Streambed Infiltration and Ground-Water Flow From the Trout Creek Drainage, an Intermittent Tributary to the Humboldt River, North-Central Nevada

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Abstract

Ground water is abundant in many alluvial basins of the Basin and Range Physiographic Province of the western United States. Water enters these basins by infiltration along intermittent and ephemeral channels, which originate in the mountainous regions before crossing alluvial fans and piedmont alluvial plains. Water also enters the basins as subsurface ground-water flow directly from the mountains, where infiltrated precipitation recharges water-bearing rocks and sediments at these higher elevations. Trout Creek, a typical intermittent stream in the Middle Humboldt River Basin in north-central Nevada, was chosen to develop methods of estimating and characterizing streambed infiltration and ground-water recharge in mountainous terrains. Trout Creek has a drainage area of about 4.8×10^7 square meters. Stream gradients range from more than 1×10^{-1} meter per meter in the mountains to 5×10^{-3} meter per meter at the foot of the piedmont alluvial plain. Trout Creek is perennial in short reaches upstream of a northeast-southwest trending normal fault, where perennial springs discharge to the channel. Downstream from the fault, the water table drops below the base of the channel and the stream becomes intermittent.

Snowmelt generates streamflow during March and April, when streamflow extends onto the piedmont alluvial plain for several weeks in most years. Rates of streambed infiltration become highest in the lowest reaches, at the foot of the piedmont alluvial plain. The marked increases in infiltration are attributed to increases in streambed permeability together with decreases in channel-bed armoring, the latter which increases the effective area of the channel. Large quartzite cobbles cover the streambed in the upper reaches of the stream and are absent in the lowest reach. Such changes in channel deposits are common where alluvial fans join piedmont alluvial plains. Poorly sorted coarse and fine sediments are deposited near the head of the fan, while finer-grained but better sorted gravels and sands are deposited near the foot.

All flow in Trout Creek is lost to infiltration in the upper and middle reaches of the channel during years of normal to below-normal precipitation. During years of above-normal precipitation, streamflow extends beyond the piedmont alluvial plain to the lower reaches of the channel, where high rates of infiltration result in rapid stream loss. The frequency and duration of streambed infiltration is sufficient to maintain high water contents and low chloride concentrations, compared with interchannel areas, to depths of at least 6 m beneath the channel. Streamflow, streambed infiltration, and unsaturated-zone thickness are all highly variable along intermittent streams, resulting in recharge that is highly variable as well.

Average annual ground-water recharge in the mountainous part of the Trout Creek drainage upstream of Marigold Mine was estimated on the basis of chloride balance to be 5.2×10^5 cubic meters. Combined with an average annual surface runoff exiting the mountains of 3.4×10^5 cubic meters, the total annual volume of inflow to alluvial-basin sediments from the mountainous part of the Trout Creek is 8.6×10^5 cubic meters, assuming that all runoff infiltrates the stream channel. This equates to about 7 percent of average annual precipitation, which is about the same percentage estimated for ground-water recharge using the original Maxey-Eakin method.

Introduction

Nevada is the driest state in the nation, receiving an average of 230 mm (9 inches) of precipitation annually (Houghton and others, 1975, p. 4). Most of Nevada is in the Great Basin, an area of the Basin and Range Physiographic Province where streams have no connection to the ocean (Eakin and others, 1976). Water is an important but limited resource that is used for a variety of purposes. Traditionally, most of the water was used for agricultural purposes on the valley lowlands. Agricultural water use predominantly involved diverting streamflows for the production of native grass and alfalfa, and pumping ground water from alluvial aquifers for irrigation, also principally of alfalfa. Recently, the rapidly increasing population, development of electric power plants, and expansion of gold-mining operations have placed additional and sometimes conflicting demands on water resources.

Estimating the quantity of water that enters the alluvial aquifers from adjacent mountains is important in assessing the water resources in the Middle Humboldt River Basin. Most of the streams that enter the basin are intermittent and flow from the mountains across large piedmont alluvial plains during periods of snowmelt (fig. 1). Piedmont alluvial plains are formed when several alluvial fans coalesce to form one large plain between the mountain front and valley floor. The distribution of recharge along these streams and the amounts of ground-water flow across the mountain front is largely unknown. Trout Creek was selected for study as a typical intermittent stream in the Middle Humboldt River Basin (fig. 2). Trout Creek is intermittent over most of its reach, but perennial where mountain springs discharge directly into the channel at higher elevations.

Purpose and Scope

The purpose of Trout Creek study was to determine the frequency, duration, and quantity of runoff and streambed infiltration from a mountain drainage that crosses a piedmont alluvial plain, and to estimate the quantity of ground-water recharge originating at various elevations of the drainage. This recharge provides subsurface flow from the mountainous part of the drainage into the adjacent alluvial basin. The scope of the study included obtaining data on streamflow, channel characteristics, geology, ground water, and precipitation, as well as developing a numerical model to simulate streamflow and streambed infiltration on the piedmont alluvial plain. Data were collected from May 1999 through October 2002.

Description of Trout Creek Drainage

Location and Drainage Area

Trout Creek drains the northwest flank of Battle Mountain near the town of Valmy, about 25 km west of the town of Battle Mountain in north-central Nevada (fig. 1). Trout Creek generally parallels Cottonwood Creek, which is immediately to the west (fig. 2). The drainage area of Trout Creek at its entrance to the Humboldt River floodplain is about 4.8×10^7 m^2 (fig. 2). North Peak of Battle Mountain is the highest point in the drainage, with an elevation of about 2,600 m above sea level. The elevation of the entrance to the Humboldt River floodplain is about 1,360 m above sea level. Stream gradients range from more than 1×10^{-1} m/m in the mountains to 5×10^{-3} m/m near the foot of the piedmont alluvial plain.

The channel of Trout Creek near Marigold Mine was relocated prior to 1999. The channel was moved westward around the mine to accommodate expansion (John Barber, Glamis Marigold Mining Company, Valmy, Nev., written commun., 2003). Originally, the stream passed through a narrow opening in Paleozoic-age rock before flowing northward onto the piedmont alluvial plain (Roberts, 1964). The original channel was incised less than a meter throughout the piedmont alluvial plain. The new channel was excavated across a narrow divide and onto the piedmont alluvial plain. The new channel reenters its original channel about 2 km downstream from Marigold Mine (fig. 2). Further downstream, the channel has been altered beneath Interstate 80 where concrete culverts are used to route streamflow beneath the highway. The channel was broadened and straightened downstream of Interstate 80 to where it passes beneath the adjacent railroad tracks. The natural stream channel continues northward until it reaches the floodplain of the Humboldt River where the channel braids into many small channels on the heavily vegetated floodplain of the Humboldt River.

Trout Creek was divided into six reaches for purposes of analysis—three mountain reaches and three piedmont alluvial plain reaches (fig. 2). Reaches in each group are designated as upper, middle, and lower.

Climate

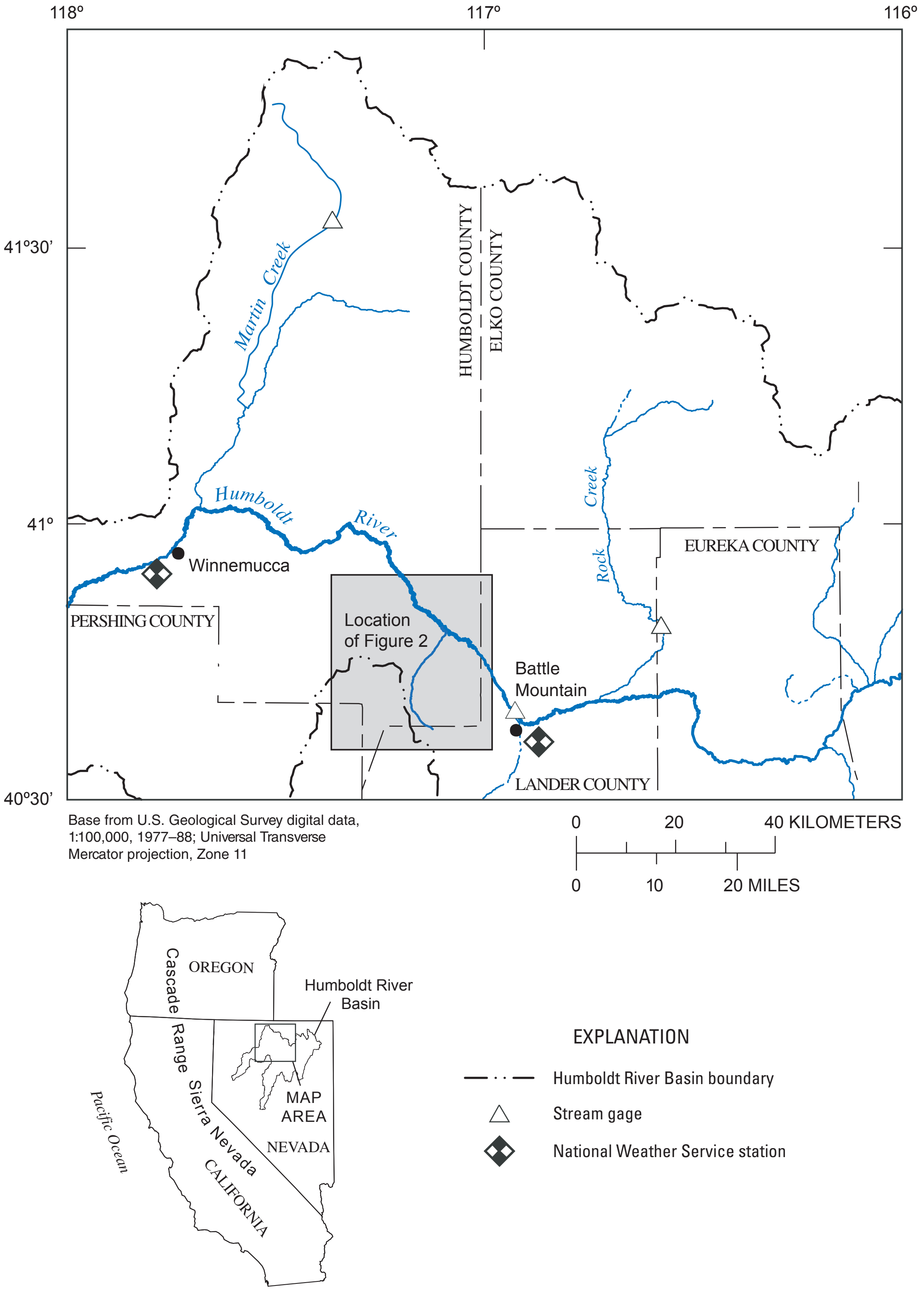
The climate of the Trout Creek drainage is typical of much of Middle Humboldt River Basin. Houghton and others (1975, p. 3) classified the study area as mid-latitude steppe, which is semi-arid with cold winters and hot summers. The climate is semi-arid because much of the moisture from the prevailing westerly winds from the Pacific Ocean condenses on the western slopes of the Sierra Nevada and Cascade Range in California and Oregon (Houghton and others, 1975) prior to reaching northern Nevada (fig. 1). Additionally, the mountain ranges within northern Nevada have a similar orographic effect on local climate whereby the mountains receive, on average, more precipitation than the adjacent valleys (chapter A, this volume).

Temperature

The mean annual temperature at the nearest long-term weather station (in the town of Battle Mountain, about 20 km east of Marigold Mine) was 10.3°C for the period 1971–2000. Monthly means ranged from –1.2°C in December and January to 23.1°C in July (fig. 3; U.S. Department of Commerce, 2003). The highest temperature recorded at Battle Mountain was 44.4 °C on July 12, 2002, whereas lowest temperature recorded was –39.4°C on December 22, 1990. A daily range of more than 20 °C is not uncommon. The large daily range in temperature is typical of dry continental-type climates in mountainous areas (Houghton and others, 1975, p. 26).

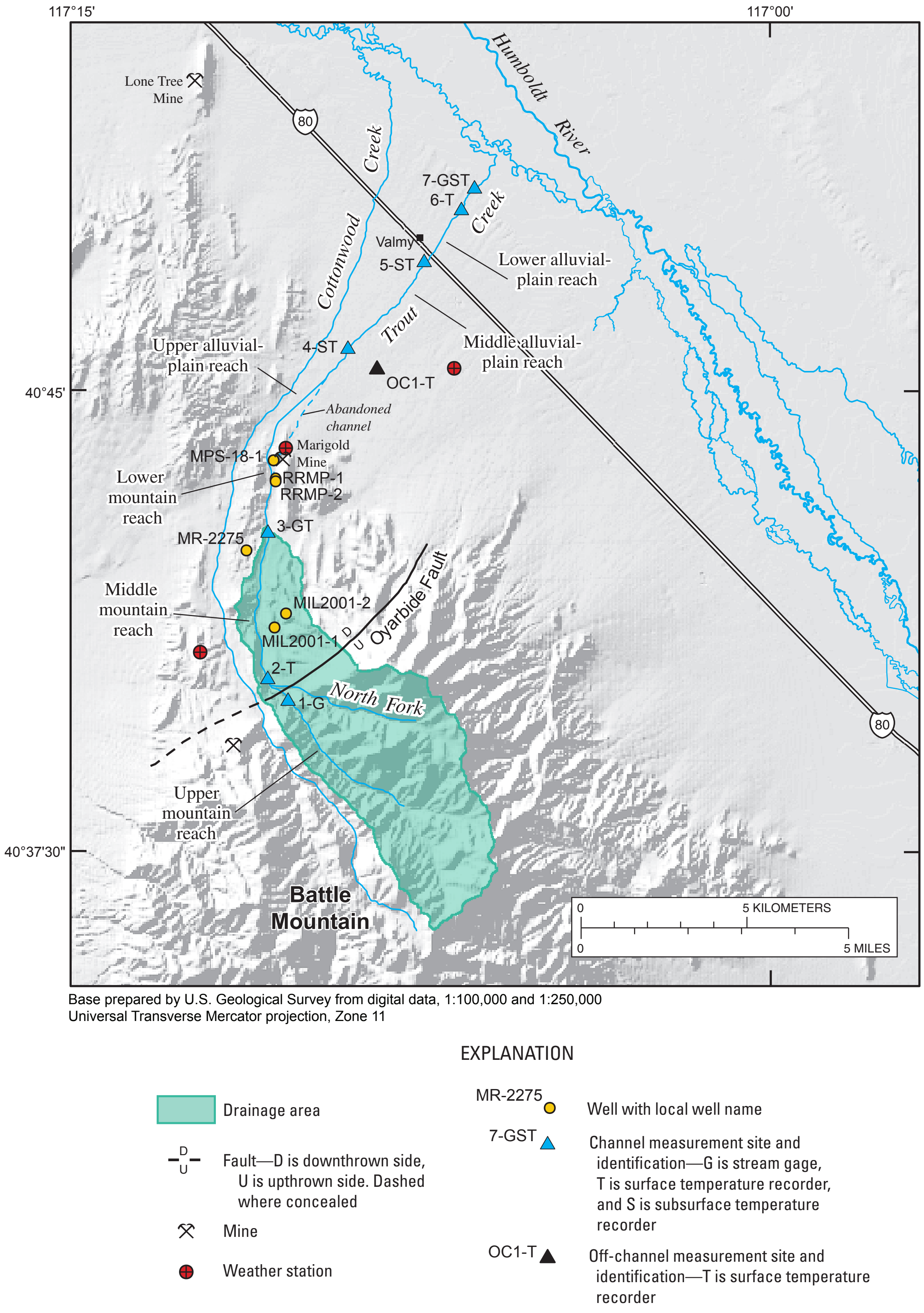
Precipitation

The mean annual precipitation at the town of Battle Mountain was 223 mm for the 30-year period 1971–2000 (U.S. Department of Commerce, 2003). Mean monthly precipitation ranged from a low of 7.1 mm in July to a high of 33 mm in May (fig. 3). Precipitation is generally less in the valleys than in the adjacent mountains. Mean annual precipitation in the Trout Creek drainage ranges from about 200 mm along the Humboldt River floodplain north of Marigold Mine



Base from U.S. Geological Survey digital data, 1:100,000, 1977–88; Universal Transverse Mercator projection, Zone 11

Figure 1. General features, selected stream gages and precipitation stations, and location of Trout Creek study area in north-central Nevada.



Base prepared by U.S. Geological Survey from digital data, 1:100,000 and 1:250,000
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Figure 2. General features, drainage area, active mines, channel measurement sites, selected wells, and precipitation stations in vicinity of Trout Creek, north-central Nevada (modified from Prudic and others, 2003). Location of figure 2 is shown in figure 1. Reaches along the piedmont alluvial plain are abbreviated to alluvial-plain reach.

to about 350 mm in the highest parts of Battle Mountain (Daly and others, 1994). Precipitation usually accumulates as snow in the mountains or as increased soil moisture in the valleys because much of the precipitation falls during the winter months when temperatures are near or below freezing and evapotranspiration is at a minimum. Snow accumulation in the valleys may remain for a few days to weeks, but snow usually accumulates in the mountains until March when daily temperatures increase above freezing. Precipitation ranges from zero on most days to more than 50 mm on rare occasions.

Annual precipitation at the Marigold Mine during water years 2000 through 2002 was consistently less than that at the weather station in Battle Mountain (station Battle Mountain4SE, Western Climate Center, 2003) but greater than that at Winnemucca (station Winnemucca WSO Airport, Western Climate Center, 2003; fig. 4). Monthly precipitation at Marigold Mine, however, was sometimes more and sometimes less than that at the weather stations. Precipitation at the Marigold Mine ranged from 232 mm in water year 2000 to 167 mm in water year 2002 (John Barber, Glamis Gold Mining Company, Valmy, Nev., written commun., 2003). Precipitation during water year 2000 was slightly above normal to normal on the basis of comparing the 30-year mean annual from 1971–2000 with precipitation during water year 2000 at Battle Mountain and Winnemucca (115 and 100 percent, respectively). Precipitation during water years 2001 and 2002 was below normal (89 and 81 percent at Battle Mountain; and 62 and 75 percent at Winnemucca, respectively). In contrast, precipitation during water year 1998 was 414 mm or 186 percent of the 30-year mean annual precipitation at Battle Mountain and 367 mm or 173 percent at Winnemucca.

Vegetation and Evapotranspiration

The mid-latitude steppe climate in Nevada has sufficient precipitation to support a cover of big sagebrush (*Artemisia tridentate*) and a variety of grasses in the valleys and dwarf pinyon (*Pinus monophylla*), juniper trees (*Juniperus osteosperm*) and grasses in the mountains (Houghton and others, 1975, p. 69). This same pattern occurs in the Trout Creek drainage (fig. 5). Dwarf pinyons and junipers are present at the higher elevations on Battle Mountain (fig. 5*A*) and give way to sagebrush and grasses on the lower slopes and on the piedmont alluvial plain that extends to the Humboldt River floodplain (fig. 5*B*). Depth to ground water is less than 15 m along the Humboldt

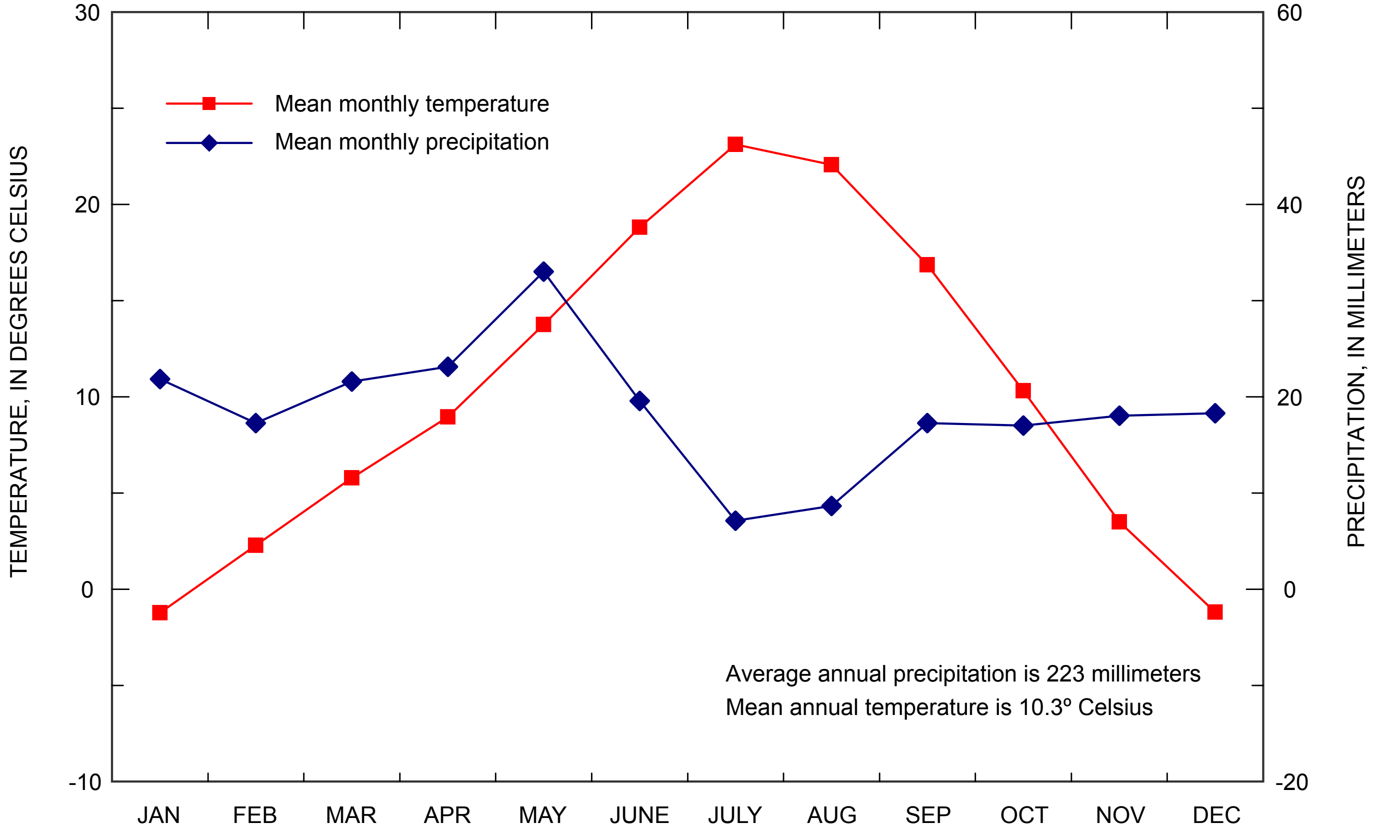


Figure 3. Mean monthly temperature and precipitation at National Weather Service Cooperative Network station Battle Mountain4SE, north-central Nevada. Location of weather station near Battle Mountain is shown in figure 1. Data are from U.S. Department of Commerce (2003).

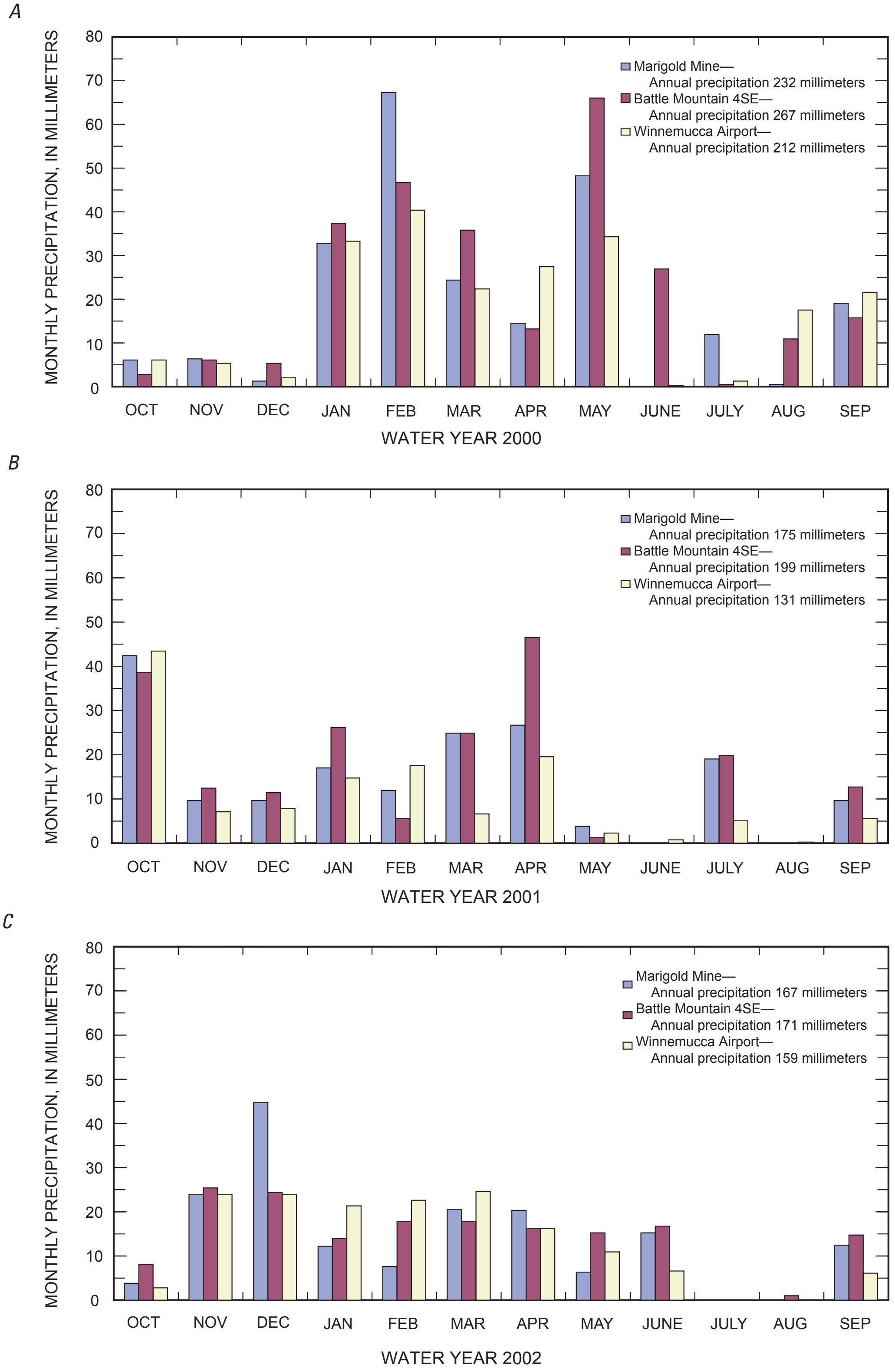


Figure 4. Comparison of monthly precipitation at Marigold Mine (John Barber, Glamis Gold Mining Company, Valmy, Nevada, written commun., 2003) with monthly precipitation at National Weather Service Cooperative Network stations near Battle Mountain and Winnemucca, Nevada for water years 2000–2002. Location of weather stations is shown in figures 1 and 2. Data for National Weather Service Cooperative Network stations are from Western Regional Climate Center (2003).

River floodplain and helps support a different plant community that consists primarily of greasewood (*Sarcobatus vermiculatus*), shadscale (*Atriplex canescens*), and rabbitbrush (*Chrysothamnus nauseosus*) along with native grasses. Various types of Willows (*Salix sp.*) are common along the active and abandoned channels of the Humboldt River. Similarly, various types of willows, chokecherry (*Prunus virginiana var. demissa*), and mountain alder (*Alnus incana sp. Tenuifolia*) are present along Trout Creek at the higher elevations on Battle Mountain (fig. 5*A*), particularly near springs where water is more prevalent.

Geology

Geology in the Trout Creek drainage is an important factor in controlling runoff to the piedmont alluvial plain and ground-water flow from the mountain into the alluvial basin. The upper mountain reach of the Trout Creek drainage (including its major tributary North Fork) is underlain by Paleozoic-age rocks that have been extensively folded and faulted (Roberts, 1964). The rocks generally have low permeability except where highly fractured (table 1). Consequently, infiltration of precipitation is limited to areas where the rocks are highly fractured or where alluvium overlies the rocks.

Both Trout Creek and its major tributary North Fork cross the northeast-southwest trending normal fault (named the Oyarbide Fault by Roberts, 1964; fig. 6) near their confluence and continue over a thin layer of younger alluvium (too thin to show on fig. 6) that covers older alluvium and Tertiary-age volcanic rocks (fig. 6, table 1). The volcanic rocks were described by Roberts (1964, p. A64) as a sequence of volcanic welded tuff and pyroclastic rocks as much as 40-m thick that extend across the drainage divide with Cottonwood Creek and are overlain by older alluvium. Springs discharge at the base of the welded tuff and pyroclastic rocks that are in contact with older alluvium just downstream of the confluence with North Fork (fig. 6).

The older alluvium is part of an alluvial fan that was deposited over a long period that probably extended through much of the Pleistocene (Roberts, 1964). The channel continues over a thin layer of younger alluvium deposited by streams that began to cut downward into the older alluvium near the end of the Pleistocene. The older alluvium near the confluence of Trout Creek with North Fork consists of layers of unsorted coarse and fine gravels in a sandy and clayey matrix that represent interlayered mudflows and fluvial deposits (Roberts, 1964, p. A50). The older alluvium beneath the channel downstream of its confluence with North Fork is generally less than 20-m thick (fig. 7).

Both younger and older alluvium are divided into two groups, alluvial-fan and valley-floor deposits (fig. 7). Although younger alluvial-fan deposits extend to the Oyarbide Fault, they are too thin to show on figure 7. Neither the younger nor older alluvial deposits are shown upstream of the fault because only a thin veneer of younger alluvium associated with the stream overlies the Paleozoic-age rocks. The older alluvial fan-deposits beneath the channel are relatively thin (about 20-m thick) upstream of the Marigold mine (fig. 7). There alluvial-fan deposits begin to thicken until they merge with floodplain deposits associated with the Humboldt River. The thickness of the younger alluvial-fan deposits is poorly constrained in the Trout Creek area but probably does not exceed 30 m on the basis of work by Cohen (1963), who found that younger alluvium (ranging from Holocene to Pleistocene age Lake Lahontan deposits) generally less than 30-m thick elsewhere in the Humboldt River floodplain.

Ground Water

Springs near the channel upstream of the Oyarbide Fault result in short perennial reaches along Trout Creek. These springs likely result from numerous localized ground-water flow systems created during the extensive folding and faulting of the rocks. Ground-water flow is generally restricted by the Oyarbide Fault as evidenced by the fact that water levels in test holes south of the fault (higher in the mountain) in the adjacent Cottonwood Creek drainage are much higher than in wells north of the fault (lower in the mountain) in the Cottonwood Creek and Trout Creek drainages. Water levels in monitoring wells north of Oyarbide Fault are far below the elevation of the stream channel, within the Paleozoic-age rocks (fig. 7). Springs that discharge at the base of welded tuffs and pyroclastic rocks downstream of the fault likely form as a result of flow through the volcanic rocks. Some of the water that discharges from the springs may originate in adjacent Cottonwood Creek, as the welded-tuff and pyroclastic-rock units both straddle the drainage between the two streams.

The water table is located in Paleozoic-age rocks until about 6 km downstream of Marigold Mine, where the deep alluvium becomes saturated and the water table is about 50 m below the channel (fig. 7). Depth to ground water gradually decreases to less than 15 m where Trout Creek enters the Humboldt River floodplain. Dewatering of the Lone Tree Mine northwest of Trout Creek (fig. 2), which began in 1992, has lowered the water table beneath Trout Creek by about 20 m at Marigold Mine (as of 2002; fig. 7).

Streamflow and Streambed-Infiltration Rates

Extent and Duration of Streamflow

Trout Creek is generally an intermittent stream. It is perennial only for short reaches where springs discharge into the channel in the upper mountain reach upstream of Oyarbide Fault. The extent and duration of streamflow was determined using stream gages and streambed temperatures.

A. Trout Creek at confluence with North Fork; view is to south

D.E. PRUDIC, U.S. GEOLOGICAL SURVEY

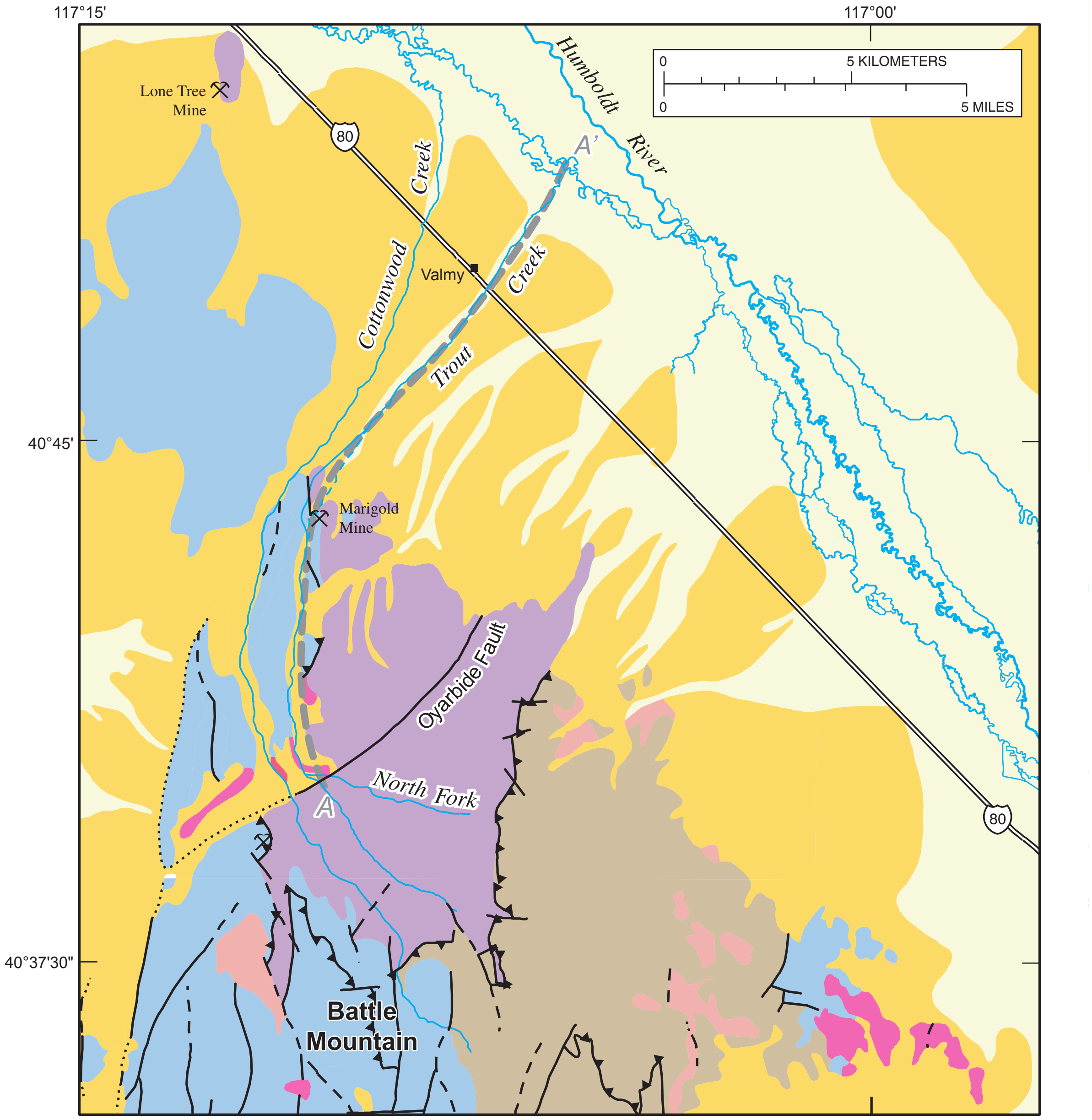
B. Trout Creek on piedmont alluvial plain below Marigold Mine; view is to north

J.L. WOOD, U.S. GEOLOGICAL SURVEY

Figure 5. Typical vegetation along Trout Creek drainage *A,* in the mountains near site 2-T where North Fork joins Trout Creek, and *B*, on piedmont alluvial plain at site 4-ST below Marigold Mine. Locations of sites 2-T and 4-ST are shown in figure 2.

Table 1. Generalized description of geologic units and hydrologic characteristics in vicinity of Trout Creek drainage, north-central Nevada.

	Age	Geologic unit	General hydrologic characteristics
Cenozoic	Quaternary	Qya – Younger alluvium, primarily valley alluvium and stream deposits. Sand and gravel deposits are interbedded with fine-grained deposits.	Sand and gravel aquifers readily yield water to wells.
	Quaternary	Ooa – Older alluvium, primarily alluvial-fan deposits, also includes some upland alluvial deposits and bench deposits. Upper parts of alluvial-fan deposits are incised. Deposits are typically poorly sorted with sand, gravel and small boulders being mixed with fine-grained materials on the upper alluvial-fans. Deposits become finer grained and better sorted on middle and lower parts of the fans. Older alluvium also underlies younger alluvium on valley floor (Cohen, 1963)	Sand and gravel deposits yield water to wells.
	Quaternary	Qtb – Basalt and olivine basalt lava flows, cinder cones, and shallow dikes.	May transmit water through fractures and interflow zones.
	Tertiary	Twt – Welded tuff and pyroclastics.	Welded tuffs have little primary porosity but may transmit water where jointed and fractured.
Cenozoic/ Mesozoic	Tertiary and Cretaceous	TKg – Granodiorite, includes all quartz bearing pre-late-Tertiary intrusive rocks.	Acts primarily as a confining unit but may transmit some water through fractures.
Paleozoic	Pennsylvanian and Permian	PPah – Antler and Havallah Sequences. Consists of Battle Formation, Middle Pennsylvanian conglomerate, minor sandstone, shale, and limestone; Antler Peak Limestone, Upper Pennsylvanian limestone and shaley limestone; and Edna Mountain Formation, Upper Permain calcareous sandstone with conglomerate and limestone. Havallah Formation, Middle Pennsylvanian and Lower Permain; shale, sandstone (or quartzite), chert, limestone, and conglomerate and Pumpernickel Formation, Pennsylvanian (?) chert, shale, and greenstone	May transmit some water if highly fractured.
	Ordovician	Ov – Valmy Formation, dark gray, black, green, and red chert, vitreous quartzite, and subordinate greenstone pillow lavas and shale.	Primarily acts as a confining unit but may transmit some water through fractures.
	Cambrian	Chsc – Consists of Harmony Formation, micaceous sandstone, arkose, shale, and subordinate calcareous shale and limestone; and Scott Canyon Formation, chert, shale, and argillite, subordinate greenstone flows, pillow lavas and pyroclastic rocks.	Primarily acts as a confining unit but may transmit some water through fractures.



Base prepared by U.S. Geological Survey from digital data, 1:100,000 and 1:250,000. Universal Transverse Mercator projection, Zone 11

Geology from Willden (1964) and Stewart and McKee (1977)

EXPLANATION

Geology

- ⬜ Quaternary younger alluvium
- 🟨 Quaternary older alluvium
- 🟥 Tertiary volcanic rocks
- 🟧 Tertiary intrusive rocks
- 🟦 Pennsylvanian and Permian rocks
- 🟪 Ordovician rocks
- 🟫 Cambrian rocks

A ▬ ▬ A' Geologic profile shown in figure 7

Faults

- ······· Concealed
- – – – Inferred
- —— Normal
- ▲—▲ Thrust

⚒ Mine

Figure 6. Geology in the vicinity of Trout Creek drainage, north-central Nevada. Geology modified from Willden (1964) and Stewart and McKee (1977).

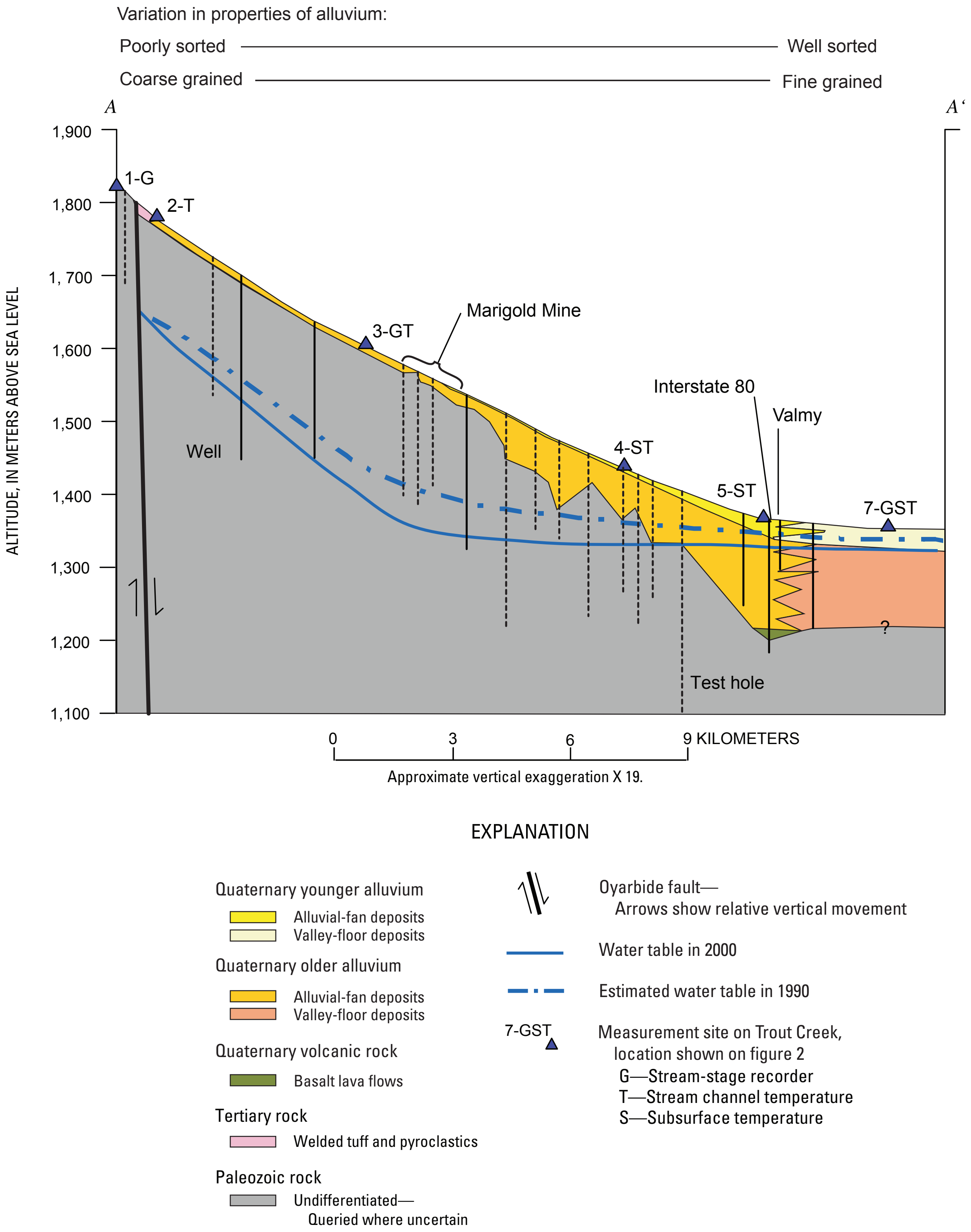


Figure 7. Geologic profile along Trout Creek, north-central Nevada (modified from Prudic and others, 2003). Geologic information is from test holes and wells drilled near Trout Creek (Glamis Gold Mining Company, Valmy, Nev., written commun., 2002 and Nevada State Engineers Office, Carson City, Nev., written commun., 2002). Water-level data are from Glamis Gold Mining Company, Nevada State Engineers Office, Newmont Mining Corporation (Winnemucca, Nev., written commun., 2002), and U.S. Geological Survey. Location of profile is shown in figure 6.

Stream Gages

A stream gage was installed at site 1-G (fig. 2) in October 1999 by Newmont Mining Corporation. Additional gages were installed as part of this project at sites 3-GT and 7-GST in March 2000 and November 1999, respectively (fig. 2). The stream gage at site 1-G was operated and maintained by personnel from Newmont Mining Corporation. Stream gages at sites 3-GT and 7-GST were operated and maintained by USGS personnel. Stage was measured every 15 minutes at site 1-G and every 30 minutes at sites 3-GT and 7-GST, using recording pressure transducers. Relationships between stage and discharge were determined on the basis of periodic discharge measurements at sites 1-G and 3-GST. A square-notch weir was installed at site 7-GST, but no streamflow was recorded at the site from November 1999 through October 2002, although streamflow had been observed at the site in April and May 1999.

Streamflow from October 1999 through September 2002 was intermittent at sites 1-G and 3-GT, with more-persistent flows at site 1-G (fig. 8). Streamflow duration at both sites was less in 2001 and 2002 as compared with 2000 because of lower than normal precipitation. Peak discharges at site 3-GT during 2000 and 2002 lagged behind the corresponding peak discharges at site 1-G such that the daily mean discharge at site 3-GT occasionally exceeded that at site 1-G. The occasional higher discharges at site 3-GT could result from intermittent flow in North Fork and from increased discharge from springs at the base of the volcanic rocks near the confluence of Trout Creek with North Fork.

The estimated annual volume of runoff at site 1-G was 5.5×10^5 m^3, 1.3×10^5 m^3, and 1.8×10^5 m^3 for water years 2000–2002, respectively. These estimated volumes are approximate because the relation between stage and discharge is poor. The estimated volume of runoff from site 3-GT was 2.1×10^5 m^3 and 1.2×10^5 m^3 for water years 2000 and 2002, respectively. No estimate of runoff was made for water year 2001 because the recording pressure transducer failed during much of the runoff period. The smaller runoff at site 3-GT compared to site 1-G is caused by streambed infiltration downstream of the fault, particularly during low-flow periods when spring discharge upstream of site 1-G maintained streamflow at the gage that was insufficient to reach site 3-GT. During low-flow periods, discharge at the spring near site 2-T was reduced to a small seep.

Streambed Temperature as Indicator of Streamflow

Streambed temperatures were used to estimate the duration of streamflow at selected locations on Trout Creek including four locations that were not instrumented with pressure transducers. Self-contained temperature loggers (Stonestrom and Blasch, 2003, p. 75) were placed at seven sites, one of which was outside the channel for reference (fig. 2). The intent of the temperature loggers was to inexpensively obtain additional information on the duration of flow along Trout Creek. Initially, temperature loggers were placed in polyvinyl chloride (PVC) housings directly on the streambed. This resulted in excessive heating during the summer. Subsequently, in March 2000, temperature loggers were buried about 7 cm below the channel or land surface.

Although streambed temperatures were generally reliable in estimating the onset of flow along Trout Creek, it was not always easy to estimate the cessation of flow. Considerable interpretation was needed to estimate the duration of streamflow from streambed temperatures alone (Prudic and others 2003). The analysis was complicated by the changing character of the temperature offset (streambed temperature minus flowing-water temperature) at the onset of flow, which generally was continuous, compared to the cessation of flow, which involved daily periods of intermittent streamflow.

An analysis of streambed temperatures at the onset of flow in March 2000 at site 3-GT was compared with available pressure-transducer data and with streambed temperature at site 2-T, where flow was continuous during the periods of intermittent flow at site 3-GT (fig. 9*A*). Minimum nightly temperatures at site 3-GT during mid-March routinely dropped below freezing, whereas the temperature of the streambed in a reach at site 2-T (upstream from 3-GT) remained above freezing. If flowing water was in the channel at site 3-GT, minimum temperatures during mid-March would also have been at or above freezing. Minimum temperatures at site 3-GT became constant at 0 °C during the early morning hours of March 22, 2000, marking the onset of flow. Once flow began, minimum temperatures at site 3-GT generally mimicked those at the upstream site 2-T. Freezing conditions in the channel during the early morning hours on March 30 and 31, 2000 were accompanied by large apparent increases in stream stage recorded by the pressure transducer installed on March 29, 2000. The large apparent increases in stream stage were an artifact of water freezing in the instrument and do not reflect streamflow (fig. 9*A*).

The minimum streambed temperatures at site 3-GT were higher than at site 2-T prior to the onset flow on April 3, 2001 at site 3-GT (fig. 9*B*), which differs from the lower minimum temperatures prior to flow in March 2000. A marked increase in stream stage was recorded at 10:30 a.m. Pacific Standard Time (PST) on April 3, 2001 during a period of above freezing temperatures. Streamflow continued until early afternoon on April 3, 2001 when the stream stage at the transducer decreased to zero. Negative pressures developed as water evaporated from the protective screen. This pattern of intermittent flow was repeated daily until April 7, 2001 when the water temperature dropped to 0 °C. High pressures caused by freezing water in the transducer caused it to fail. Minimum temperatures at site 3-GT became lower than those at site 2-T after the onset of intermittent flow and continued to be lower until April 16, 2001 when the pattern of minimum temperatures mimicked those at site 2-T. Flow was continuous after April 16. When flow became continuous is not precisely known.

The cessation of streamflow at site 3-GT was also difficult to assess from temperature data alone because of daily periods of intermittent streamflow. Streamflow at site 3-GT became intermittent in the afternoon of June 4, 2000 as indicated by the pressure transducer readings, which resulted in a slight deflection in the temperature profile (fig. 10*A*). However, the minimum temperatures during these periods of no streamflow remained similar to those at site 2-T because of residual moisture in the sediments following the period of daily streamflow. The onset of flow on June 5, 2000 also resulted in a slight increase in temperature during the morning hours, although it is not as pronounced as when flow ceased. The slight changes in temperature associated with the onset and cessation of flow on the basis of the pressure transducer readings from June 4 through June 6, 2000 were used to evaluate intermittent flow from June 7 to June 17, 2000 (fig. 10*B*) during the period without data from the pressure transducer. The onset of flow in the morning generally resulted in a subtle increase in the streambed temperature whereas the cessation of flow generally resulted in a marked decrease in the slope of the streambed temperature. Although the precise timing of intermittent flow each day is uncertain, streambed temperatures suggest that intermittent flow continued daily through June 13. Afterwards the streambed dried sufficiently that minimum temperatures at site 3-GT were consistently higher than those at site 2-T, where flow was continuous.

Duration of streamflow also was estimated at three locations using nested thermocouple wires placed at 5 depths between 10 and 150 cm beneath the channel (sites 4-ST, 5-ST, and 7-GST; fig. 2; Prudic and others, 2003). Temperatures from the thermocouple wires were measured every 30 minutes using dataloggers. During streamflow, heat in the stream is advected downward as water infiltrates into the stream channel. Streamflow in Trout Creek reached site 4-ST in April 2000 and again in April 2002, based on subsurface temperatures. No streamflow was observed throughout the study at sites 5-ST or 7-GST. Streambed temperatures generally showed a consistent diurnal pattern in maximum and minimum temperatures prior to the onset of streamflow at site 4-ST on April 9, 2000 (fig. 11*A*), whereas temperatures began to fluctuate in response to temperature in the stream after the onset of streamflow.

Although all temperatures in the subsurface beneath site 4-ST responded to periods of streamflow, temperatures

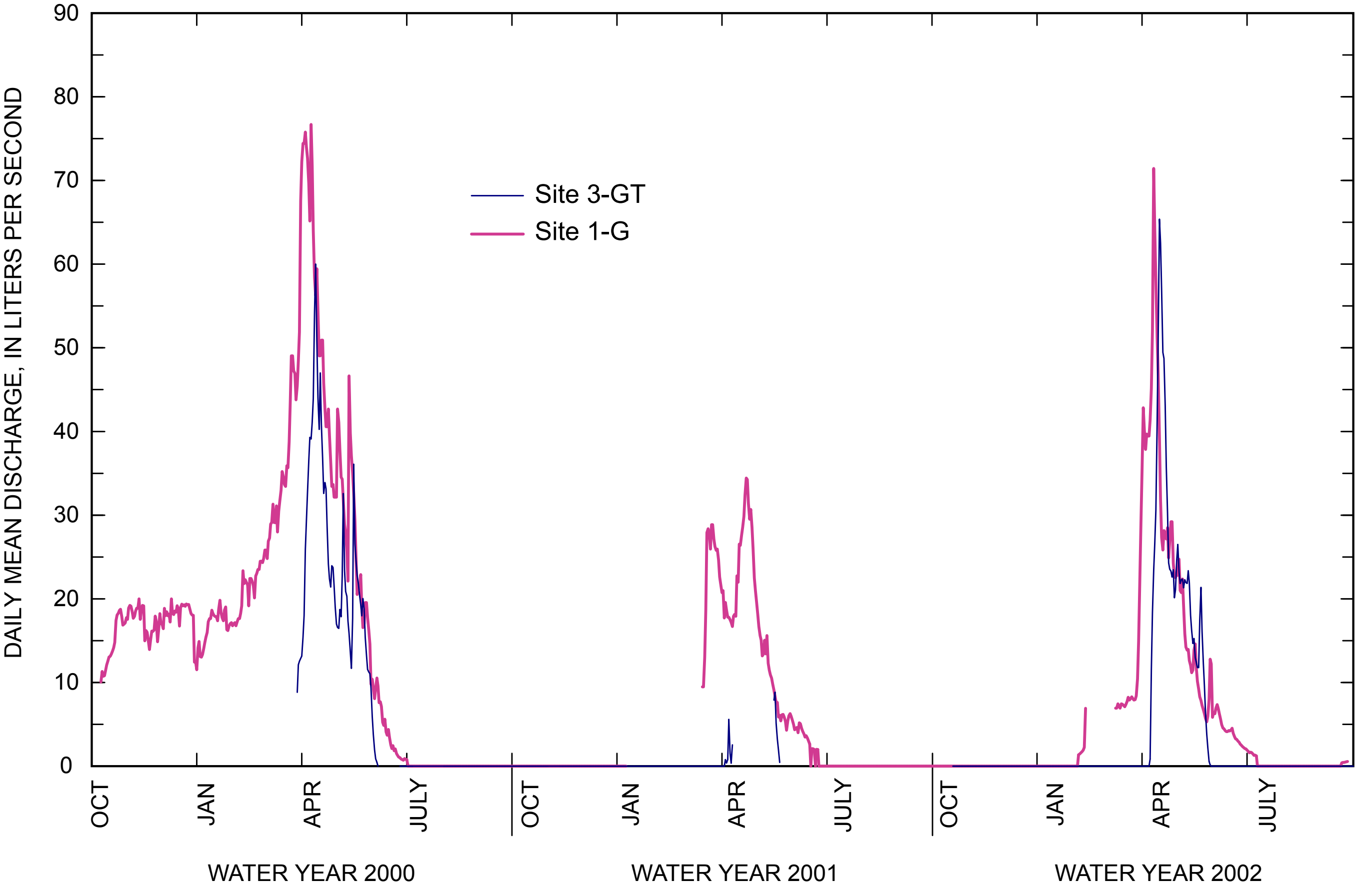


Figure 8. Daily mean discharge at sites 1-G and 3-GT on Trout Creek during water years 2000 through 2002. Daily mean discharge estimated from pressure measurements recorded every 15 minutes at site 1-G and every 30 minutes at 3-GT. Data at site 1-G is from Newmont Mining Corporation (Winnemucca, NV, written commun., 2002). Location of sites is shown in figure 2.

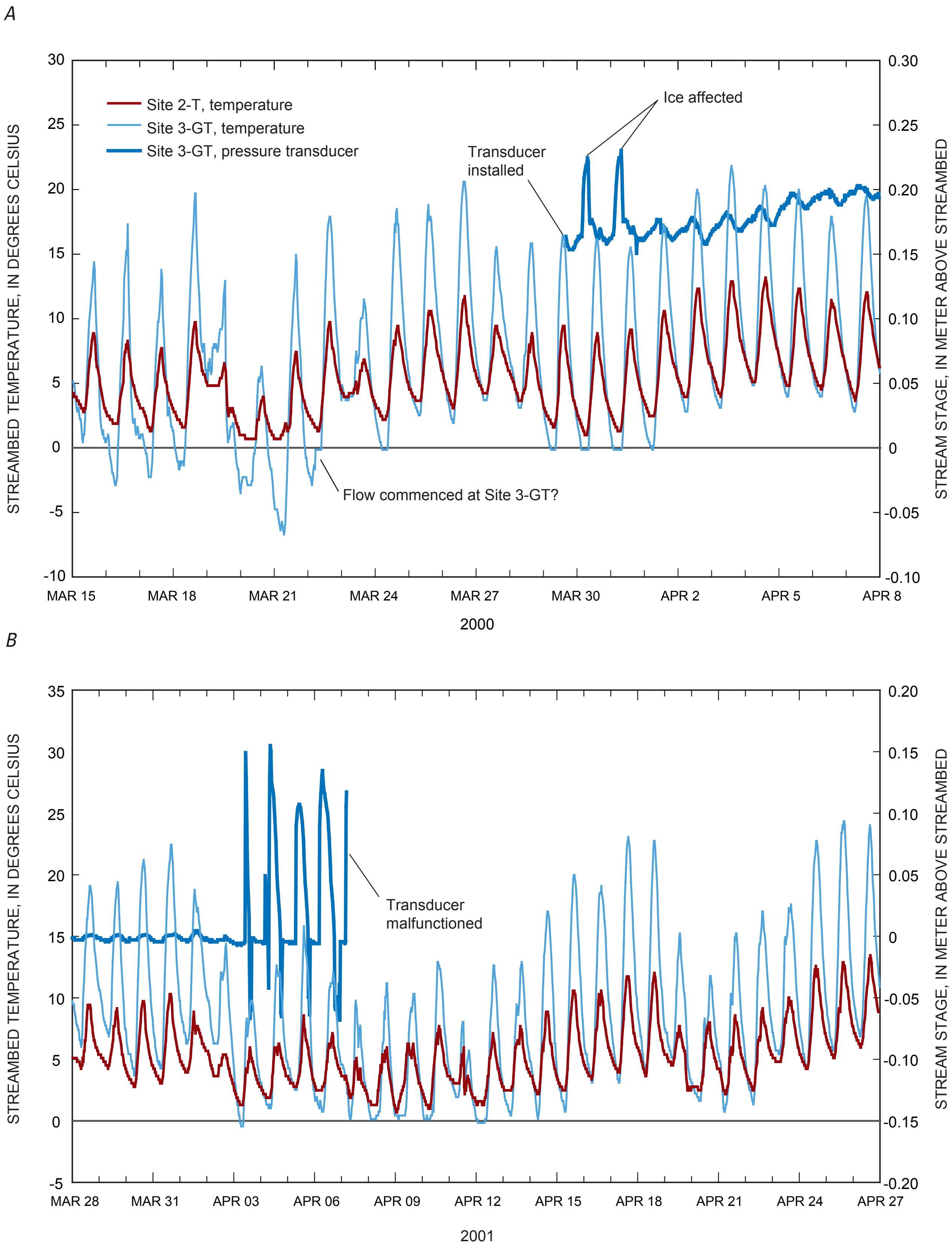


Figure 9. Commencement of streamflow at site 3-GT evaluated using stream stage measured by a pressure transducer and streambed temperatures at sites 2-T and 3-GT in *A*, March 2000 and *B*, April 2001. Location of sites 2-T and 3-GT is shown in figure 2.

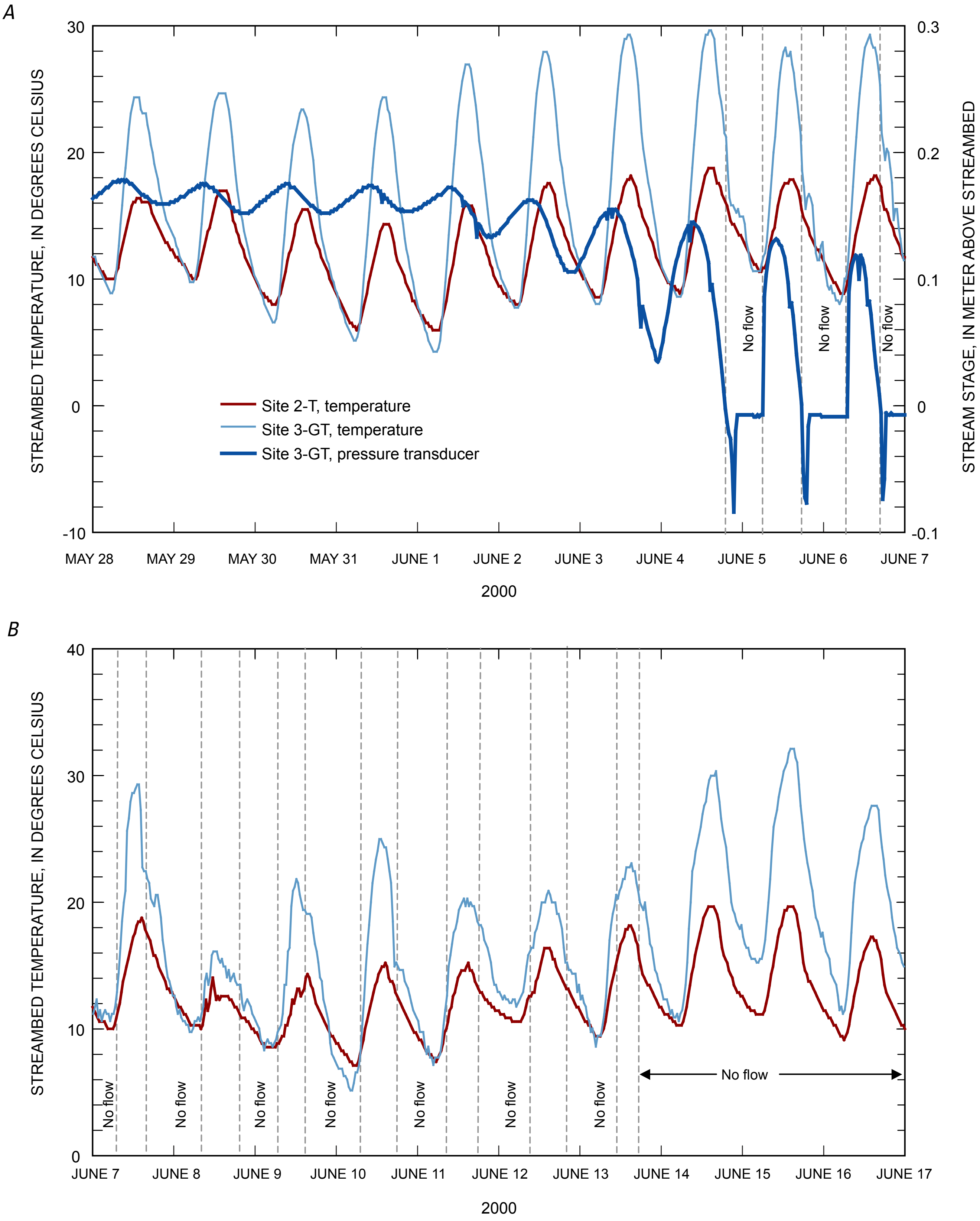


Figure 10. Cessation of streamflow at site 3-GT evaluated using *A*, streambed temperature at sites 2-T and 3-GT and stream stage from pressure transducer at site 3-GT during first week of June 2000, and *B*, estimates of periods of no flow from streambed temperature during second week of June 2000. Location of sites 2-T and 3-GT is shown in figure 2.

between depths of 20 and 138 cm were used to assess general periods of intermittent or discontinuous flow in the channel because changes in air temperature (caused by clouds and rain) affected the response of the shallowest thermocouple. When flow became intermittent is uncertain because gravity drainage continued through the sediments after flow ceased in the channel. However, diurnal fluctuations at depths of 100 and 138 cm decreased noticeably after April 27, 2000, suggesting streambed infiltration had ceased prior to this date. Temperature fluctuations increased again on May 1, which may indicate intermittent streamflow on that date.

The duration of streamflow was also estimated at site 4-ST from subsurface temperatures for 2002. The subsurface temperature data in 2002 were affected by the heating of the data logger inside of its shelter, which caused the temperature readings to have an additional, but spurious, diurnal signal at all depths due to the transient offset between the temperature of the wiring panel and the data-logger's internal thermocouple reference temperature (Stonestrom and Blasch, 2003, p. 77-79). The signal was removed by fitting polynomial equations to the temperature at a depth of 138 cm during the early morning hours (4:30 to 6:30 PST), when temperatures were near their minimums. The removal of the natural diurnal signal at the depth of 138 cm also removed the diurnal signal at the 100 m depth but did not greatly affect the diurnal signals at the shallower depths (fig. 11*B*). The overall effect of removing the signal from heating of the datalogger inside its shelter was to reduce the sensitivity of the subsurface temperature to changes in stream temperatures. Thus, the data in 2002 was used only to estimate the duration of flow.

Streamflow began April 14 and continued until April 23 on the basis of sudden decreases in the surface and subsurface temperatures. Another brief period from May 1 to May 3 may have been a period of intermittent streamflow. Estimating brief periods of discontinuous streamflow or the exact moment when streamflow in the channel ceases entirely is difficult using subsurface temperature profiles because drainage through the sediments beneath the streambed continues for some time after streamflow ceases.

No streamflow was observed at sites 5-ST, 6-T, and 7-GST during water years 2000–2002. However, streamflow was observed and measured along the entire channel during May 1999. Streamflow extended past site 7-GST during an initial reconnaissance on April 28, 1999. Discharge measurements were made along the channel from site 2-T to 7-GST on May 12, 1999, and self-contained temperature loggers were placed in the channel on May 13, 1999. Streamflow remained continuous at the uppermost temperature site (2-T) from May to October 1999, but further downstream, streamflow was intermittent at sites 3-GT, 4-ST, 5-ST, 6-T, and 7-GST.

The minimum-daily streambed temperatures at all sites generally followed the same pattern as that at site 2-T during May 1999, although the minimum-daily temperature increased downstream. This pattern continued until June 11, 1999 when the minimum-daily temperature at site 7-GST began to deviate markedly from the minimum-daily temperature of the upstream sites, and was followed by similar deviations at sites 6-T, 5-ST, 4-ST, and 3-GT. The deviation of the minimum-daily temperature was used to indicate when flow ceased at each site (fig. 12). The rapid rate of retreat of streamflow between sites 7-GST and 5-ST, in about 2 days, as compared with the rate between sites 5-ST and 4-ST and between sites 4-ST and 3-GT (both in about 8 days) suggests that streambed-infiltration rates are higher downstream of site 5-ST (Interstate 80). The more rapid retreat downstream of site 5-ST also is consistent with a marked increase in streambed infiltration rates estimated from discharge measurements on May 12, 1999, as discussed in the following section. Estimates of the duration of streamflow at the different sites are summarized in table 2. The duration of streamflow lasted longer at sites 1-G and 2-T than further downstream.

Streambed-Infiltration rates

Streambed-infiltration rates were estimated by subtracting discharge measurements between selected reaches of the channel and from subsurface temperatures at site 4-ST. Discharge measurements were made at all sites on May 12, 1999; at sites 2-T, 3-GT, and 4-ST on April 13, 2000; and at sites 3-GT and 4-ST on April 19, 2000 and May 11, 2000. Measurements of streamflow during 2001 and 2002 were limited to sites 1-G, 2-T, and 3-GT because streamflow was insufficient to reach the lower sites.

Estimates From Discharge Measurements

Discharge measurements for May 12, 1999, and April 13, April 19, and May 11, 2000 are plotted in relation to the distance downstream of site 1-G (fig. 13). The discharge measurements that were made on May 12, 1999 were during a period when there had been sustained flow in the channel for at least 2 weeks prior to the measurement and flow continued along the channel for several weeks following the measurement (table 2). Similarly, flow commenced at site 3-GT on March 22, 2000 and from the pressure transducer, flow peaked near the discharge measurement on April 13, 2000, and declined through the measurements on April 19, and May 11, 2000.

Discharge measurements for May 12, 1999 show a slight increase in streamflow between site 2-T and site 3-GT because of tributary inflow from North Fork of Trout Creek and from a spring immediately downstream of site 2-T. Stream discharge decreases proportionately with distance downstream of site 3-GT for all dates until site 5-ST. Discharge decreased dramatically downstream of site 5-ST on May 12, 1999, indicating a substantial increase in the streambed-infiltration rate at the foot of the piedmont alluvial plain. Estimated uncertainty in the discharge measurements are about 5 percent for measured discharges exceeding 100 L/s, 8 percent for discharges between 50 and 100 L/s and 10 percent for discharges less than 50 L/s.

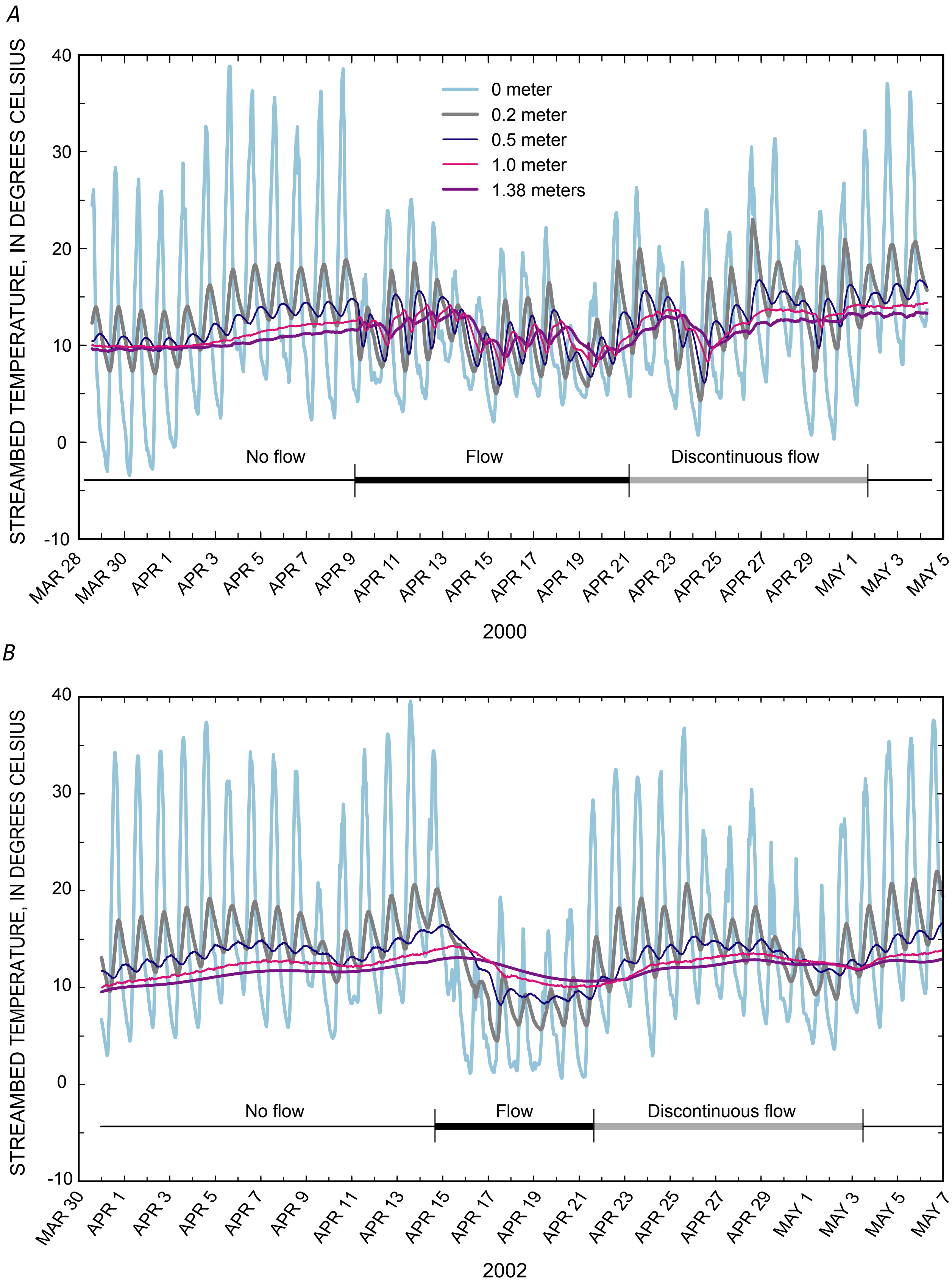


Figure 11. Streamflow duration estimated from subsurface temperatures beneath streambed at site 4-ST for *A*, April-May 2000 and *B*, April-May 2002. Location of site 4-ST is shown in figure 2.

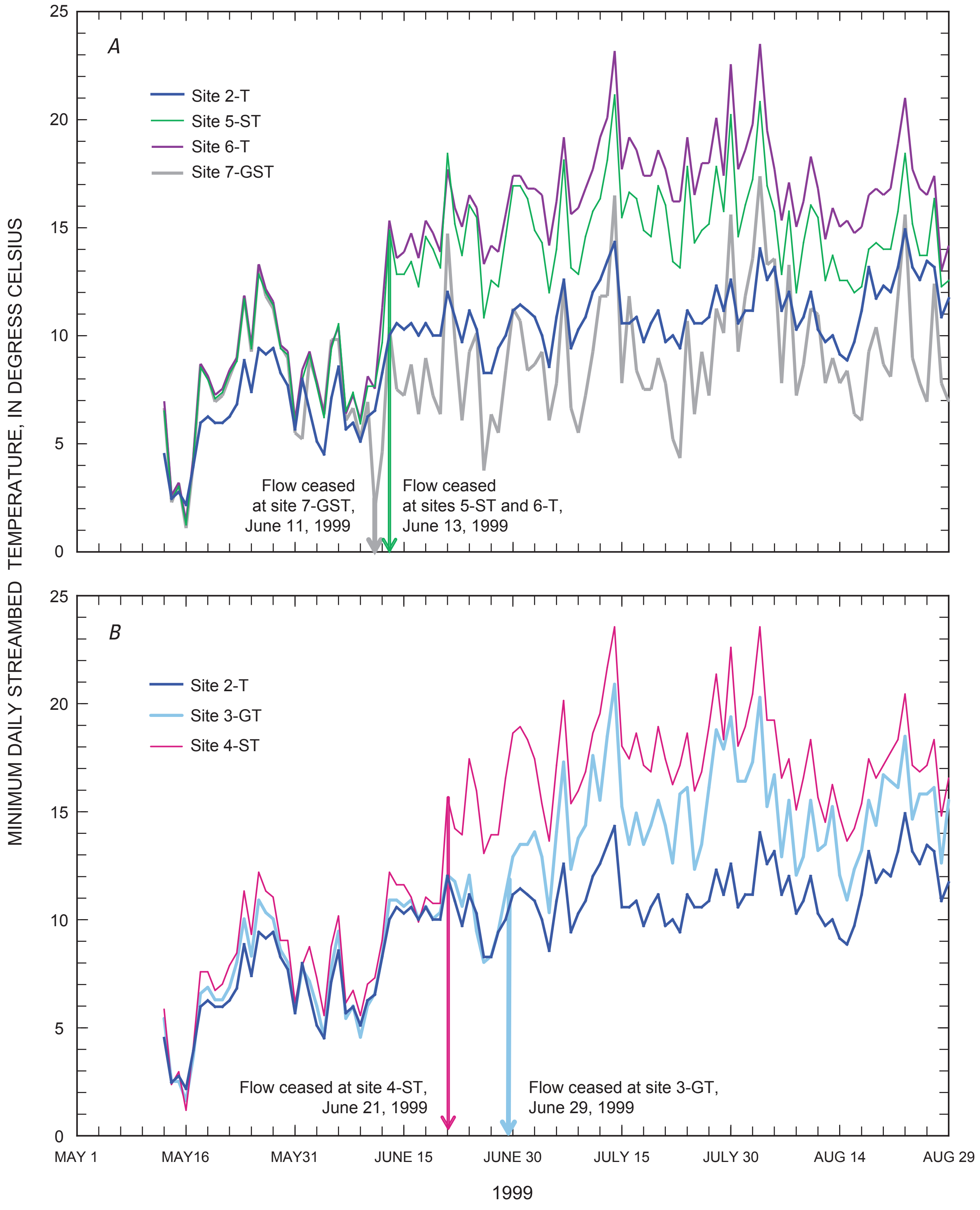


Figure 12. Estimates of flow cessation along Trout Creek between sites 2-T and 7-GST from May 13, 1999 to August 29, 1999 determined from daily minimum streambed temperatures. Flow was continuous at site 2-T through September 30, 1999. Self-contained temperature loggers in Trout Creek were placed on streambed in polyvinyl chloride (PVC) housing attached to a cable secured to a metal stake. Location of sites is shown in figure 2.

Table 2. Estimates of streamflow duration at selected locations along Trout Creek from May 1999 to October 2002, north-central Nevada.

[Site locations are shown in figure 2. Letters following site numbers denote: G, recording pressure transducer (stream gage); T, surface-temperature logger; S, subsurface-temperature logger. Other abbreviations: <, less than; (?), uncertain. Flow durations may include brief periods of intermittent flow]

Sites	Water Year			
	(1) 1999	(2) 2000	(3) 2001	(4) 2002
1-G	(?)	Oct. 1 – July 7	Mar. 20 – June 29	Sept. 30 – July 12
2-T	<Apr. 28 – Sept. 30	Oct. 1 – July 20(?)	Mar. 20 – June 27	(?) – July 10
3-GT	<Apr. 28 – June 29	Mar. 22 – June 14	Apr. 5 – May 23	Apr. 7 – May 29
4-ST	<Apr. 28 – June 21	Apr. 9 – May 19	No flow	Apr. 14 – Apr. 23 May 1 – May 3
5-ST	<Apr. 28 – June 13	No flow	No flow	No flow
6-T	<Apr. 28 – June 13	No flow	No flow	No flow
7-GST	<Apr. 28 – June 11	No flow	No flow	No flow

[1] Duration for water year 1999 was compiled from an initial reconnaissance on April 28 and from minimum daily temperatures from surface-temperature loggers installed May 13.

[2] Pressure transducer at 1-G installed October 13, 1999, by Newmont Mining Corporation. Flow duration during October 1–October 13 was estimated from surface-temperature logger at site 2-T. Although flow ceased at site 1-G on July 7, water remained ponded at gage for several days. End of flow at site 2-T is difficult to determine because streambed at logger was shaded by willows. Flow at site 4-ST was intermittent during the period between April 20 and May 19.

[3] Surface-temperature and subsurface-temperature loggers malfunctioned at site 4-ST during April and May 2001. Neutron-moisture measurements indicate flow did not reach site 4-ST during the period of missing record.

[4] No data from surface-temperature logger at site 2-T from October 1, 2001 to June 4, 2002.

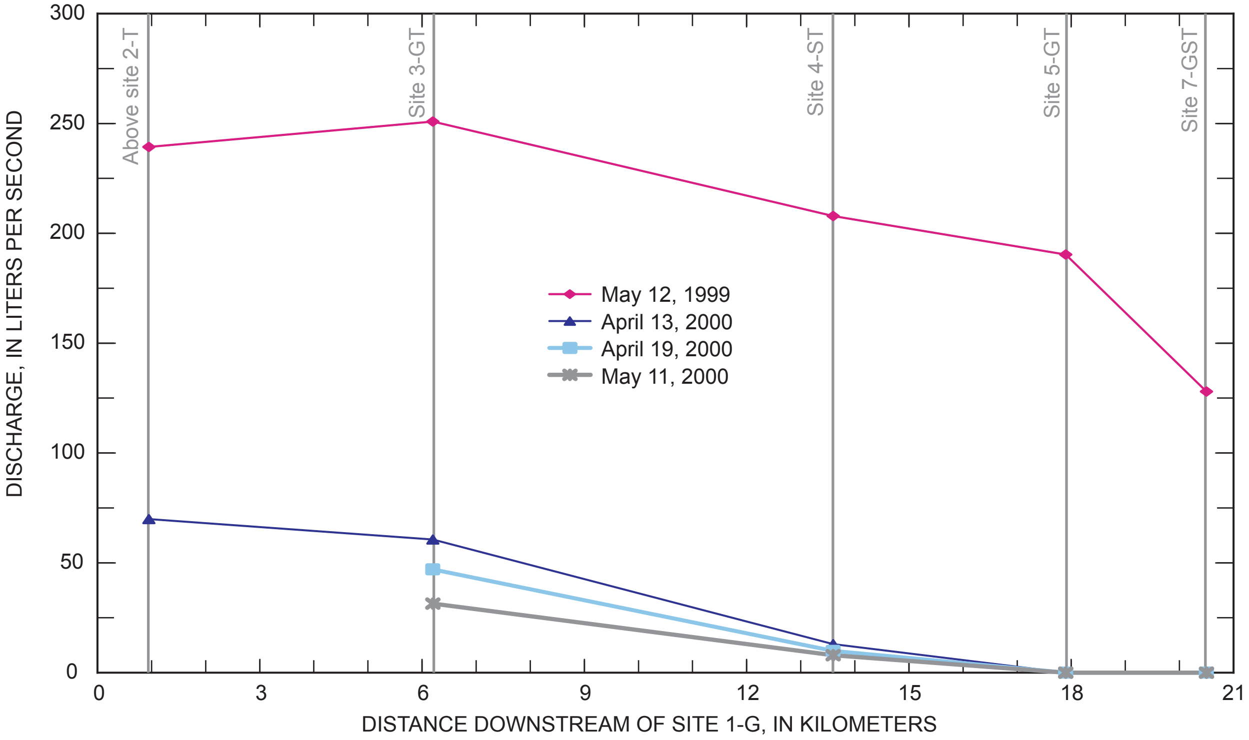


Figure 13. Measured discharge along Trout Creek on May 12, 1999; April 13 and 19, 2000; and May, 11, 2000. Measurements were made between 7:30 a.m. and 12:00 pm on May 12, 1999; 7:00 a.m. and 9:00 a.m. on April 13, 2000; 12:45 pm and 1:45 pm on April 19, 2000; and 10:00 a.m. and 11:30 a.m. on May 11, 2000. All times are Pacific Standard Time and measurements were made starting at upstream site except on May 11, 2000 when measurements started at downstream site. Location of sites is shown in figure 2.

Streambed-infiltration rates (volumetric flow per unit area) were estimated for stream reaches downstream of site 3-GT because of unknown contributions to the channel between sites 2-T and 3-GT. The estimates were made by dividing the measured loss with the streambed area. Streambed area was estimated by multiplying the channel length between sites with the average stream width (table 3). The average stream width was estimated as the average stream width measured at the sites because channel cross sections do not vary greatly between sites 3-GT and 7-GST (Niswonger and others, 2005). Loss rates in percent of flow at the upstream site are summarized in table 3. Although loss rates between sites 3-GT and 5-ST were similar for all dates, the loss rate in percent of flow at the upstream site for May 12, 1999 was less than those for the three measurements made in April and May, 2000 because of the much higher discharges. The percent of flow loss between sites exceeded the estimated uncertainty in discharge measurements except between sites 4-ST and 5-ST on May 12, 1999 where the loss was about the same as the sum of the uncertainty in the two measurements.

The streambed-infiltration rate on May 12, 1999 was estimated between 0.1 and 0.2 m/d upstream of site 5-ST, whereas it increased nearly an order of magnitude to 1.1 m/d downstream. The streambed-infiltration rate between sites 3-GT and 4-ST was about 0.46 m/d on April 13, 2000 near the peak discharge period and decreased to 0.22 m/d on May 11, 2000 (table 3). This decrease in the streambed-infiltration rate may result from errors in the measured discharges, which were estimated to be about 10 percent of the measured discharge or in the estimate of the average stream width. Streambed-infiltration rates can also be affected by the natural diurnal variation in streamflow along the channel, which is more pronounced during periods of less streamflow. Additionally, accumulation of fines on the streambed during flow recession can also reduce infiltration rates (Burkham, 1970). Even though the streambed-infiltration rate estimated on May 11, 2000 was similar to that estimated for May 12, 1999, uncertainty in the streambed-infiltration rates make it difficult to assess if the decrease in rates estimated during 2000 are real or the result of measurement errors.

The much greater streambed-infiltration rate along the lower reach of the piedmont alluvial plain (downstream of site 5-ST) was not initially anticipated because finer-grained sediment is normally deposited after the break in slope on alluvial fans and piedmont alluvial plains, and coarse-grained sediment is normally associated with the upper, steeper parts (Rachocki, 1981). Greater distal streambed-infiltration rates also were observed during the spring of 2004 (Niswonger and others, 2005). Two factors are likely responsible for the increased streambed-infiltration rates in the lower reaches of the channel. First, the streambed along the upper reach of the piedmont alluvial plain is armored with large quartzite cobbles (up to 15 cm in diameter), whereas the lower reach is primarily sand and gravel (up of 2 cm in diameter). The space between the larger cobbles is generally filled with fine-grained materials (sand and silt) through which infiltration occurs. Because the large cobbles are impermeable, the effective area for infiltration is less in the upper reach than in the lower reach. Second, the deposits in the upper reach are less sorted and more heterogeneous than those on the lower reach. Poorly sorted heterogeneous deposits generally have a lower effective hydraulic conductivity than better sorted and more homogeneous deposits. This implies that greater streambed-infiltration rates could occur near the base of the alluvial fans or piedmont alluvial plains in many areas of the desert Southwest.

Estimates From Subsurface Temperature Profiles

Streambed-infiltration rate from subsurface temperature profiles was estimated at site 4-ST on April 13 through April 19, 2000, several days after the commencement of streamflow. Estimates were not made at the other temperature sites 5-ST and 7-GST because no streamflow occurred at these locations. A two-dimensional, variably saturated, water-flow and heat-transport model developed by Healy and Ronan (1996) was used in the analysis, as described in Niswonger (2001) and Niswonger and Prudic (2003). The modeled region included no-flow vertical boundaries located 15 m on either side of the channel, a specified stream depth and temperature within channel, and a constant-elevation water table (zero matric pressure) and temperature (17 °C) at a depth of about 30 m. The bottom boundary conditions were based on measurements in well MPS-18-1 (fig. 2). The lateral boundaries were extended 15 m beyond the channel so as not to inhibit lateral ground-water flow. Thermal and hydraulic properties used in the model are listed in table 4.

Hydraulic conductivity was adjusted until the modeled temperature at depths of 20 and 50 cm approximated the measured temperatures. The best-fit simulation to the measured temperatures at depths of 20 and 50 cm (fig. 14) resulted in the simulated peak arrival times that were consistently earlier than measured, however decreasing the arrival time in the model resulted in a worse fit to the diurnal amplitude. The resultant streambed-infiltration rate was 0.46 m/d and the saturated streambed hydraulic conductivity was 0.56 m/d (Niswonger, 2001; and Prudic and others, 2003). This streambed-infiltration rate is the same as that estimated from discharge measurements on April 13, 2000 (table 3).

Uncertainty in the estimate of the rate of streambed infiltration was analyzed using a Monte Carlo technique (Niswonger and Rupp, 2000). An analysis was done to evaluate the error in sediment thermal properties on the predicted streambed-infiltration rate. Thermal conductivity of the sediment was assumed normally distributed with a mean and standard deviation of 2.3 and 0.63 W/m °C, respectively. The volumetric heat capacity of the dry sediments also was assumed normally distributed with a mean and standard deviation of 2.6×10^6 and 0.21×10^6 J/m^3 °C, respectively. The mean for the volumetric heat capacity differed from the manually calibrated value listed in table 4 because the Monte Carlo technique included the effects of correlation with the thermal conductivity (Niswonger and Rupp, 2000). The standard deviation of

Table 3. Estimates of streambed-infiltration rates from discharge measurements along Trout Creek between May 1999 and May 2000, north-central Nevada.

[Site locations are shown in figure 2. Letters following site numbers denote: G, recording pressure transducer (stream gage); T, surface-temperature logger; S, subsurface-temperature logger. Multiple instruments were deployed at most sites. All values are rounded to two significant figures. Abbreviations: m, meters; L/s, liters per second; %, percent; m^3/m^2 d, cubic meters per square meter per day; —, flow did not reach downstream site]

Selected reach		Channel length, in m	Streamflow loss,		[1] Average channel width, in m	[2] Streambed infiltration rate, in m^3/m^2 d
Upstream site	Downstream site		in L/s	in % of flow		
		May 12, 1999				
3-GT	4-ST	7,400	43	17	2.7	0.19
4-ST	5-ST	4,300	18	8	2.7	0.13
5-ST	7-GST	2,600	62	32	2.0	1.1
		April 13, 2000				
3-GT	4-ST	7,400	47	79	1.2	0.46
4-ST	5-ST	—	13	100	—	—
		April 19, 2000				
3-GT	4-ST	7,400	37	79	1.3	0.33
4-ST	5-ST	—	10	100	—	—
		May 11, 2000				
3-GT	4-ST	7,400	24	75	1.3	0.22
4-ST	5-ST	—	8	100	—	—

[1] Average width for each reach was estimated as the average width of the upstream and downstream measurement site. Channel cross sections vary little between sites 3-GT and 7-GST (Niswonger and others, 2005).

[2] Streambed infiltration rate was estimated first by multiplying the loss (in liters per second) between sites with the product of 1,000 liters per cubic meter and 86,400 seconds per day to obtain cubic meters per day, and then by dividing the loss in cubic meters per day with the product of the channel length and average width to obtain a volumetric streambed infiltration rate per unit area of channel.

Table 4. Unsaturated zone properties used to determine hydraulic conductivity and streambed-infiltration rate from subsurface temperatures at site 4-ST during April 2000 (Niswonger, 2001; and Niswonger and others, 2005).

[Thermal dispersivity assumed analogous to solute dispersivity. Abbreviations: m, meters; J/m^3 °C, joules per cubic meter per degree Celsius; W/m°C, watts per square meter per degree Celsius per meter]

Unsaturated property	Value	Source
van Genuchten/Mualem alpha, in m^{-1}	0.847	Kosugi and others (2002)
van Genuchten/Mualem *n* (dimensionless)	4.8	Kosugi and others (2002)
Residual water content, in m^3/m^3	0.072	Kosugi and others (2002)
Porosity, in m^3/m^3	0.36	Core samples
Dispersivity, in m	0.1	Fetter (1993)
Volumetric heat capacity of dry sediment, in J/m^3 °C	2.0×10^6	Stonestrom and Blasch (2003)
Thermal conductivity of sediment at residual water content, in W/m°C	1.4	Hopmans and Dane (1986)
Thermal conductivity of sediment at saturation, in W/m°C	2.3	Stonestrom and Blasch (2003)

the streambed-infiltration rate converged to a value of 0.12 m/d after 180 realizations. The ninety-five percent confidence interval in the predicted streambed-infiltration rate was ±0.24 m/d or about half the estimated rate.

A similar analysis tested the temperature-measurement error on the predicted streambed-infiltration rate. The normal distribution of temperature error was estimated on the basis of manufacturer specifications and from instrument installation. The mean and standard deviations for the temperature-measurement error were 0 and 0.2 °C, respectively (Niswonger and Rupp, 2000). The ninety-five percent confidence interval in the predicted streambed-infiltration rate was only ±0.07 m/d indicating the greatest error was caused by uncertainty in the sediment thermal properties. These analyses suggest that estimates of streambed-infiltration rates from subsurface temperature profiles may have errors similar in magnitude as those from discharge measurements. Finally, extrapolation of streambed-infiltration rates from subsurface temperature profiles may be difficult where hydraulic conductivity is variable along the channel.

Modeling Streambed Infiltration Along Trout Creek

This section briefly summarizes the development of and results from a numerical model that was used to simulate streamflow losses along Trout Creek from streambed infiltration. Additional details are given in Niswonger (2001) and Niswonger and others (2005). The model was used to estimate the duration of flow and volumes of infiltration along the channel in water years 2000 and 2002. The underlying approach could be used for any stream that is separated from the underlying ground water by an unsaturated zone. The minimum requirements for simulating duration of streamflow and quantity of streambed infiltration with the model include data on: (1) streamflow at the mountain front, (2) channel length and cross sectional areas, (3) streambed-infiltration rates in relation to stream stage, and (4) streambed hydraulic properties.

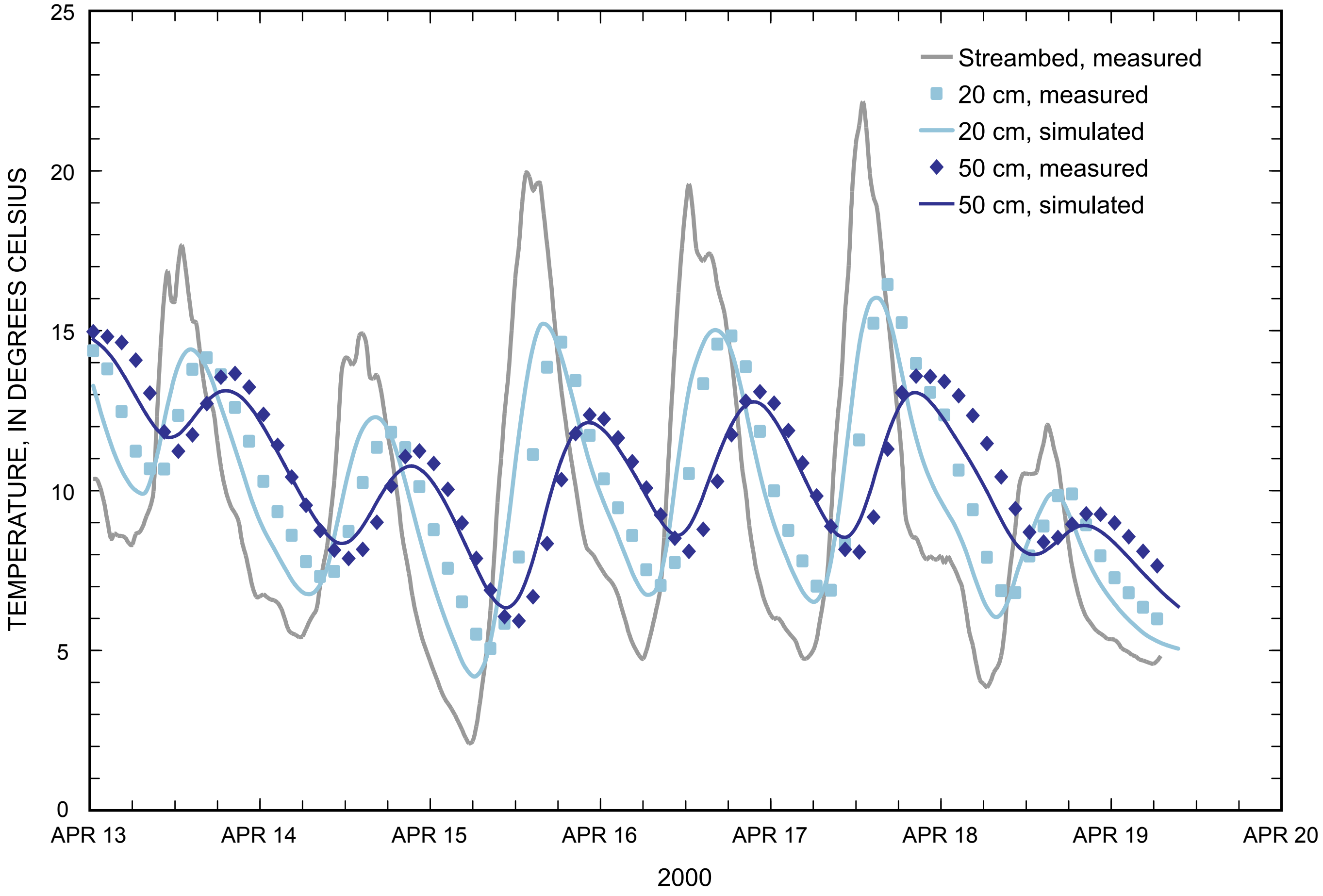


Figure 14. Comparison of simulated to measured temperatures for depths 20 and 50 centimeters beneath Trout Creek at site 4-ST from April 13 to April 20, 2000 (from Prudic and others, 2003). Location of site 4-ST is shown in figure 2.

Description of Model

The numerical model was specifically formulated to treat the case of a stream separated from its underlying aquifer by a thick unsaturated zone, which is typical for most streams that flow across alluvial fans or piedmont alluvial plains in the Middle Humboldt River Basin. The model was used to evaluate the duration and quantity of infiltration along the channel during periods of streamflow.

The model solves the one-dimensional form of the Saint-Venant equations for surface-water flow (Strelkoff, 1970), modifying streamflow to account for infiltration losses into the streambed. The Saint-Venant equations can be written (modified from Chow and others, 1988):

$$\frac{\partial y}{\partial t}+\frac{1}{B}\frac{\partial Q}{\partial x}=0 \ , \qquad (1)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\beta\, Q^2}{A}\right)+g\,A\frac{\partial y}{\partial x}+g\,A\frac{Q|Q|}{S^2}=0\,, \qquad (2)$$

where

y = water-surface elevation, in meters,

t = time, in seconds,

B = channel width at water surface, in meters,

Q = streamflow, in cubic meters per second,

x = distance down the channel, in meters,

β = momentum correction factor, dimensionless,

g = gravity, in meters per second per second,

A = cross-sectional area, in square meters, and

S = stream hydraulic conveyance, in cubic meters per second.

The momentum correction factor, β, is used to correct the overall momentum flux for non-uniform velocity distributions (Strelkoff, 1970). The stream hydraulic conveyance, S, is a composite of stream-geometric parameters—area, roughness, and hydraulic radius—equal to the ratio of stream discharge to square root of friction slope in the Manning equation (Dalrymple and Benson, 1968; see equation 4 for definition).

Spatial derivatives of streamflow, which include losses from streambed infiltration, were estimated using the Preissman four-point finite-difference method (Cunge and others, 1980). The spatial derivative for streamflow in equation 1 was represented as:

$$\frac{1}{B}\frac{\partial Q}{\partial x}=\left\{\frac{\sum\limits_{j\in I_{ju}}Q_j^{k+1}-\sum\limits_{j\in O_{ju}}Q_j^{k+1}}{F_{ju}^{k+1}}+\frac{\sum\limits_{j\in I_{jd}}Q_j^{k+1}-\sum\limits_{j\in O_{jd}}Q_j^{k+1}}{F_{jd}^{k+1}}\right\}\ , \qquad (3)$$

where

$\sum\limits_{j\in I_{ju}}Q_j^{k+1}$ = sum of inflows between midpoints of reach j–1 and reach j,

$\sum\limits_{j\in O_{ju}}Q_j^{k+1}$ = sum of outflows between midpoints of reach j–1 and reach j,

$\sum\limits_{j\in I_{jd}}Q_j^{k+1}$ = sum of inflows between midpoints of reach j and reach j+1,

$\sum\limits_{j\in O_{jd}}Q_j^{k+1}$ = sum of outflows between midpoints of reach j and reach j+1,

F_{ju}^{k+1} = area (plan view) between midpoints of reach j–1 and reach j, and

F_{jd}^{k+1} = area (plan view) between midpoints of reach j and reach j+1.

The sum of all outflows between reach midpoints in equation 3 includes the streambed infiltration.

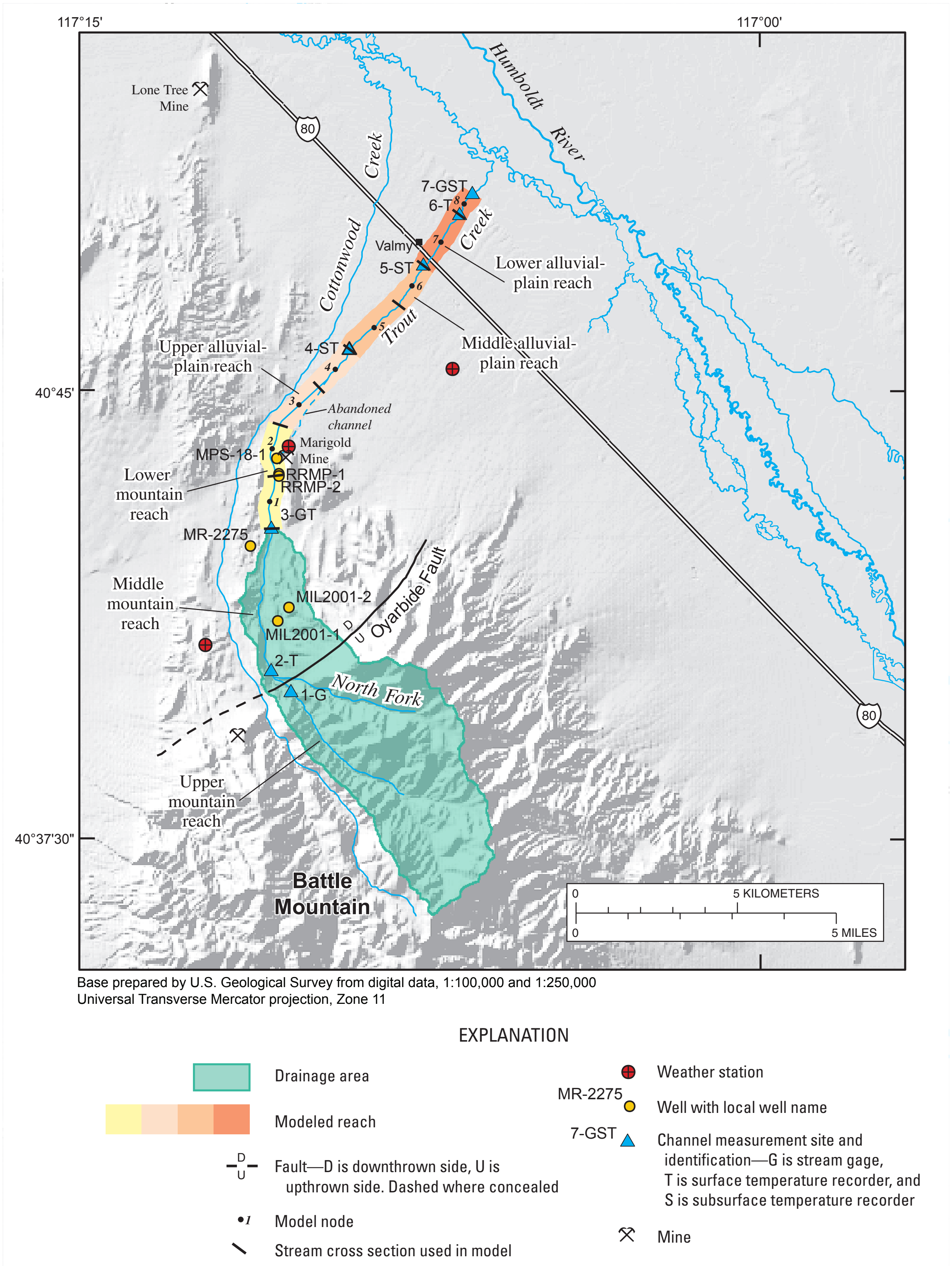
The stream hydraulic conveyance (*S*) in metric form is (Chow and others, 1988):

$$S=\frac{AR^{2/3}}{n}\ , \qquad (4)$$

where R is hydraulic radius (meters), and n is Manning's roughness coefficient (dimensionless). Manning's roughness coefficient was estimated from channel characteristics (Phillips and Ingersoll, 1998). Trout Creek was characterized with a single value of Manning's roughness coefficient equal to 0.03.

Trout Creek was divided into reaches between adjacent cross sections (fig. 15). Streamflow was computed at the midpoint (or node) of each reach, and streambed infiltration was calculated over a reach as a function of stream depth and wetted area of the channel. Irregular stream cross sections were used in the model to account for changes in the channel dimensions along the channel. All model variables dependent on stream depth were determined in the model using tables that relate the value of each variable to stream depth. The system of non-linear algebraic equations resulting from the finite-difference approximations was solved using Newton Raphson and lower-upper (LU) decomposition matrix-solution techniques (Burden and Faires, 1997).

The upstream boundary at site 3-GT was specified as time-variable discharge and stage (depth plus elevation of streambed). During periods of supercritical streamflow, the downstream boundary was not required. During periods of subcritical streamflow, the streambed elevation was assigned to the next cross section downstream of streamflow cessation.



Base prepared by U.S. Geological Survey from digital data, 1:100,000 and 1:250,000
Universal Transverse Mercator projection, Zone 11

Figure 15. Location of cross sections, and modeled nodes and reaches used to simulate streamflow and streambed infiltration along Trout Creek, north-central Nevada (modified from Prudic and others, 2003). Reaches along the piedmont alluvial plain are abbreviated to alluvial-plain reach.

Tables relating streambed infiltration to stream depth were estimated for each of nine cross sections using a variably saturated two-dimensional model (VS2DT; Healy, 1990; locations of cross sections are shown in fig. 15). Streambed infiltration as a function of depth was computed using twenty simulations at each cross section. Stream depth was held constant in each simulation until infiltration across the streambed became approximately constant. Vertical no-flow boundaries at the end of each cross section were extended 15 m on either side of the channel to allow for ground-water flow away from the channel. A zero pressure head was assigned at the water-table elevation. Initial conditions for the unsaturated zone were assigned on the basis of residual water content of 0.07 m^3/m^3 (Niswonger, 2001) estimated from the water content in core samples. Hydraulic conductivity of 0.56 m/d estimated from the subsurface temperature profile at site 4-ST was initially assigned to the unsaturated zone at all cross sections.

Distribution of Streambed Infiltration

The initial simulation assumed a steady discharge at site 3-GT equal to the measured discharge on May 12, 1999. The simulation reproduced the measured stream discharges upstream of site 5-ST but could not reproduce the measured discharges and streambed-infiltration rates between sites 5-ST and 7-GST (lower reach of the piedmont alluvial plain). Thus the hydraulic conductivity for this reach was increased to 1.2 m/d in order to match the measured discharge at site 7-GST. The hydraulic conductivity was only slightly greater than the 1.1 m/d estimated for the streambed-infiltration rate from discharge measurements and average stream widths (table 3). Tables relating streambed infiltration to stream depth for cross sections between sites 5-ST and 7-GST were revised on the basis of the higher estimate of hydraulic conductivity and model results for May 12, 1999 closely matched the measured streamflows (fig. 16). The correlation coefficient of simulated to measured streamflows was 0.98. The distribution of hydraulic conductivities used for the May 12, 1999 simulation was used for the simulation of streamflow from March 31 to April 27, 2000. The simulation of streamflow for April 13, 2000 also closely matched the measured streamflows during the time period that streamflows were measured on that date (fig. 16).

The simulation of May 12, 1999 was further evaluated by comparing simulated and measured stream depth and velocity at each measurement site. Simulated stream depths ranged

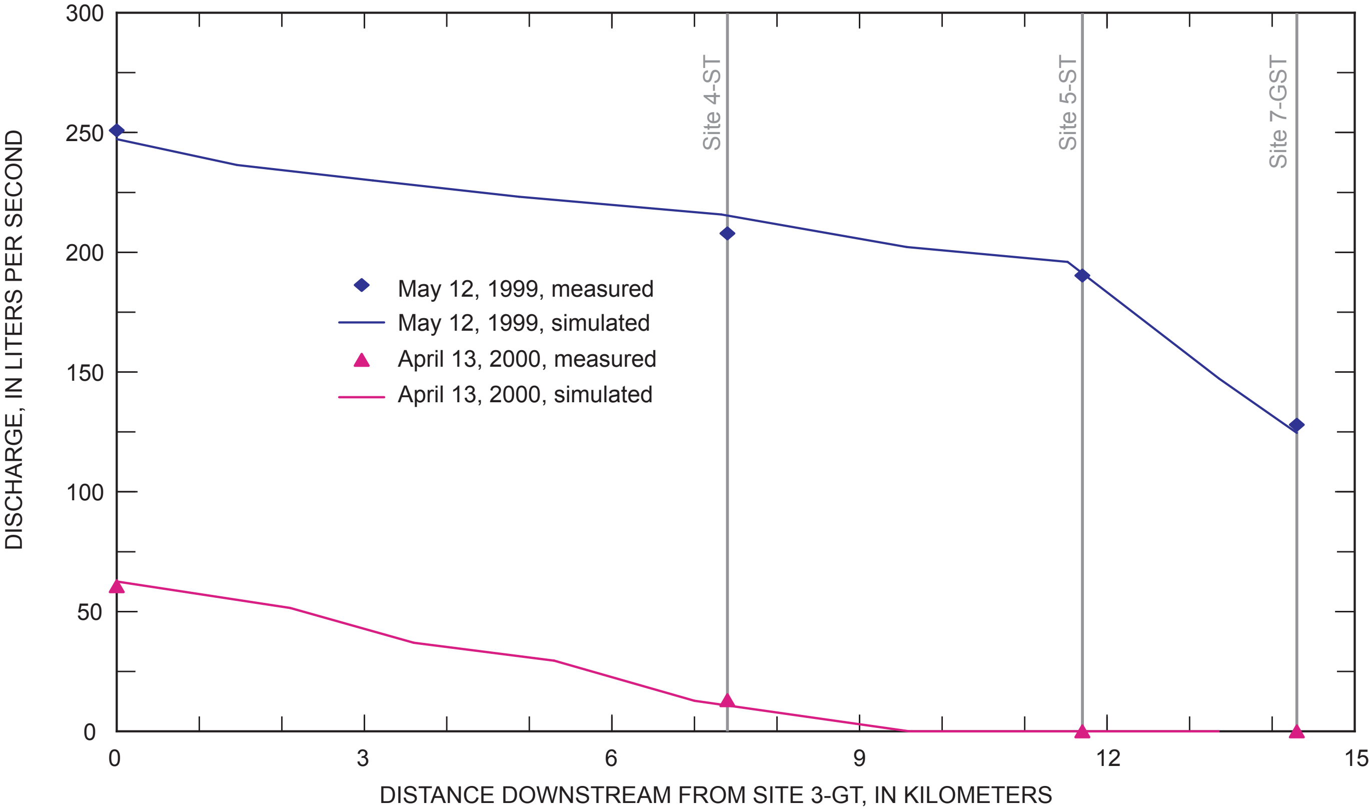


Figure 16. Comparison of simulated with measured discharge along Trout Creek for May 12, 1999 and April 13, 2000 (modified from Prudic and others, 2003). Simulated discharge on each date was calculated at the end of each cross section during the same time period as the measured discharge. Location of measurement sites, cross sections, and model nodes and reaches are shown in figure 15.

from 0.07 to 0.17 m at the nine cross sections (median value was 0.11 m) whereas, measured stream depths ranged from 0.11 to 0.15 m at the four measurement sites (median value was 0.13 m). Simulated stream velocities ranged from 0.57 to 1.3 m/s at the nine cross sections (median value was 0.84 m/s), whereas the measured velocity ranged from 0.52 to 0.80 m/s at the four measurement sites (median value was 0.65 m/s). Matches between simulated and observed depths and velocities are reasonably good given the uncertainties in channel characteristics over the relatively long reaches that were being simulated. No attempt was made to adjust Manning's roughness coefficient or the momentum correction factor (β), the latter which was assigned a value of one. Increasing Manning's roughness coefficient or decreasing the momentum correction factor would have decreased the velocities and increased stream depths in a manner that could have better matched the measured depths and velocities. However, this adjustment also would have resulted in slightly increased streambed-infiltration rates that would have decreased the simulated streamflow.

The simulation of streamflow from March 29 to June 7, 2000 and 2002 approximately matched the observed distribution of streamflow along the channel during both years (fig. 17). Streambed infiltration was limited to the lower mountain and upper and middle reaches of the piedmont alluvial plain, as simulated streamflow did not extend to site 5-ST. The terminus of simulated streamflow was between nodes 5 and 6 during the period of peak flow in 2000 and 2002. The simulated streamflow at node 5, just downstream of site 4-ST, began on April 5 in 2000 and on April 12 in 2002, slightly earlier than indicated by the temperature data at 4-ST (table 2). The model does not account for initially higher infiltration rates caused by capillary pressure gradients when the leading edge of streamflow encounters a dry streambed, which creates a bias towards early arrivals when the streambed moisture content is low. Continuous flow was simulated from April 5 to April 24, 2000 and from April 15 to April 20, 2002, generally replicating the period of continuous flow inferred from the temperature data at site 4-ST.

Diurnal variation in streamflow was observed at site 3-GT and likely results from daily variations in snowmelt. The diurnal variation in streamflow at site 3-GT propagated downstream in a manner that produced a time-varying change in the location of streamflow cessation. Simulated streamflows at different places along the channel profile show this time-dependent migration in the location of streamflow cessation (fig. 17).

The simulation of streamflow down the channel during the period of flow from March 29 through June 7, 2000 and 2002 was used to estimate the cumulative percentage of streambed infiltration for the lower-mountain and upper and middle piedmont alluvial-plain reaches (fig. 18). Total simulated streambed infiltration for the period was 2.0×10^5 and 1.2×10^5 m^3 for water years 2000 and 2002, respectively. Because the simulation period did not include the onset of flow on March 22, 2000, the estimated total streambed infiltration for the water year was slightly lower than the estimated annual runoff (2.1×10^5 m^3). Although the pressure transducer was not installed until March 29, 2000, annual runoff includes an estimate of flow for the period between the onset of flow and March 29, 2000.

The model of unsteady streamflow with infiltration provides a means for estimating cumulative volumes of streambed infiltration and flow durations for different conditions of peak discharge and runoff. Streambed infiltration is limited to the lower mountain section at the onset and cessation of flow each spring, as shown for 2002 at site 3-GT (fig. 18*B*). Cumulative simulated streambed infiltration for a given reach along the channel varies as a function of flow at site 3-GT. Cumulative simulated streambed infiltration for 2000 was initially divided equally between the lower-mountain and upper piedmont alluvial-plain reaches because the model simulation began when the pressure transducer was installed rather than the beginning of flow, as in 2002. Slightly less than half of the cumulative streambed infiltration was simulated along the lower mountain section during 2000, whereas slightly more than half was simulated during 2002, when runoff was less. Modeled cumulative streambed infiltration in the middle piedmont alluvial plain reach gradually increased in both years until streamflow became smaller than streambed losses in the higher reaches.

Streamflow measured at site 3-GT and simulated at model nodes 2–5 for water year 2000 lasted longer than the streamflow at the same locations for water year 2002, even though peak discharges were nearly the same (fig. 19). The difference in flow duration along Trout Creek for water years 2000 and 2002 is reflected in the simulated streamflows shown in figure 19 whereby a longer period of low flow following the peak discharge during spring snowmelt was measured at site 3-GT during 2000 than during 2002. The extended period of runoff measured during the spring of 2000 was in part caused by a single large storm in May that produced 48 mm of precipitation at the Marigold Mine (fig. 4). The difference in May precipitation accounts for much of the difference in annual precipitation between 2000 and 2002 and illustrates the importance of precipitation in winter and spring on the duration of flow in the Trout Creek drainage.

Runoff in 1999 was relatively high. Flow was observed along the entire channel in April and May. On May 11, 1999, streamflow losses measured by sampling cross sections with a hand-held flow meter were higher in the lower reach of the piedmont alluvial plain (5-ST to 7-GST, fig. 16) than those measured upstream, indicating a higher streambed-infiltration rate on the lower alluvial plain. Greater streamflow losses on the lower plain were again observed throughout a series of repeated measurements in March and April of 2004 (Niswonger and others, 2005). About 50 percent of the simulated cumulative streambed infiltration occurred on the lower piedmont alluvial plain (Niswonger and others, 2005). Thus, during years of above-average runoff, as in May 1999 and March and April 2004, a large percentage of streambed infiltration occurs there. Greater streambed infiltration combined with an unsaturated zone that is less than 15-m thick likely results in more rapid recharge than higher on the piedmont alluvial plain where the streambed-infiltration rate is less and the unsaturated zone can exceed 50 m in thickness.

Ground-Water Recharge

The source of ground water in the Trout Creek drainage is probably limited to precipitation that falls within its drainage area. Little ground water can flow into the Trout Creek drainage upstream of Oyarbide Fault from adjacent drainages because the underlying rocks are relatively impermeable and because the land surface drops quickly in all of the surrounding drainages. However, older alluvium, welded tuff and pyroclastic rocks are continuous across the drainage divide between Trout and Cottonwood Creeks just downstream of the Oyarbide Fault (Roberts, 1964, plate 7). Limited data on ground-water levels upstream and downstream of the fault in the Cottonwood drainage, together with the elevation of springs at the base of the volcanic rocks in the Trout Creek drainage, suggest that the springs could represent ground-water discharge from the Cottonwood Creek drainage. Additionally, rocks of the Havallah Sequence (table 1) are exposed along the divide between the two drainages and could

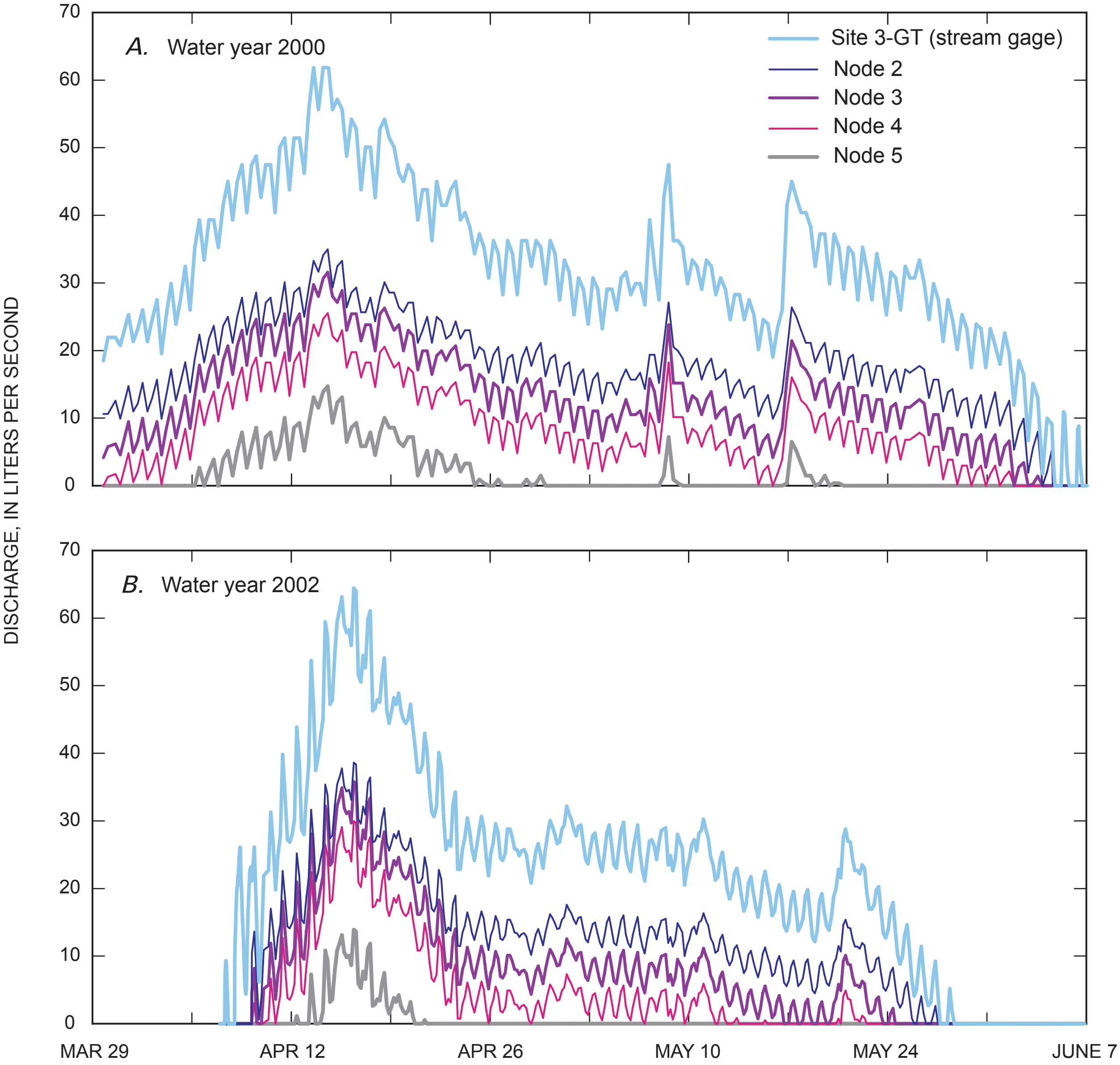


Figure 17. Discharge at site 3-GT and discharge at model nodes 2, 3, 4, and 5 simulated from *A*, March 29–June, 2000, and *B*, March 29–June 7, 2002. Locations of site 3-GT and model nodes are shown in figure 15.

allow ground water flow from the parallel Cottonwood Creek drainage to encroach along the northwestern boundary of the Trout Creek drainage. Test hole MR-2275, drilled near the crest between the two drainages into the Havallah Sequence, yielded more water than test holes and wells drilled into the Valmy Formation in the Trout Creek drainage.

Ground-water recharge in the Trout Creek drainage primarily occurs as concentrated infiltration along Trout Creek and its tributaries and as diffuse recharge from infiltration of precipitation higher on the mountain. Ground-water recharge occurs from these sources only after percolation through the unsaturated zone. Precipitation on the piedmont alluvial plain is insufficient to result in ground-water recharge because any deficits in soil-water storage must be satisfied before deep percolation leading to recharge can occur. Potential soil-water storage on the alluvial plain is large, and virtually all water added to soil storage during periods of precipitation is lost to evapotranspiration during spring and summer.

Evidence for Deep Percolation Beneath Trout Creek

Although streambed-infiltration rates were estimated from discharge measurements and from subsurface temperature profiles at shallow depths beneath the channel, they are

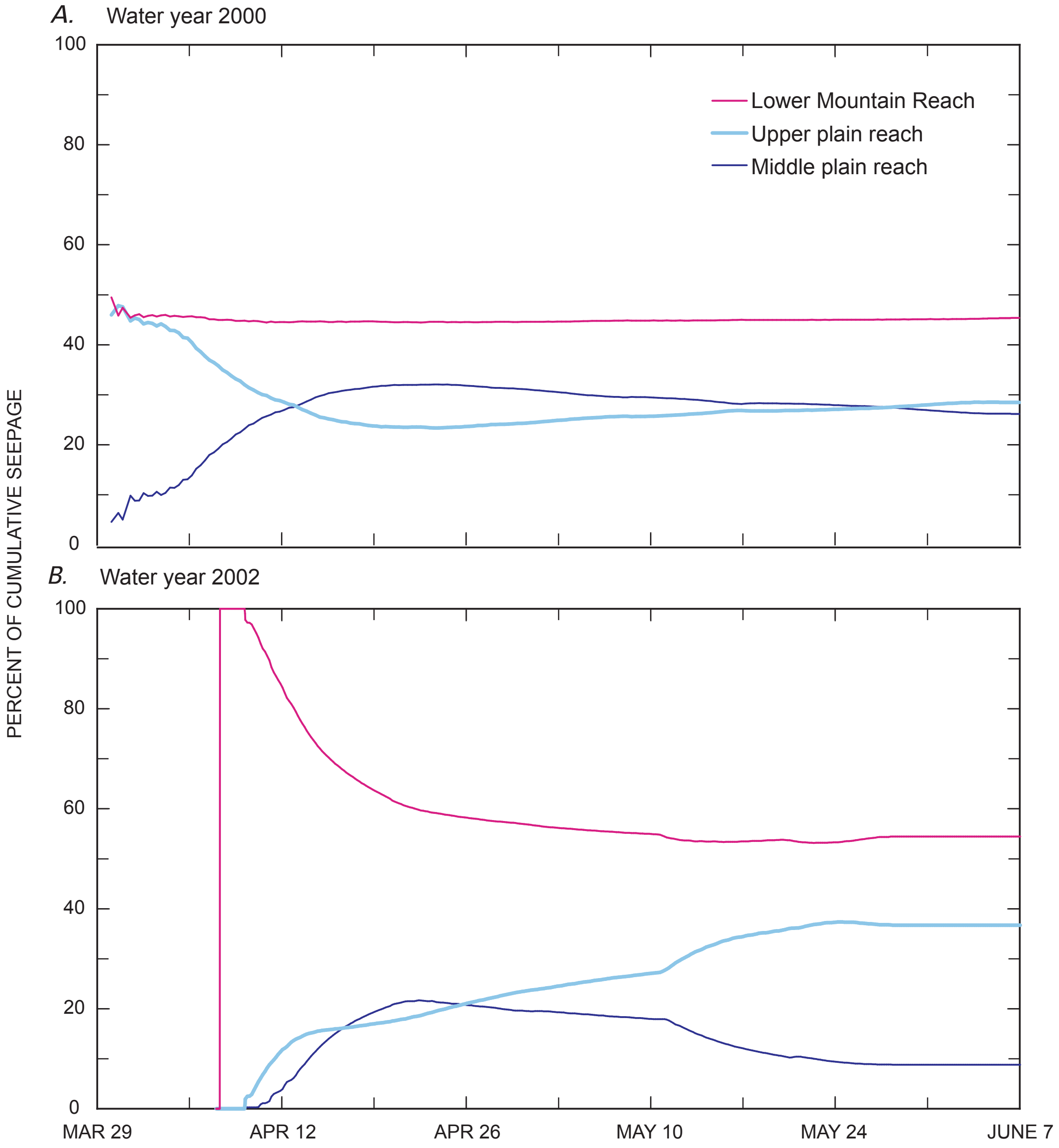


Figure 18. Percentage of cumulative streambed infiltration along lower mountain and upper and middle piedmont alluvial plain reaches simulated for *A*, March 29–June 7, 2000, and *B*, March 29–June 7, 2002. Location of reaches is shown in figure 15.

only an estimate of the quantity of water that infiltrates through the streambed and not the rate of recharge at the water table. Percolation through the unsaturated zone beneath the stream channel from intermittent streamflow results in delay and attenuation of streamflow-infiltration transients. The dynamics of percolation depend on the hydraulic and storage properties of the unsaturated zone. Lateral spreading of percolating water will further delay and attenuate recharge by spreading infiltrated water over a larger area than the channel width. If lateral spreading of infiltrated water occurs at sufficiently shallow depths, additional water will be lost to evapotranspiration.

Direct evidence for deep percolation along and adjacent to the channel was obtained by drilling holes to depths of 6 to 8 m, collecting samples for water content and chloride concentration, and installing access tubes for neutron-moisture measurements. In November 1999, two test holes were drilled at site 5-ST, one in the channel and one 20 m from the channel. An additional test hole was drilled in the channel at site 7-GST (fig. 15). Test holes were drilled with a hollow-stem auger. Core samples were collected every 1.5 m using a 5-cm diameter by 60-cm long split-spoon sampler. Coring was not always successful because of coarse gravels. Grab samples were usually obtained where coring was not possible. When each hole reached its final depth, thin-wall aluminum tubing having a diameter of 5 cm and sealed at the bottom was placed inside the hollow-tube auger. Augers were removed and the annular space around the tubing filled with polyurethane foam, following the procedure of Zawislanski and Faybishenko (1999).

The trailer-mounted auger rig was not sufficiently robust to penetrate the first meter of large cobbles at site 4-ST, at which

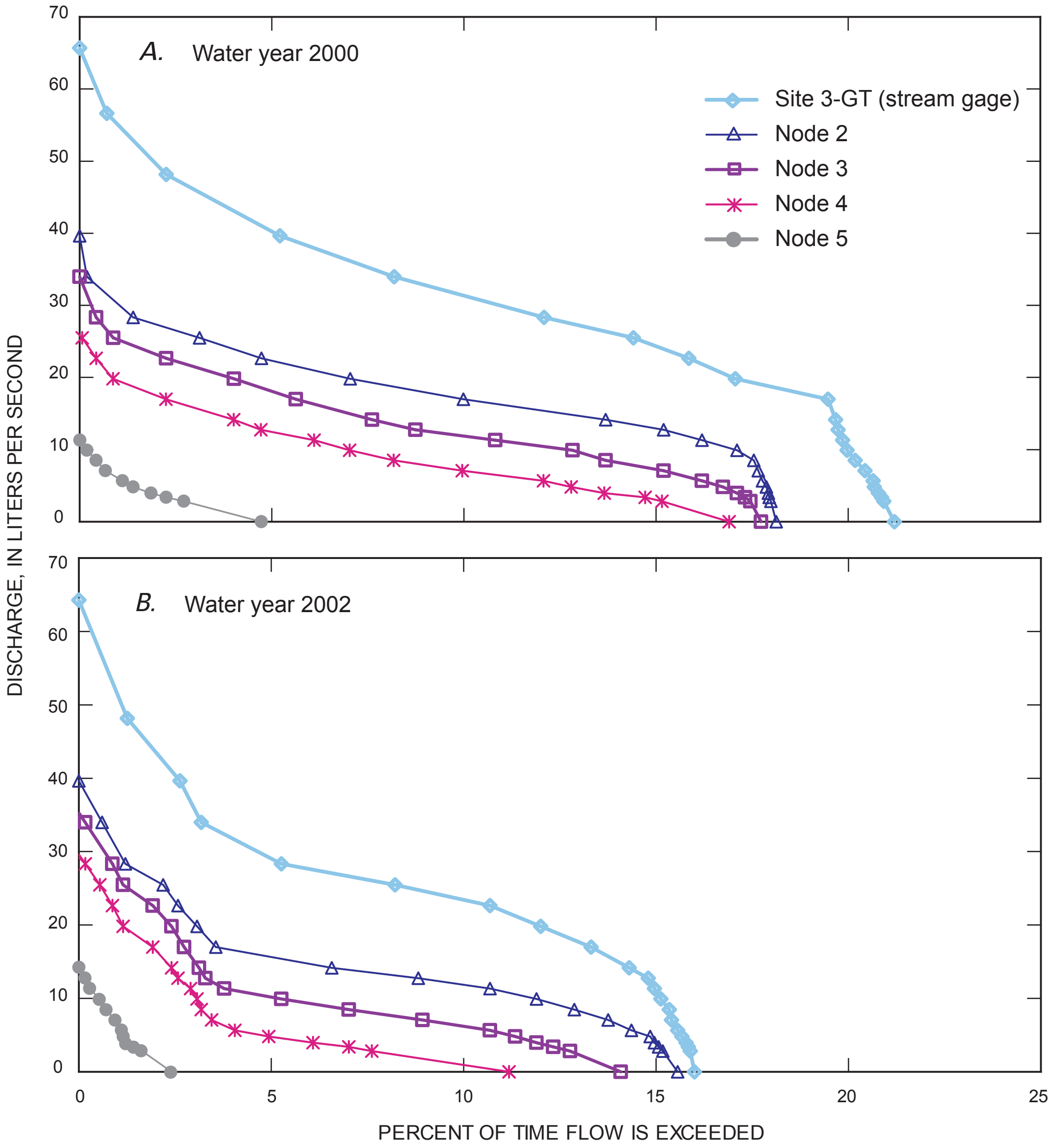


Figure 19. Flow duration at site 3-GT and selected model nodes for water years *A*, 2000 and *B*, 2002. Location of site 3-GT and model nodes is shown in figure 15.

point drilling efforts were suspended. A rotary exploration drill rig from the Marigold Mine became available the following November that was capable of penetrating solid rock. One test hole each was drilled to a depth of 6.6 m in the channel at sites 3-GT and 4-ST. The drill bit was roughly 10-cm in diameter. Air was used to circulate cuttings to the surface that were collected in bags at 0.75 m intervals, starting from land surface. Saturated sediment was not encountered in either hole. Thin-walled aluminum tubing was placed into each hole and the space around the tubing filled with polyurethane foam, as before.

Neutron measurements were related to water content by developing a relation between neutron count ratios (ratio of the number of counts at a given depth in the access tube to the standard shielded count) to water content for the three access holes at or near sites 5-ST and 7-GST. The exploration rig used for install the access tubes at sites 3-GT and 4-ST was not equipped to collect core samples and thus, the neutron count ratios for these holes could not be directly related to water content. Instead, a general relation was developed by comparing neutron count ratios in a similar installation placed next to a calibrated neutron access hole at Eagle Valley in Carson City, Nev. Volumetric water contents are shown in figure 20. Water-content profiles from borehole to borehole are only approximately comparable, due to uncertainties of calibration. In contrast, temporal changes are fairly robust.

Neutron measurements at site 3-GT showed marked changes in water content throughout the profile beneath the channel during periods of streamflow (April and May 2001 and May 2002). The relatively deep percolation at site 3-GT is consistent with the periodic appearance of water in two wells located about 500 m downstream of site 3-GT and in the upstream end of the original channel at Marigold Mine. The wells were drilled to depths of 13 and 58 m and were dry except each spring during and after runoff events in Trout Creek (fig. 21). The quick response of water levels in the wells near site 3-GT to streamflow indicates that infiltration in the lower mountain channel forms temporarily perched zones above the regional water table and that deep percolation is rapid.

Neutron measurements at site 4-ST were consistent with temperature data indicating that streamflow between November 2000 and October 2002 was limited to one brief period, during the spring of 2002. The water content in the channel at sites 5-ST and 7-GST decreased from March 2000 to October 2002, indicating that the channel was mostly dry during the study period. These data are also consistent with pressure-transducer data at site 7-GST, which indicated that no streamflow occurred during the study.

The neutron access hole in the channel at site 5-ST revealed water contents that were considerably higher than those 20 m away from the channel (fig. 20*E*), indicating that flow at 5-ST, though infrequent, was sufficient to maintain higher water contents in the unsaturated zone beneath the channel even after long periods without flow. The lower water contents in the access tube 20 m west of site 5-ST also suggests that lateral spreading in near-surface layers does not extend far from the channel. This observation is supported by a general lack of vegetation next to the channel downstream of 3-GT (fig. 5*B*).

Chloride concentrations in the subsurface were low and uniform beneath the channel, even at sites on the lower piedmont alluvial plain, whereas the subsurface chloride concentrations measured 20 from the channel at site 5-ST were high and displayed a distinct peak at about 1.5 m (fig. 22). Expressed in terms of pore-water concentration, the peak value was about 1,800 mg/L. The lowest value, measured at a depth 6 m beneath the channel, was 70 mg/L. The median chloride concentration at the off-channel site was 250 mg/L, considerably higher than the 17.5 mg/L median value at sites 5-ST and 7-GST.

Chloride concentration in pore water beneath the channel was nearly the same as the average of 7 surface-water samples collected from Trout Creek near Marigold Mine, and 6 samples collected near site 4-ST. Samples were collected between March 1998 and May 2002. No sample was collected May 2002 at the downstream site. Chloride concentrations ranged from 10.2 to 18.8 mg/L at the upstream site, and from 9.8 to 20.2 mg/L at the downstream site (U.S. Department of Interior, Bureau of Land Management, 2003, p. 3–33). Median (mean) concentrations were 14.9 (15.2) mg/L at the upstream site and 14.6 (15.1) mg/L at the downstream site.

Chloride concentrations at the two upper sites (3-GT and 4-ST) likely are similar to those in Trout Creek and at the lower sites because the chloride concentration per gram of sediment was nearly the same. These results suggest that the frequency of streamflow in the channel along the lower reach of the piedmont alluvial plain, and associated quantity of deep percolation, is sufficient to prevent the accumulation of salts observed away from the channel.

Mountain Recharge

Ground-water heads in wells upstream of site 3-GT indicate that diffuse ground-water recharge occurs high in the mountains. Because data are not available to accurately determine ground-water recharge from hydraulic considerations, an estimate of average annual ground-water recharge in the Trout Creek drainage upstream of site 3-GT was made using the chloride mass-balance method (see, for example, Dettinger, 1989). The chloride mass-balance method assumes that: (1) all chloride in ground water comes from precipitation and dry fall in the drainage upstream of site 3-GT, (2) no chloride is derived from rocks as water percolates to the water table, and (3) a balance exists between chloride deposited from the atmosphere in the drainage upstream of site 3-GT and chloride that exits in the drainage downstream of site 3-GT, both in streamflow and in ground-water flow (that is, annualized fluxes of chloride and water are approximately in steady state, with no changes in storage). Ground-water recharge (in cubic meters per year) can be estimated using the following equation (modified from Dettinger, 1989):

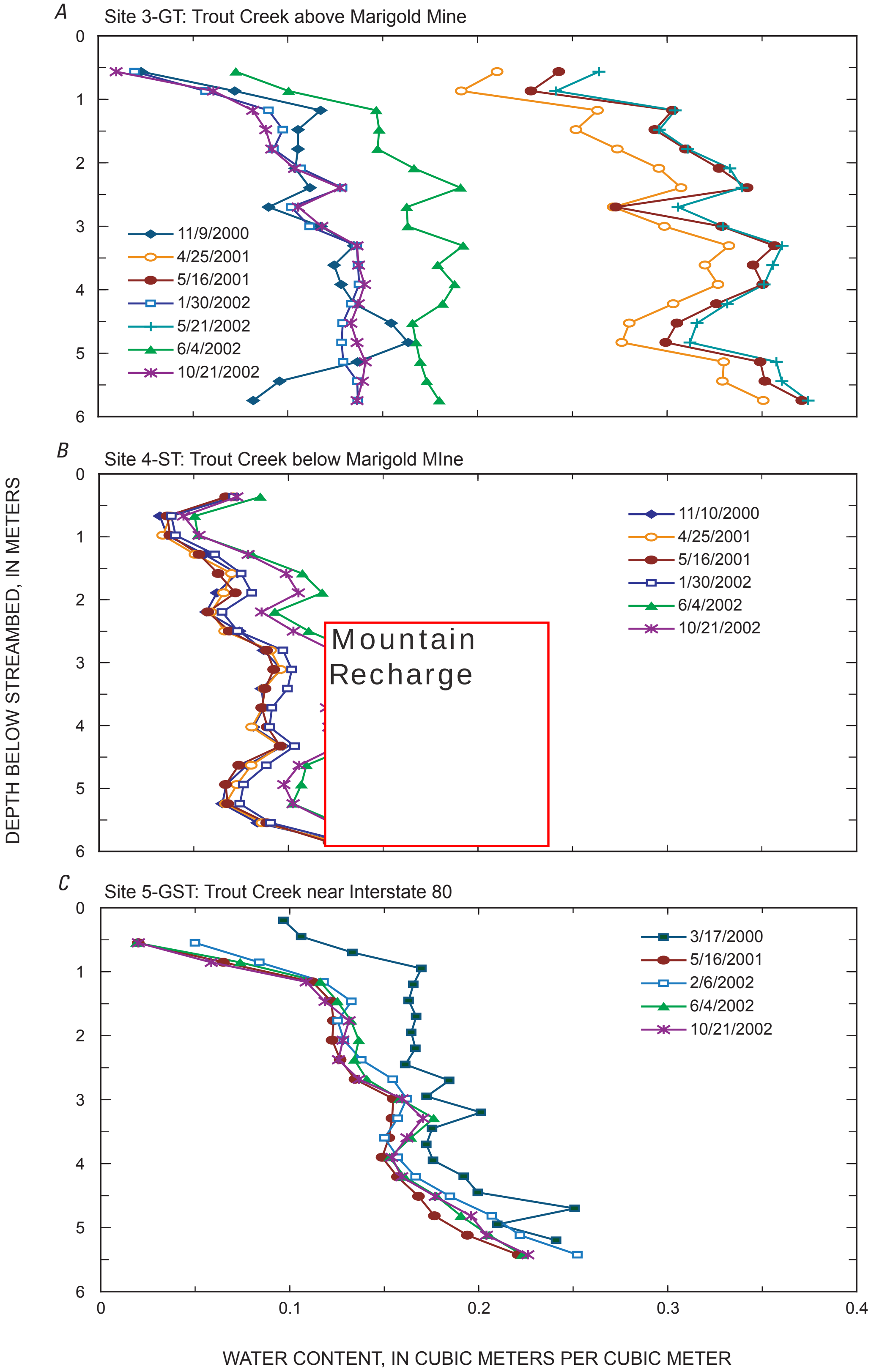


Figure 20. Approximate water content in unsaturated zone beneath and next to Trout Creek estimated from neutron-moisture measurements taken from March 2000 to October 2002 at *A*, site 3-GT, *B*, site 4-ST, *C*, site 5-ST, *D*, site 7-GST, and *E*, twenty meters west of site 5-ST. Location of sites is shown in figure 15.

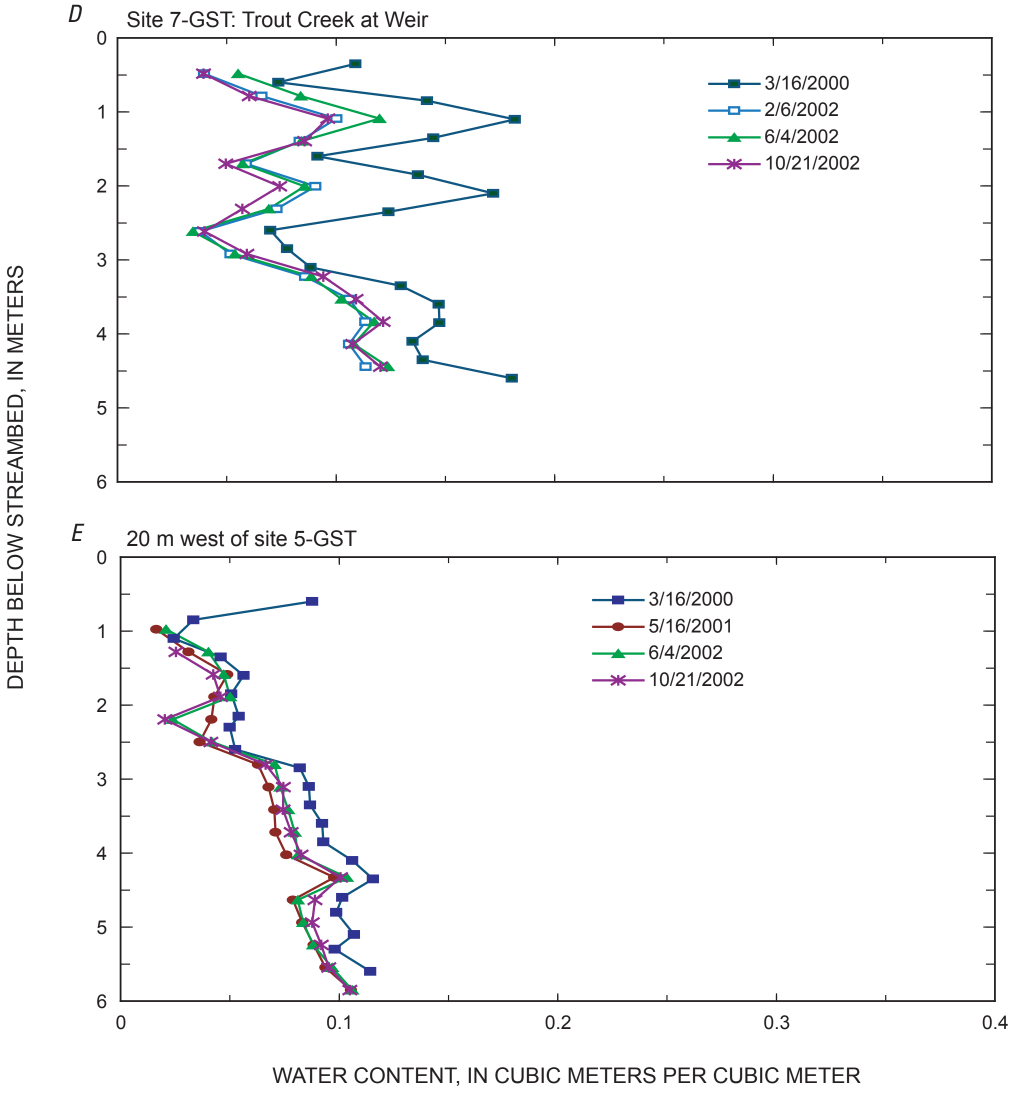


Figure 20.—Continued.

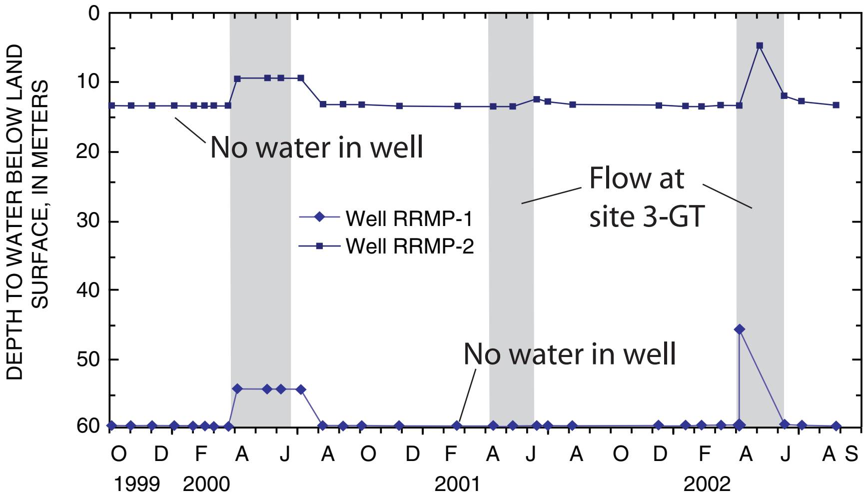


Figure 21. Depth to water in two wells near Trout Creek and Marigold Mine for water years 2000 to 2002. Location of site is shown in figure 15. Data are from Jonn Barber, Glamis Marigold Mining Company, written commun., 2003.

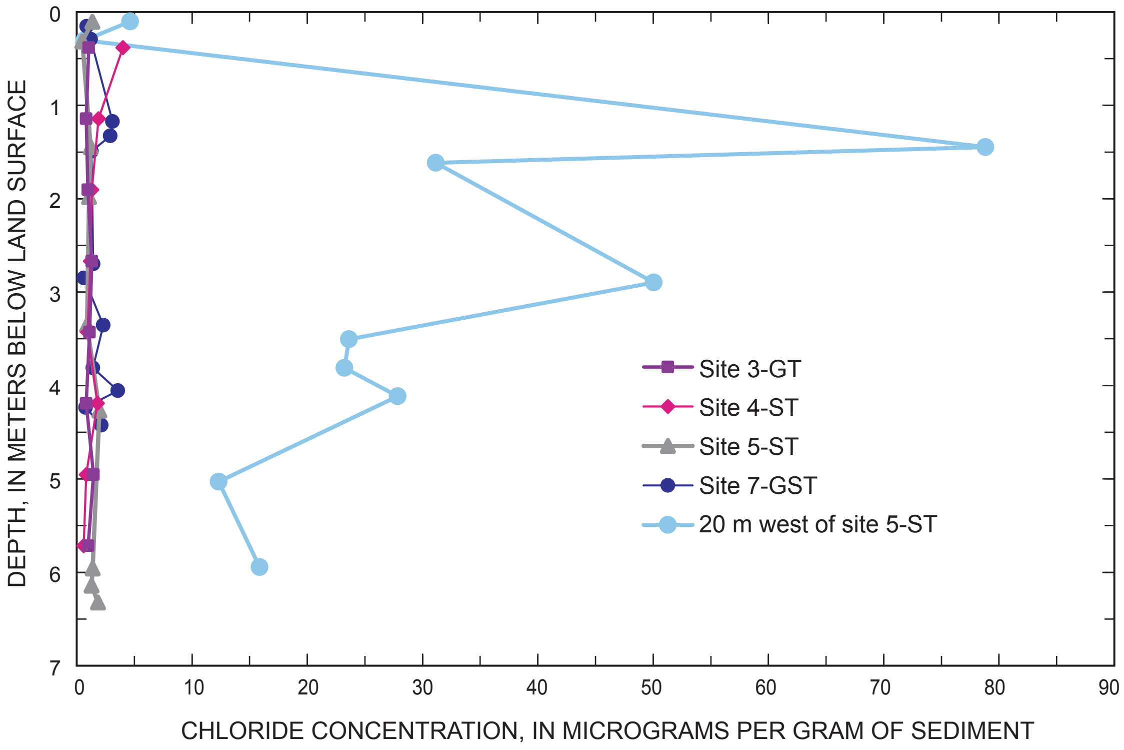


Figure 22. Chloride concentrations in cores and cuttings collected from test holes drilled into unsaturated alluvium beneath and adjacent to Trout Creek. Core samples and cuttings were collected from test holes drilled November 1999 at sites 5-ST and 7-GST and cuttings were collected from test holes drilled November 2000 at sites 3-GT and 4-ST. Location of sites is shown in figure 15.

$$Q_{gw} = \frac{Q_p\ (C_p)}{C_{gw}} - \frac{Q_{sr}\ (C_{sr})}{C_{gw}}, \qquad (5)$$

where

Q_{gw} = average annual ground-water recharge, in millions of cubic meters,

C_{gw} = average chloride concentration in ground water, in milligrams per liter,

Q_p = average annual volume of precipitation, in millions of cubic meters,

C_p = average chloride concentration of precipitation, in milligrams per liter,

Q_{sr} = average annual surface runoff, in millions of cubic meters, and

C_{sr} = average chloride concentration of surface runoff, in milligrams per liter.

Separate estimates of the mass of chloride in precipitation and runoff are needed because ground-water recharge is calculated from the difference. The chloride in precipitation is an effective value that includes chloride in dust (dry deposition).

The average annual volume of precipitation was estimated from a precipitation map derived from a statistical topographically based model (Daly and others, 1994), which uses average annual precipitation from surrounding meteorologic stations over a 30-year period (1961–1990). This approach was advantageous because it produced orographically realistic estimates even for the highest elevations in the Trout Creek drainage. The estimates compare well with the independently measured data from the precipitation stations already discussed in this report.

The drainage area upstream of site 3-GT is 38 km^2, where the average annual precipitation ranged from 267 to 368 mm. The total annual volume of precipitation was determined by dividing the precipitation range into four equal zones, and estimating the area of each. The estimated volume of precipitation for the drainage upstream of site 3-GT was 1.28×10^7 m^3/yr (table 5).

An estimate of long-term average runoff for the Trout Creek gage, with two years of record, can sometimes be made on the basis of correlations with nearby streams having similar characteristics and longer periods of record. Long-term gages on small streams to the northwest and northeast—Martin Creek near Paradise Valley, about 100 km northwest, and Rock Creek near Battle Mountain, about 50 km northeast—showed greater annual runoff in 2002 than in 2000 (Allander and others, 2001 and Berris and others, 2003). Thus precipitation patterns in those watersheds can differ substantially from the precipitation pattern in the Trout Creek drainage.

Consequently, average annual runoff at site 3-GT was estimated by adjusting annual runoff for 2000 and 2002 at site 3-GT on the basis of annual runoff of the Humboldt River near Battle Mountain (about 25 km east of site 3-GT). Humboldt River data were obtained from Allander and others, 2001; Berris and others, 2003; and Stockton and others, 2004. The annual runoff of the Humboldt River during water year 2000 was 53 percent of the long-term average (1886–1897, 1921–1924, 1945–1981, and 1991–2003). Annual runoff during 2002 was 42 percent of the long-term average. Since these data approximately matched the record at Trout Creek, the average annual runoff at site 3-GT was estimated by assuming that the ratio of annual runoff in the Trout Creek basin to annual runoff at the Humboldt River near Battle Mountain was roughly representative of the longer period of Humboldt River record. With this assumption, the estimated long-term average annual runoff for Trout Creek at site 3-GT was 3.4×10^5 m^3.

Chloride concentrations in precipitation (including dryfall) were determined on the basis of two chloride collectors—one on the piedmont alluvial plain east of Trout Creek and the other near the fault in the Cottonwood Creek drainage, west of Trout Creek (fig. 15 and table 6). The chloride concentrations in precipitation and dryfall from the two sites were assumed to represent an average annual chloride concentration. The chloride collectors consisted of a 2-liter polyethylene bottle connected by silicone-rubber tubing to an 8-cm diameter funnel, which was attached to the top of a fence post. Mineral oil was placed in the bottom of the bottle to prevent evaporation. The collectors were located at the weather stations operated by the mines. Samples were retrieved in the spring and fall of each year, starting in April 2000.

Volumetrically averaged chloride concentrations in precipitation for the period November 1999 to November 2002 was 1.3 mg/L at site 1 on the piedmont alluvial plain north of Marigold Mine and 2.1 mg/L at site 2, on the mountain south of Marigold Mine. Omitting the first sample collected at site 2, which had a concentration of 7.4 mg/L that was never approached by subsequent samples, resulted in the same volumetrically averaged chloride concentration as site 1(table 6). The concentration is roughly twice the average 0.6 mg/L of chloride in bulk-precipitation reported by Dettinger (1989) for stations in Nevada but within the range of measured values. On the basis of the similarity in the volumetrically averaged chloride at the two sites during the study period, average annual bulk chloride in precipitation was assumed to be 1.3 mg/L throughout the Trout Creek drainage.

The average chloride concentration of runoff is about 15 mg/L, based on thirteen chloride samples collected between March 1998 and May 2002 (U.S. Department of Interior, Bureau of Land Management, 2003, p. 3–33). Ground-water samples were collected from three monitoring wells and one test hole, in October 2002. Chloride concentrations in the wells nearest the fault (MIL2001-1 and MIL2001-2; fig. 15) were 23.1 and 24.4 mg/L, respectively. The other two sites (well MPS-18 and test hole MR-2275; fig. 15), near site 3-GT, had chloride concentrations of 20.9 and 18.4 mg/L, respectively (table 7). The average chloride concentration from all wells was 22 mg/L, rounded to two significant figures.

Average annual ground-water recharge in Trout Creek drainage upstream of site 3-GT was estimated using equation 5. Estimates of average annual precipitation, runoff, and volume-averaged chloride concentrations of precipitation, runoff, and ground water are given in table 8. The resulting ground-water recharge upstream of site 3-GT is 5.2×10^5 m^3. The estimated quantity of ground-water recharge within the entire Trout Creek drainage is assumed equal to ground water flow from the mountain block to the adjacent alluvial basin because the water table is far below land surface (fig. 7). This calculation neglects any net changes in ground-water storage caused by operations at the Lone Tree Mine. If all the average annual runoff is assumed to infiltrate prior to reaching the Humboldt River floodplain, the total water yield from the Trout Creek drainage upstream of site 3-GT is 8.6×10^5 m^3, or 7 percent of the average annual precipitation (table 8).

This percentage is the same as that estimated by using the original Maxey-Eakin method (Maxey and Eakin, 1949), given that the mean annual precipitation in the drainage is roughly 340 mm (13.3 inches). Additionally, the total water yield from the Trout Creek drainage is about the same as that estimated for two watersheds entering Eagle Valley in greater Carson City, Nev., which have similar values of average annual precipitation (Maurer and Berger, 1997, p. 34).

The fact that more than half of the recharge to ground water occurs in the mountains indicates that the consolidated rocks making up the mountain block have a higher permeability than initially expected on the basis of the geologic descriptions of the units (table 1), at least near the surface. Evidence of high near-surface permeability in the consolidated rocks can be seen in the ground-water gradient shown on figure 8. In 2002, the ground-water gradient between the fault and Marigold Mine was about $4x10^{-2}$ m/m, whereas the gradient on the piedmont alluvial plain north of the mine was less than $4x10^{-3}$ m/m. Assuming that ground-water flow in the Trout Creek drainage upstream of Marigold Mine is limited to the upper 300 m of saturated consolidated rocks and that the width of the ground-water-flow system is 1.5 km at site 3-GT, the bulk hydraulic conductivity of the consolidated rocks in the drainage upstream of Marigold Mine is estimated to be 0.08 m/d. The lower hydraulic gradient in the consolidated rocks below Marigold Mine indicates an increase in permeability.

Tritium (^3H), a cosmogenically produced isotope of hydrogen with a half-life of 12.3 years, was detected in water from wells MIL2001-1 and MPS-18 at 140 and 86 Bq/L, respectively (table 7). Depth to ground water in these wells exceeded 135 m below land surface (table 7). The presence of tritium at these levels indicates that a substantial portion of ground water at these locations represents recharge that occurred after 1950.

Table 5. Average annual volume of precipitation in Trout Creek drainage upstream of site 3-GT, north-central Nevada.

[Location of site 3-GT is shown in figure 15. Precipitation from the statistical-topographic model of Daly and others (1994) using data from 1961–1990. Abbreviations: mm, millimeters; m^2, square meters; m^3, cubic meters]

Annual precipitation range, in mm	Average annual precipitation, in mm	Area, in m^2	Volume, in m^3
267–292	279	4.07×10^6	1.14×10^6
292–318	305	4.43×10^6	1.35×10^6
318–343	330	6.30×10^6	2.08×10^6
343–368	356	2.31×10^7	8.21×10^6
	Total	3.79×10^7	1.28×10^7

Table 6. Chloride concentration of precipitation in the vicinity of Trout Creek drainage, north-central Nevada.

[Locations of precipitation sites are shown in figure 15. All samples analyzed at the U.S. Geological Survey laboratory in San Diego, Calif., using ion chromatography. Abbreviations: mL, milliliters; mg, milligrams; mg/L, milligrams per liter; NWIS #, National Water Information System site identifier; <, less than; —, not applicable]

Sample period:		Volume of precipitation, in mL	Mass of chloride, in mg	Chloride, dissolved, in mg/L	Precipitation, in mm:	
Starting date	Ending date				at indicated site	[1] at Marigold Mine
Site 1, piedmont alluvial plain, north of Marigold Mine (NWIS 404522117074801)						
11/09/1999	04/18/2000	215	0.09	0.4	56	147
04/18/2000	10/10/2000	237	0.38	1.6	62	80
10/10/2000	04/04/2001	254	0.18	0.7	66	116
04/04/2001	10/18/2001	124	0.26	2.1	32	36
11/07/2001	05/21/2002	299	0.48	1.6	78	136
05/21/2002	11/20/2002	135	0.20	1.5	35	33
	Totals	1,264	1.59		329	548
		Volume-averaged chloride concentration		1.3		
Site 2, mountain reach of Cottonwood Creek, near Oyarbide Fault (NWIS 404034117114501)						
11/09/1999	04/19/2000	235	1.7 (?)	7.4 (?)	61	147
04/19/2000	10/10/2000	345	<0.14	<0.4	90	80
10/10/2000	04/04/2001	304	0.43	1.4	79	116
04/04/2001	10/18/2001	210	0.40	1.9	55	36
11/07/2001	05/21/2002	448	0.81	1.8	117	136
05/21/2002	11/20/2002	242	0.31	1.3	63	33
	Totals	1,784	3.79	—	465	548
		Volume-averaged chloride concentration		2.1		
	[2] Totals	1,549	2.09	—	404	401
		Volume-average chloride concentration		1.3		

[1] Precipitation at Marigold Mine, from monthly totals, shown for comparison.

[2] Omitting sample period 11/09/1999–04/19/2000.

Table 7. Selected water-quality data from wells in Trout Creek drainage near or upstream of site 3-GT, north-central Nevada.

[Location of wells and test hole shown in figure 15. All samples processed through U.S. Geological Survey laboratory in Arvada, Color. Abbreviations: m, meters; mg/L, milligrams per liter, ^{3}H, tritium activity and 2-standard deviation counting uncertainty; Bq/L, becquerels per liter; δD, delta dueterium; δ^{18}O, delta oxygen-18; ‰, per mil deviation from sea water (Gonfiantini, 1978)]

[1]Well or test hole name	Date sampled	Depth below land surface: well screen, in m	Depth below land surface: water level, in m	Chloride, in mg/L	^{3}H, in Bq/L	δD, in ‰	δ^{18}O, in ‰
MPS-18-1	10/21/2002	204–229	217.6	18.4	86 ± 51	−124.5	−16.14
[2]MR-2275	10/23/2002	Open hole	135.0	20.9	−8 ± 51	−125.0	−15.95
MIL2001-1	10/22/2002	283–307	213.0	23.1	140 ± 51	−123.3	−15.80
MIL2002-2	10/23/2002	277–302	257.9	24.4	27 ± 27	−124.7	−16.04
			Average	22			

[1] National Water Information System (NWIS) site-identification numbers are: 404357117103301 (well MPS-18-1), 404228117113201 (test hole MR-2275), 404105117104101 (well MIL2001-1), and 404115117102001(well MIL2002-2).

[2] Ground-water sample was collected when depth of hole reached 317 meters. The polymer drilling mud and several well-bore volumes of water were pumped from the hole the day before sampling. Additional water was pumped at 360 liters per minute for 15 minutes immediately before sampling.

Table 8. Estimate of ground-water recharge in mountain part of drainage upstream of site 3-GT using chloride-balance method, Trout Creek drainage, north-central Nevada.

[Location of streamflow-gaging station is shown in figure 15. Abbreviations: PTTN, precipitation; GW, ground water; mg/L, milligrams per liter; m^3, cubic meters; %, percent]

Average chloride concentration in: [1]PTTN, in mg/L	Average chloride concentration in: [2]Runoff, in mg/L	Average chloride concentration in: [3]GW, in mg/L	Estimated average annual volume of: [4]PTTN, in m^3	Estimated average annual volume of: [5]Runoff, in m^3	Estimated average annual volume of: [6]GW recharge, in m^3	Average annual runoff plus GW flow, in m^3	Average annual runoff plus GW flow, in % PTTN
1.3	15.	22.	$128. \times 10^5$	3.4×10^5	5.2×10^5	8.6×10^5	7

[1] Volume-averaged bulk chloride concentration in precipitation (wetfall plus dryfall) from samples collected between April 2000 and November 2002 (table 6).

[2] Average chloride concentration in runoff from thirteen Trout Creek samples collected upstream of Marigold Mine between March 1998 and May 2002 (U.S. Department of Interior, Bureau of Land Management, 2003, p. 3-33).

[3] Average chloride concentration in ground water from samples collected in October 2002 (table 7).

[4] From table 6.

[5] Average annual volume of runoff was from annual runoff at site 3-GT for water years 2000 and 2002, adjusted to long-term average annual runoff using gage on Humboldt River near Battle Mountain, about 25 kilometers to the east.

[6] Average annual volume of ground-water recharge upstream of site 3-GT, calculated on the basis of equation 5.

The stable isotopes of hydrogen, expressed as δD (delta deuterium, the normalized difference, relative to sea water, of the ratio of deuterium, ^{2}H, to ordinary hydrogen, ^{1}H), ranged from 123 to 125 per mil. The stable isotopes of oxygen, expressed as δ^{18}O (the similarly normalized difference in the ratio of ^{18}O to ^{16}O), ranged from 15.8 to 16.1 per mil. The range was within the uncertainty of each estimate ($\pm$ 2 per mil for δD and $\pm$ 0.2 per mil for δ^{18}O). The δD values are similar to those measured in winter precipitation in central Nevada (Smith and others, 2002) again suggesting that ground-water recharge is from modern-day precipitation.

Summary and Conclusions

Trout Creek has an actively recharged ground-water system, controlled by the combination of geologic features and precipitation. Much of the precipitation in the Trout Creek drainage falls during winter months, when temperatures are near or below freezing and evapotranspiration is small. Precipitation therefore generally accumulates as snow at the higher elevations in the watershed. Streamflow produced by precipitation and snowmelt was observed near the mountain front for periods of 4 to 8 weeks during water years 1999 through 2002. Streamflow commenced in March or April and ceased in May or June. Streamflow in Trout Creek in 1999 reached the Humboldt River floodplain from April to June, following a winter of above-normal precipitation. In contrast, streamflow reached only the middle reach of the piedmont alluvial plain during the normal to below-normal precipitation years of 2000 through 2002.

The extent and duration of flow along the channel was determined using several methods, including analysis of streambed temperatures obtained with single-channel data loggers, subsurface temperature profiles obtained with a thermocouple nest, and pressure transducers. The pressure transducers provided the most reliable estimates of the duration of flow, although they were damaged by freezing. The onset of flow could be reasonably estimated from the self-contained temperature loggers and subsurface temperature profiles. Long periods of no flow generally could be determined by evaluating differences in minimum daily temperatures. However, estimating brief periods of intermittent flow that often occurred each day near the end of runoff was difficult because the thermal signal of drainage cessation is indistinct.

A numerical model that simulated unsteady streamflow with streambed infiltration was used to estimate the duration of streamflow and the annual percentage of streambed infiltration for selected reaches of Trout Creek. Analysis of simulation results indicate that cumulative streambed infiltration along the channel varied as a function of runoff in the mountain drainage upstream of site 3-GT. Simulated flow did not extend past the middle reach of the piedmont alluvial plain during 2000 and 2002, consistent with field observations. The model was also used to simulate streambed infiltration losses for May 12, 1999. Model results matched measured flows in the lower reaches of the piedmont alluvial plain when streambed-infiltration rates were increased by a factor of two.

The model has utility in evaluating streambed infiltration along similar intermittent streams provided that streamflow is measured near the mountain front, that channel lengths and cross-sectional areas characterized reasonably well, and that the relation between stream stage and streambed-infiltration rate is known for each reach with distinctive properties.

Although the upper and middle reaches on the piedmont alluvial plain constituted the greatest area of channel, more streambed infiltration occurred along the lowest reach whenever flow extended to it. The marked increase in streambed infiltration along the lower reach of the piedmont alluvial plain was attributed to the combination of an increase in the permeability and to a decrease in channel armoring. Armoring of the upstream portion of the channel by large quartzite cobbles embedded in a sand matrix decreased the effective area for streambed infiltration. Channel deposits in the lower reaches lack armoring, consisting only of fine gravels and sands. The armoring of the upper reaches is a nearly ubiquitous feature of fan deposition in which poorly sorted coarse sediments are deposited near the head of a fan and better-sorted and finer-grained sediments are deposited near the foot.

Percolation beneath the channel in areas of streamflow was indicated by increased water content to depths of 6 m, as determined by neutron logging. Water contents beneath the channel were higher and more variable than water contents 20 m away from the channel. Chloride concentrations beneath the channel to depths of at least 6 m were substantially lower than those away from the channel. The data indicate active recharge beneath the channel stemming from infiltration that remains relatively focused during subsequent percolation. The frequency and duration of streambed infiltration is sufficient to maintain relatively high water contents and low chloride concentrations to depths of at least 6 m beneath the channel, compared with interchannel areas.

Variability in climate affects discharge and duration of streamflow onto the piedmont alluvial plain, which shifts the balance between downstream infiltration losses and mountain-block ground-water recharge. During years of normal to below-normal precipitation, all streamflow is lost to streambed infiltration along the lower mountain reach and upper to middle reaches of the piedmont alluvial plain. During periods of above-normal precipitation, streambed infiltration is greater along the lower reaches of the drainage. This result is likely typical for other watersheds in the Middle Humboldt River Basin. The timing, duration, magnitude, and location of annual streambed infiltration and ground-water recharge from intermittent streams that flow across alluvial fans and piedmont alluvial plains vary strongly, but in a systematic way, with variations in precipitation patterns.

Average annual ground-water recharge in the mountainous portion of the Trout Creek drainage was estimated on the basis of chloride mass balance to be roughly 5.2×10^5 m^3. Near the mountain front, the average annual volume of runoff was 3.4×10^5 m^3. This latter estimate was based on two years of record from Trout Creek (water years 2000 and 2002) adjusted by the variation in long-term runoff of the Humboldt River near Battle Mountain, Nev. Annual runoff from Trout Creek in water years 2000 and 2002 was 2.1×10^5 and 1.2×10^5 m^3, respectively. Annual runoff of the Humboldt River for those two years was 53 and 42 percent of the long-term average runoff. The combined annual volume of ground-water recharge and surface runoff from the Trout Creek drainage near the mountain front was 8.6×10^5 m^3, which is about 7 percent of the estimated average annual precipitation in the mountain-block part of the drainage. The sum of mountain-block runoff plus ground-water recharge to annual precipitation estimated in this study, on an average annual basis, closely matches the original Maxey-Eakin estimate for ground-water recharge.

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