.2
PC8,448	12-05-00	0905	87	87	mv	2.6	620	480	420	18.0
PC8,688	12-05-00	0855	87	86	mv	2.4	650	490	420	18.0
PC8,938	12-05-00	0850	86	86	mv	2.4	620	470	430	18.3
PC9,298	12-05-00	0825	85	85	mv	2.4	630	480	420	18.3
PC9,608	12-05-00	0815	80	82	mv	2.5	660	490	410	18.4
PC9,938	12-05-00	0805	85	87	mv	2.5	680	490	420	18.5
PC10,328	12-05-00	0800	82	82	mv	2.5	660	500	420	18.5
PC10,748	12-05-00	0745	84	83	mv	2.4	660	470	430	18.6
PC11,483	12-05-00	0730	86	81	mv	2.5	670	500	430	18.8

Table 5. Chemical data for synoptic samples collected in Piceance Creek Basin, December 4–7, 2000—Continued

[mg/L, milligrams per liter; HCO₃, bicarbonate; CaCO₃, calcium carbonate; nd, no data; mv, missing value; e, estimated; <, less than; μg/L, microgram per liter; pCi/L, picocurie per liter]

Site name	Sample collection Date	Sample collection Time	Calcium, dissolved (mg/L)	Mag-nesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potas-sium, dissolved (mg/L)	Bicar-bonate (mg/L as HCO₃)	Alk-alinity (mg/L as total CaCO₃)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)
Main-stem sites—Continued										
PC14,789	12-06-00	1005	79	85	200	2.5	mv	480	430	19.2
PC16,210	12-06-00	0910	84	88	200	2.5	mv	520	430	19.1
PC17,860	12-06-00	0805	86	81	200	2.4	mv	520	430	20.0
PC20,708	12-06-00	1030	81	83	200	2.5	720	490	410	20.1
PC23,721	12-06-00	0945	81	78	270	2.5	860	650	410	37.9
PC24,787	12-06-00	0900	83	85	270	2.5	800	590	410	33.6
PC28,348	12-06-00	0745	82	87	280	2.6	mv	600	420	34.4
Input sites										
RGS	12-04-00	0900	110	200	360	1.8	mv	640	1,210	24.9
HGS	12-07-00	1220	32	100	650	1.9	1,570	1,290	700	43.9
PT16,225	12-06-00	0925	73	50	110	2.0	370	330	240	15.2
AFS	12-04-00	1225	17	48	3,540	7.3	mv	6,860	100	900

Site name	Sample collection Date	Sample collection Time	Fluoride, dis-solved (mg/L)	Bro-mide, dis-solved (mg/L)	Silica, dis-solved (mg/L)	Total dis-solved solids (mg/L)	Nitrite, dis-solved (mg/L)	Nitrite plus nitrate, dis-solved (mg/L)	Am-monia, dis-solved (mg/L)	Ammonia plus organic nitrogen, dissolved (mg/L)	Phos-phorus, dis-solved (mg/L)
Main-stem sites											
PC0	12-07-00	1040	0.61	0.10	16.4	1,000	nd	nd	nd	nd	nd
PC180	12-07-00	1035	.93	mv	16.6	1,030	nd	nd	nd	nd	nd
PC420	12-07-00	1030	.59	mv	16.6	1,030	nd	nd	nd	nd	nd
PC660	12-07-00	1020	.59	mv	16.5	1,020	nd	nd	nd	nd	nd
PC1,080	12-07-00	1015	.63	mv	16.6	1,050	nd	nd	nd	nd	nd
PC1,320	12-07-00	1005	.59	mv	16.6	1,060	nd	nd	nd	nd	nd
PC1,560	12-07-00	0955	.59	mv	16.8	1,040	nd	nd	nd	nd	nd
PC1,960	12-07-00	0945	.62	mv	16.7	1,050	nd	nd	nd	nd	nd
PC2,205	12-07-00	0935	.67	mv	17.0	1,080	.01	.69	e .04	.28	<.06
PC2,445	12-07-00	0925	.94	mv	16.7	1,050	nd	nd	nd	nd	nd
PC2,685	12-07-00	0920	.61	mv	16.9	1,060	nd	nd	nd	nd	nd
PC2,925	12-07-00	0910	.60	mv	16.5	1,060	nd	nd	nd	nd	nd
PC3,105	12-07-00	0900	.59	mv	17.0	1,060	nd	nd	nd	nd	nd
PC3,278	12-07-00	0845	.60	mv	16.8	1,060	nd	nd	nd	nd	nd
PC3,505	12-07-00	0835	.92	mv	17.7	1,070	nd	nd	nd	nd	nd
PC3,735	12-07-00	0825	.60	mv	16.4	1,050	nd	nd	nd	nd	nd
PC3,935	12-07-00	0815	1.19	mv	16.6	1,060	nd	nd	nd	nd	nd
PC4,180	12-07-00	0800	.68	mv	16.8	1,100	.01	.67	e .04	.30	<.06
PC4,420	12-07-00	0755	.64	mv	16.6	1,050	nd	nd	nd	nd	nd
PC4,660	12-07-00	0745	.62	mv	16.5	1,050	nd	nd	nd	nd	nd
PC4,900	12-07-00	0735	.63	mv	16.7	1,070	nd	nd	nd	nd	nd
PC5,040	12-07-00	0727	.61	mv	16.5	1,050	nd	nd	nd	nd	nd
PC5,280	12-07-00	0700	.59	mv	16.5	1,100	.01	.66	.05	.32	<.06

Table 5. Chemical data for synoptic samples collected in Piceance Creek Basin, December 4–7, 2000—Continued

[mg/L, milligrams per liter; HCO₃, bicarbonate; CaCO₃, calcium carbonate; nd, no data; mv, missing value; e, estimated; <, less than; µg/L, microgram per liter; pCi/L, picocurie per liter]

Site name	Sample collection Date	Time	Fluoride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Silica, dissolved (mg/L)	Total dissolved solids (mg/L)	Nitrite, dissolved (mg/L)	Nitrite plus nitrate, dissolved (mg/L)	Ammonia, dissolved (mg/L)	Ammonia plus organic nitrogen, dissolved (mg/L)	Phosphorus, dissolved (mg/L)
						Main-stem sites—Continued					
PC6,625	12-07-00	1147	0.59	mv	16.5	1,080	nd	nd	nd	nd	nd
PC6,625	12-05-00	1040	1.15	mv	16.7	1,100	nd	nd	nd	nd	nd
PC6,813	12-05-00	1020	.60	mv	16.6	1,100	nd	nd	nd	nd	nd
PC7,028	12-05-00	1010	.65	mv	16.7	1,100	nd	nd	nd	nd	nd
PC7,248	12-05-00	0955	.66	mv	16.7	1,110	nd	nd	nd	nd	nd
PC7,498	12-05-00	0945	.66	mv	16.6	1,100	nd	nd	nd	nd	nd
PC7,738	12-05-00	0935	.57	mv	16.5	1,090	nd	nd	nd	nd	nd
PC7,978	12-05-00	0930	.64	mv	15.3	1,110	nd	nd	nd	nd	nd
PC8,098	12-05-00	0915	.69	mv	16.5	1,160	.01	.66	.06	.32	<.06
PC8,448	12-05-00	0905	.64	mv	18.2	1,120	nd	nd	nd	nd	nd
PC8,688	12-05-00	0855	.58	mv	16.9	1,120	nd	nd	nd	nd	nd
PC8,938	12-05-00	0850	.62	mv	16.0	1,120	nd	nd	nd	nd	nd
PC9,298	12-05-00	0825	.67	mv	16.6	1,110	nd	nd	nd	nd	nd
PC9,608	12-05-00	0815	.66	mv	16.1	1,100	nd	nd	nd	nd	nd
PC9,938	12-05-00	0805	.69	mv	16.6	1,130	nd	nd	nd	nd	nd
PC10,328	12-05-00	0800	.63	mv	15.9	1,110	nd	nd	nd	nd	nd
PC10,748	12-05-00	0745	.66	mv	17.0	1,110	nd	nd	nd	nd	nd
PC11,483	12-05-00	0730	.69	mv	16.8	1,150	.01	.61	.06	.33	<.06
PC14,789	12-06-00	1005	.64	.10	17.0	1,130	nd	nd	nd	nd	nd
PC16,210	12-06-00	0910	.67	.09	16.8	1,160	nd	nd	nd	nd	nd
PC17,860	12-06-00	0805	.68	.12	17.0	1,150	.01	.70	.06	.37	<.06
PC20,708	12-06-00	1030	.67	.09	16.8	1,110	nd	nd	nd	nd	nd
PC23,721	12-06-00	0945	.90	.12	16.9	1,300	.01	.67	.15	.49	e .05
PC24,787	12-06-00	0900	.86	.13	16.4	1,260	nd	nd	nd	nd	nd
PC28,348	12-06-00	0745	.79	.19	17.3	1,290	nd	nd	nd	nd	nd
						Input sites					
RGS	12-04-00	0900	.37	.20	21.6	2,310	nd	nd	nd	nd	nd
HGS	12-07-00	1220	2.77	.20	15.5	2,330	nd	nd	nd	nd	nd
PT16,225	12-06-00	0925	.40	.11	16.4	710	nd	nd	nd	nd	nd
AFS	12-04-00	1225	15.5	.69	.8	8,760	nd	nd	nd	nd	nd

Site name	Sample collection Date	Time	Orthophosphorus, dissolved (mg/L)	Aluminum, dissolved (µg/L)	Antimony, dissolved (µg/L)	Arsenic, dissolved (µg/L)	Barium, dissolved (µg/L)	Beryllium, dissolved (µg/L)	Boron, dissolved (µg/L)	Cadmium, dissolved (µg/L)	Chromium, dissolved (µg/L)
						Main-stem sites					
PC0	12-07-00	1040	nd	mv	0.11	1.7	75	nd	160	nd	nd
PC180	12-07-00	1035	nd	mv	.16	1.2	73	nd	160	nd	nd
PC420	12-07-00	1030	nd	mv	.12	1.2	73	nd	160	nd	nd
PC660	12-07-00	1020	nd	mv	.13	1.2	72	nd	160	nd	nd
PC1,080	12-07-00	1015	nd	mv	.13	1.1	73	nd	160	nd	nd
PC1,320	12-07-00	1005	nd	mv	.12	1.2	74	nd	170	nd	nd

Table 5. Chemical data for synoptic samples collected in Piceance Creek Basin, December 4–7, 2000—Continued

[mg/L, milligrams per liter; HCO₃, bicarbonate; CaCO₃, calcium carbonate; nd, no data; mv, missing value; e, estimated; <, less than; μg/L, microgram per liter; pCi/L, picocurie per liter]

Site name	Sample collection Date	Sample collection Time	Ortho-phos-phorus, dissolved (mg/L)	Alum-inum, dissolved (μg/L)	Anti-mony, dissolved (μg/L)	Arsenic, dissolved (μg/L)	Barium, dissolved (μg/L)	Beryllium, dissolved (μg/L)	Boron, dissolved (μg/L)	Cad-mium, dissolved (μg/L)	Chro-mium, dissolved (μg/L)
						Main-stem sites—Continued					
PC1,560	12-07-00	0955	nd	mv	0.13	1.2	72	nd	160	nd	nd
PC1,960	12-07-00	0945	nd	mv	.12	1.2	74	nd	160	nd	nd
PC2,205	12-07-00	0935	0.02	mv	.12	e 2.0	74	<0.06	170	0.04	<0.8
PC2,445	12-07-00	0925	nd	mv	.11	1.1	73	nd	170	nd	nd
PC2,685	12-07-00	0920	nd	mv	.12	1.3	74	nd	170	nd	nd
PC2,925	12-07-00	0910	nd	mv	.12	1.3	73	nd	180	nd	nd
PC3,105	12-07-00	0900	nd	mv	.11	1.4	73	nd	170	nd	nd
PC3,278	12-07-00	0845	nd	mv	.19	1.4	73	nd	160	nd	nd
PC3,505	12-07-00	0835	nd	mv	.15	1.3	73	nd	170	nd	nd
PC3,735	12-07-00	0825	nd	mv	.11	1.3	74	nd	170	nd .	nd
PC3,935	12-07-00	0815	nd	mv	.11	1.5	74	nd	170	nd	nd
PC4,180	12-07-00	0800	.02	mv	.12	2.1	75	<.06	200	.04	<.8
PC4,420	12-07-00	0755	nd	mv	.13	1.4	74	nd	160	nd	nd
PC4,660	12-07-00	0745	nd	mv	.12	1.5	74	nd	170	nd	nd
PC4,900	12-07-00	0735	nd	mv	.12	1.3	73	nd	170	nd	nd
PC5,040	12-07-00	0727	nd	mv	.12	1.4	73	nd	160	nd	nd
PC5,280	12-07-00	0700	.02	mv	.12	e 1.9	76	<.06	170	.05	<.8
PC6,625	12-07-00	1147	nd	mv	.12	1.5	86	nd	170	nd	nd
PC6,625	12-05-00	1040	nd	<1.0	.11	1.7	78	nd	190	nd	nd
PC6,813	12-05-00	1020	nd	1.1	.13	2.1	78	nd	180	nd	nd
PC7,028	12-05-00	1010	nd	1.0	.12	1.6	74	nd	180	nd	nd
PC7,248	12-05-00	0955	nd	2.2	<.05	2.3	80	nd	190	nd	nd
PC7,498	12-05-00	0945	nd	1.6	<.05	2.2	78	nd	180	nd	nd
PC7,738	12-05-00	0935	nd	1.1	.12	2.3	78	nd	180	nd	nd
PC7,978	12-05-00	0930	nd	1.3	<.05	2.3	78	nd	190	nd	nd
PC8,098	12-05-00	0915	.04	1.1	.13	e 1.9	79	<.06	190	.59	<.8
PC8,448	12-05-00	0905	nd	1.3	<.05	2.4	78	nd	190	nd	nd
PC8,688	12-05-00	0855	nd	<1.0	.12	2.4	78	nd	180	nd	nd
PC8,938	12-05-00	0850	nd	2.7	<.05	2.4	79	nd	190	nd	nd
PC9,298	12-05-00	0825	nd	1.7	<.05	2.4	78	nd	190	nd	nd
PC9,608	12-05-00	0815	nd	<1.0	.11	1.3	72	nd	180	nd	nd
PC9,938	12-05-00	0805	nd	<1.0	.12	1.6	74	nd	200	nd	nd
PC10,328	12-05-00	0800	nd	2.3	<.05	2.5	77	nd	190	nd	nd
PC10,748	12-05-00	0745	nd	1.4	.16	1.6	78	nd	180	nd	nd
PC11,483	12-05-00	0730	.05	<1.0	.13	e 1.9	81	<.06	180	e .03	<.8
PC14,789	12-06-00	1005	nd	1.2	.18	2.0	79	nd	190	nd	nd
PC16,210	12-06-00	0910	nd	1.5	<.05	2.4	79	nd	190	nd	nd
PC17,860	12-06-00	0805	.03	<1.0	.13	e 1.7	81	<.06	190	e .03	e .5
PC20,708	12-06-00	1030	nd	1.3	<.05	2.2	82	nd	190	nd	nd
PC23,721	12-06-00	0945	.06	<1.0	.14	e 1.8	110	<.06	220	.20	<.8
PC24,787	12-06-00	0900	nd	1.2	<.05	2.6	100	nd	230	nd	nd
PC28,348	12-06-00	0745	nd	1.2	.17	2.0	100	nd	260	nd	nd

Table 5. Chemical data for synoptic samples collected in Piceance Creek Basin, December 4–7, 2000—Continued

[mg/L, milligrams per liter; HCO$_3$, bicarbonate; CaCO$_3$, calcium carbonate; nd, no data; mv, missing value; e, estimated; <, less than; µg/L, microgram per liter; pCi/L, picocurie per liter]

Site name	Sample collection		Ortho-phos-phorus, dissolved (mg/L)	Alum-inum, dissolved (µg/L)	Anti-mony, dissolved (µg/L)	Arsenic, dissolved (µg/L)	Barium, dissolved (µg/L)	Beryllium, dissolved (µg/L)	Boron, dissolved (µg/L)	Cad-mium, dissolved (µg/L)	Chro-mium, dissolved (µg/L)
	Date	Time									
Input sites											
RGS	12-04-00	0900	nd	2.5	.05	1.9	21	nd	330	nd	nd
HGS	12-07-00	1220	nd	mv	.05	7.6	56	nd	560	nd	nd
PT16,225	12-06-00	0925	nd	<1.0	.16	1.9	71	nd	120	nd	nd
AFS	12-04-00	1225	nd	4.4	<.05	2.2	4,740	nd	1,160	nd	nd

Site name	Sample collection		Cobalt, dis-solved (µg/L)	Copper, dis-solved (µg/L)	Iron, dis-solved (µg/L)	Lead, dis-solved (µg/L)	Lith-ium, dis-solved (µg/L)	Man-ganese, dis-solved (µg/L)	Mercury, dis-solved (µg/L)	Molyb-denum, dis-solved (µg/L)	Nickel, dis-solved (µg/L)
	Date	Time									
Main-stem sites											
PC0	12-07-00	1040	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC180	12-07-00	1035	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC420	12-07-00	1030	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC660	12-07-00	1020	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC1,080	12-07-00	1015	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC1,320	12-07-00	1005	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC1,560	12-07-00	0955	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC1,960	12-07-00	0945	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC2,205	12-07-00	0935	0.49	2.2	<10	<0.08	mv	85	<0.23	7.9	2.6
PC2,445	12-07-00	0925	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC2,685	12-07-00	0920	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC2,925	12-07-00	0910	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC3,105	12-07-00	0900	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC3,278	12-07-00	0845	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC3,505	12-07-00	0835	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC3,735	12-07-00	0825	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC3,935	12-07-00	0815	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC4,180	12-07-00	0800	.49	2.3	<10	<.08	mv	83	<.23	8.1	2.6
PC4,420	12-07-00	0755	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC4,660	12-07-00	0745	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC4,900	12-07-00	0735	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC5,040	12-07-00	0727	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC5,280	12-07-00	0700	.50	2.2	e 6.3	<.08	mv	82	<.23	7.9	2.7
PC6,625	12-07-00	1147	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC6,625	12-05-00	1040	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC6,813	12-05-00	1020	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC7,028	12-05-00	1010	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC7,248	12-05-00	0955	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC7,498	12-05-00	0945	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC7,738	12-05-00	0935	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC7,978	12-05-00	0930	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC8,098	12-05-00	0915	.50	2.0	<10	<.08	12.3	84	<.23	8.5	1.3
PC8,448	12-05-00	0905	nd	nd	<10	nd	nd	nd	nd	nd	nd

Table 5. Chemical data for synoptic samples collected in Piceance Creek Basin, December 4–7, 2000—Continued

[mg/L, milligrams per liter; HCO$_3$, bicarbonate; CaCO$_3$, calcium carbonate; nd, no data; mv, missing value; e, estimated; <, less than; µg/L, microgram per liter; pCi/L, picocurie per liter]

Site name	Sample collection Date	Sample collection Time	Cobalt, dissolved (µg/L)	Copper, dissolved (µg/L)	Iron, dissolved (µg/L)	Lead, dissolved (µg/L)	Lithium, dissolved (µg/L)	Manganese, dissolved (µg/L)	Mercury, dissolved (µg/L)	Molybdenum, dissolved (µg/L)	Nickel, dissolved (µg/L)
						Main-stem sites—Continued					
PC8,688	12-05-00	0855	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC8,938	12-05-00	0850	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC9,298	12-05-00	0825	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC9,608	12-05-00	0815	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC9,938	12-05-00	0805	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC10,328	12-05-00	0800	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC10,748	12-05-00	0745	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC11,483	12-05-00	0730	0.52	2.0	<10	<0.08	11.9	79	<0.23	8.8	1.4
PC14,789	12-06-00	1005	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC16,210	12-06-00	0910	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC17,860	12-06-00	0805	.50	2.0	<10	<.08	12.8	74	<.23	9.0	1.0
PC20,708	12-06-00	1030	nd	nd	<10	nd	nd	nd	nd	nd	nd
PC23,721	12-06-00	0945	.54	2.0	<10	e .04	21.7	72	<.23	8.4	1.2
PC24,787	12-06-00	0900	nd	nd	<30	nd	nd	nd	nd	nd	nd
PC28,348	12-06-00	0745	nd	nd	<30	nd	nd	nd	nd	nd	nd
						Input sites					
RGS	12-04-00	0900	nd	nd	30	nd	nd	nd	nd	nd	nd
HGS	12-07-00	1220	nd	nd	e 27	nd	nd	nd	nd	nd	nd
PT16,225	12-06-00	0925	nd	nd	<10	nd	nd	nd	nd	nd	nd
AFS	12-04-00	1225	nd	nd	<100	nd	nd	nd	nd	nd	nd

Site name	Sample collection Date	Sample collection Time	Selenium, dissolved (µg/L)	Silver, dissolved (µg/L)	Strontium, dissolved (µg/L)	Vanadium, dissolved (µg/L)	Zinc, dissolved (µg/L)	Gross-alpha radioactivity (pCi/L)	Gross-beta radioactivity, (pCi/L)	Uranium, natural, dissolved ((µg/L)	Organic carbon, dissolved (mg/L)
						Main-stem sites					
PC0	12-07-00	1040	nd	nd	2,880	nd	1.6	nd	nd	nd	nd
PC180	12-07-00	1035	nd	nd	2,940	nd	2.0	nd	nd	nd	nd
PC420	12-07-00	1030	nd	nd	2,970	nd	2.3	nd	nd	nd	nd
PC660	12-07-00	1020	nd	nd	2,910	nd	2.5	nd	nd	nd	nd
PC1,080	12-07-00	1015	nd	nd	2,950	nd	1.8	nd	nd	nd	nd
PC1,320	12-07-00	1005	nd	nd	3,050	nd	2.1	nd	nd	nd	nd
PC1,560	12-07-00	0955	nd	nd	2,990	nd	2.0	nd	nd	nd	nd
PC1,960	12-07-00	0945	nd	nd	3,000	nd	1.8	nd	nd	nd	nd
PC2,205	12-07-00	0935	e 1.5	<1	3,020	e 4.2	2.3	3.1	<4.0	3.5	3.6
PC2,445	12-07-00	0925	nd	nd	3,010	nd	2.3	nd	nd	nd	nd
PC2,685	12-07-00	0920	nd	nd	3,030	nd	2.3	nd	nd	nd	nd
PC2,925	12-07-00	0910	nd	nd	3,100	nd	1.5	nd	nd	nd	nd
PC3,105	12-07-00	0900	nd	nd	3,100	nd	1.8	nd	nd	nd	nd
PC3,278	12-07-00	0845	nd	nd	3,080	nd	2.0	nd	nd	nd	nd
PC3,505	12-07-00	0835	nd	nd	3,040	nd	1.5	nd	nd	nd	nd
PC3,735	12-07-00	0825	nd	nd	3,070	nd	1.7	nd	nd	nd	nd

Table 5. Chemical data for synoptic samples collected in Piceance Creek Basin, December 4–7, 2000—Continued

[mg/L, milligrams per liter; HCO$_3$, bicarbonate; CaCO$_3$, calcium carbonate; nd, no data; mv, missing value; e, estimated; <, less than; μg/L, microgram per liter; pCi/L, picocurie per liter]

Site name	Sample collection Date	Sample collection Time	Sele-nium, dissolved (μg/L)	Silver, dis-solved (μg/L)	Strontium, dissolved (μg/L)	Vana-dium, dis-solved (μg/L)	Zinc, dis-solved (μg/L)	Gross-alpha radio-activity (pCi/L)	Gross-beta radio-activity, (pCi/L)	Uranium, natural, dis-solved ((μg/L)	Organic carbon, dis-solved (mg/L)
					Main-stem sites—Continued						
PC3,935	12-07-00	0815	nd	nd	2,990	nd	1.9	nd	nd	nd	nd
PC4,180	12-07-00	0800	<2.4	<1	3,390	e 7.5	1.9	3.8	<4.0	3.5	3.9
PC4,420	12-07-00	0755	nd	nd	2,940	nd	1.5	nd	nd	nd	nd
PC4,660	12-07-00	0745	nd	nd	3,000	nd	2.0	nd	nd	nd	nd
PC4,900	12-07-00	0735	nd	nd	3,040	nd	2.4	nd	nd	nd	nd
PC5,040	12-07-00	0727	nd	nd	2,930	nd	1.9	nd	nd	nd	nd
PC5,280	12-07-00	0700	<2.4	<1	3,140	e 6.9	2.0	5.0	<4.0	3.5	3.7
PC6,625	12-07-00	1147	na	na	2,960	na	1.6	na	na	na	na
PC6,625	12-05-00	1040	nd	nd	2,970	nd	2.2	nd	nd	nd	nd
PC6,813	12-05-00	1020	na	na	2,970	na	1.6	na	na	na	na
PC7,028	12-05-00	1010	na	na	3,020	na	1.3	na	na	na	na
PC7,248	12-05-00	0955	na	na	3,070	na	2.0	na	na	na	na
PC7,498	12-05-00	0945	na	na	2,990	na	2.5	na	na	na	na
PC7,738	12-05-00	0935	na	na	3,020	na	1.6	na	na	na	na
PC7,978	12-05-00	0930	na	na	3,060	na	1.8	na	na	na	na
PC8,098	12-05-00	0915	e 1.4	<1	3,350	e 6.4	2.2	3.8	<4.0	3.6	3.8
PC8,448	12-05-00	0905	na	na	3,060	na	2.1	na	na	na	na
PC8,688	12-05-00	0855	na	na	3,020	na	1.5	na	na	na	na
PC8,938	12-05-00	0850	na	na	2,980	na	2.2	na	na	na	na
PC9,298	12-05-00	0825	na	na	2,950	na	2.3	na	na	na	na
PC9,608	12-05-00	0815	na	na	2,900	na	1.1	na	na	na	na
PC9,938	12-05-00	0805	na	na	2,990	na	1.4	na	na	na	na
PC10,328	12-05-00	0800	na	na	2,880	na	2.8	na	na	na	na
PC10,748	12-05-00	0745	na	na	2,930	na	1.9	na	na	na	na
PC11,483	12-05-00	0730	<2.4	<1	3,120	e 4.7	1.6	<3.0	8.8	3.6	3.9
PC14,789	12-06-00	1005	na	na	2,980	na	1.7	na	na	na	na
PC16,210	12-06-00	0910	na	na	3,000	na	2.4	na	na	na	na
PC17,860	12-06-00	0805	e 1.6	<1	3,050	e 5.0	1.3	4.3	<4.0	3.8	4.0
PC20,708	12-06-00	1030	na	na	2,810	na	2.0	na	na	na	na
PC23,721	12-06-00	0945	<2.4	<1	2,860	e 6.2	1.5	3.0	<4.0	3.7	4.3
PC24,787	12-06-00	0900	na	na	2,840	na	1.9	na	na	na	na
PC28,348	12-06-00	0745	na	na	2,880	na	1.6	na	na	na	na
					Input sites						
RGS	12-04-00	0900	na	na	6,930	na	6.0	na	na	na	na
HGS	12-07-00	1220	na	na	3,000	na	2.0	na	na	na	na
PT16,225	12-06-00	0925	na	na	1,590	na	<1.0	na	na	na	na
AFS	12-04-00	1225	na	na	4,070	na	6.7	na	na	na	na

Table 6. Comparison of selected constituent concentrations for duplicate water-quality samples collected in Piceance Creek Basin, December 4–7, 2000

[RPD, relative percent difference; mg/L, milligram per liter; µg/L, microgram per liter; NA, not applicable]

Dissolved constituent	Site PC3,305 12/7/00 at 0835 and 0836		Site PC8,448 12/5/00 at 0905 and 0906		Site BURKE[1] 12/4/00 at 1035 and 1036		Site PC28,348 12/6/00 at 0745 and 0746	
	Concen-tration	RPD[2]	Concen-tration	RPD[2]	Concen-tration	RPD[2]	Concen-tration	RPD[2]
Calcium, mg/L	92	0	87	0	54	0	82	0
	92		87		54		82	
Magnesium, mg/L	84	0	87	1.1	68	0	87	0
	84		86		68		87	
Potassium, mg/L	2.4	4.1	2.6	8.0	1.4	0	2.6	0
	2.5		2.4		1.4		2.6	
Chloride, mg/L	16	0	18	0	8.1	0	34	0
	16		18		8.1		34	
Silica, mg/L	18	11	18	5.7	20	0	17	6.1
	16		17		20		16	
Sulfate, mg/L	420	0	420	0	340	0	420	0
	420		420		340		420	
Aluminum, µg/L	5.8	19	1.3	7.4	<1	NA	1.2	70
	7.0		1.4		<1		2.5	
Barium, µg/L	73	1.4	78	0	38	0	100	0
	74		78		38		100	
Boron, µg/L	170	0	190	0	120	0	260	8.0
	170		190		120		240	
Strontium, µg/L	3,040	0	3,060	1.7	2,060	.5	2,880	1.0
	3,040		3,010		2,070		2,850	
Bromide, mg/L	1.59	11	1.98	6.2	.07	13	.18	0
	1.43		1.86		.08		.18	

[1] The site BURKE was a domestic well. Although the site is not incorporated in the text of the report, these data do provide an adequate measurement of sample bias and are included in this table.

[2] Relative percent difference is calculated by dividing the absolute value of the concentration difference by the mean of the concentrations. The quotient is shown as a percentage.

Table 7. Water-quality data for field blanks processed December 5 and December 7, 2000

Field parameter or dissolved constituent	Processed after site PC8,098 12/5/00 at 0915	Processed after site PC2,205 12/7/00 at 0935
pH, standard unit	7.7	7.9
Specific conductance, microsiemens per centimeter	3.9	4.0
Calcium, milligram per liter	<.011	.011
Magnesium, milligram per liter	<.008	<.008
Sodium, milligram per liter	<.06	<.06
Potassium, milligram per liter	<.09	<.09
Alkalinity, milligram per liter	2.0	1.6
Sulfate, milligram per liter	<.11	<.11
Chloride, milligram per liter	<.08	<.08
Fluoride, milligram per liter	<.16	<.16
Silica, milligram per liter	<.48	<.48
Aluminum, microgram per liter	<1	6.3
Antimony, microgram per liter	<.048	<.048
Arsenic, microgram per liter	<.18	<.18
Barium, microgram per liter	<1	<1
Boron, microgram per liter	<13	<13
Iron, microgram per liter	<10	<10
Strontium, microgram per liter	<.8	<.8
Zinc, microgram per liter	<1	5.1

Roderick F. Ortiz—BASELINE CHARACTERIZATION OF WATER QUALITY AND MASS LOADING IN PICEANCE CREEK, RIO BLANCO COUNTY, COLORADO, DECEMBER 2000

USGS/WRIR 02-4134