Using Tracers to Evaluate Streamflow Gain-Loss Characteristics of Terror Creek, in the Vicinity of a Mine-Permit Area, Delta County, Colorado, Water Year 2003

By Cory A. Williams and Kenneth J. Leib

Prepared in cooperation with

DELTA COUNTY

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CONVERSION FACTORS, DATUMS, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
feet (ft)	0.3048	meter
yard (yd)	0.9144	meter
mile (mi)	1.609	kilometer
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter
	Flow rate	
cubic feet per second (ft^3/s)	0.02832	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram
ton, short (2,000 lb)	0.9072	megagram

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).
Elevation, as used in this report, refers to distance above the vertical datum.
Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).
Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

L/min liters per minute
mL milliliters
BLM Bureau of Land Management
NaBr sodium bromide
USDA U.S. Department of Agriculture
USGS U.S. Geological Survey
NWQL U.S. Geological Survey National Water-Quality Laboratory
WY Water year—A continuous 12-month period representing an annual hydrologic cycle selected to present data relative to hydrologic or meteorological phenomena. The water year used by the U.S. Geological Survey runs from October 1 through September 30 and is designated by the year in which it ends.

Using Tracers to Evaluate Streamflow Gain-Loss Characteristics of Terror Creek, in the Vicinity of a Mine-Permit Area, Delta County, Colorado, Water Year 2003

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Abstract

In 2003, the U.S. Geological Survey, in cooperation with Delta County, initiated a study to characterize streamflow gain-loss in a reach of Terror Creek, in the vicinity of a mine-permit area planned for future coal mining. This report describes the methods of the study and includes results from a comparison of two sets of streamflow measurements using tracer techniques following the constant-rate injection method. Two measurement sets were used to characterize the streamflow gain-loss associated with reservoir-supplemented streamflow conditions and with natural base-flow conditions.

A comparison of the measurement sets indicates that the streamflow gain-loss characteristics of the Terror Creek study reach are consistent between the two hydrologic conditions evaluated. A substantial streamflow gain occurs between measurement locations 4 and 5 in both measurement sets, and streamflow is lost between measurement locations 5 and 7 (measurement set 1, measurement location 6 not visited) and 5 and 6 (measurement set 2). A comparison of the measurement sets above and below the mine-permit area (measurement locations 3 and 7) shows a consistent loss of 0.37 and 0.31 cubic foot per second (representing 5- and 12-percent streamflow losses normalized to measurement location 3) for measurement sets 1 and 2, respectively. This indicates that similar streamflow losses occur both during reservoir-supplemented and natural base-flow conditions, with a mean streamflow loss of 0.34 cubic foot per second for measurement sets 1 and 2.

Findings from a previous investigation support the observed streamflow loss between measurement locations 3 and 7 in this study. The findings from the previous investigation indicate a streamflow loss of 0.59 cubic foot per second occurs between these measurement locations.

Statistical testing of the differences in streamflow between measurement locations 3 and 7 indicates that there is a discernible streamflow loss. The p-value of 0.0236 for the parametric paired t-test indicates that there is a 2.36-percent probability of observing a sample mean difference of 0.34 cubic foot per second if the population mean is zero. The p-value of 0.125 for the nonparametric exact Wilcoxon signed rank test indicates that there is a 12.5-percent probability of observing a sample mean difference this large if the population mean is zero.

The similarity in streamflow gain-loss between measurement sets indicates that the process controlling streamflow may be the same between the two hydrologic conditions evaluated. Gains between measurement locations 4 and 5 may be related to hyporheic flow from tributaries that were dry during the study. No other obvious sources of surface water were identified during the investigation. The cause for the observed streamflow loss between measurement locations 5 and 6 is unknown but may be related to mapped local faulting, 100 years of coal mining in the area, and aquifer recharge.

Introduction

Terror Creek, in western Colorado along the North Fork Gunnison River (fig. 1), is situated among sedimentary rock formations of Cretaceous age that are rich in economical deposits of coal. Underground coal mining has been active in the North Fork Gunnison River area since about 1900. The Bowie mine has been active in the area between Hubbard and Terror Creeks since about 1952 (Chaney and others, 1987). Mine operators anticipate increasing mining activity to the western part of the mine-permit area, including the area directly beneath the surface of Terror Creek (J.E. Stover, J. E. Stover and Associates, written commun., 2001) (fig. 1).

Coal mining at the mine-permit area employs a continuous mining technique to extract the coal. This technique begins with the extraction of coal in a crosshatch pattern, referred to as first mining, which leaves regularly spaced pillars of coal to support the roof of the mine. Later these support columns are removed to increase the amount of coal available for extraction. Removal of the support columns can cause fractures and subsidence in the formations overlying the coal seam (Dunrud, 1976). The exact extent of the potential fracturing is not known and will be minimized by performing first mining only (no pillar extraction) for areas immediately near Terror Creek (J.E. Stover, J. E. Stover and Associates, oral commun., 2004). If fracturing extends to near ground surface, streamflow in Terror Creek

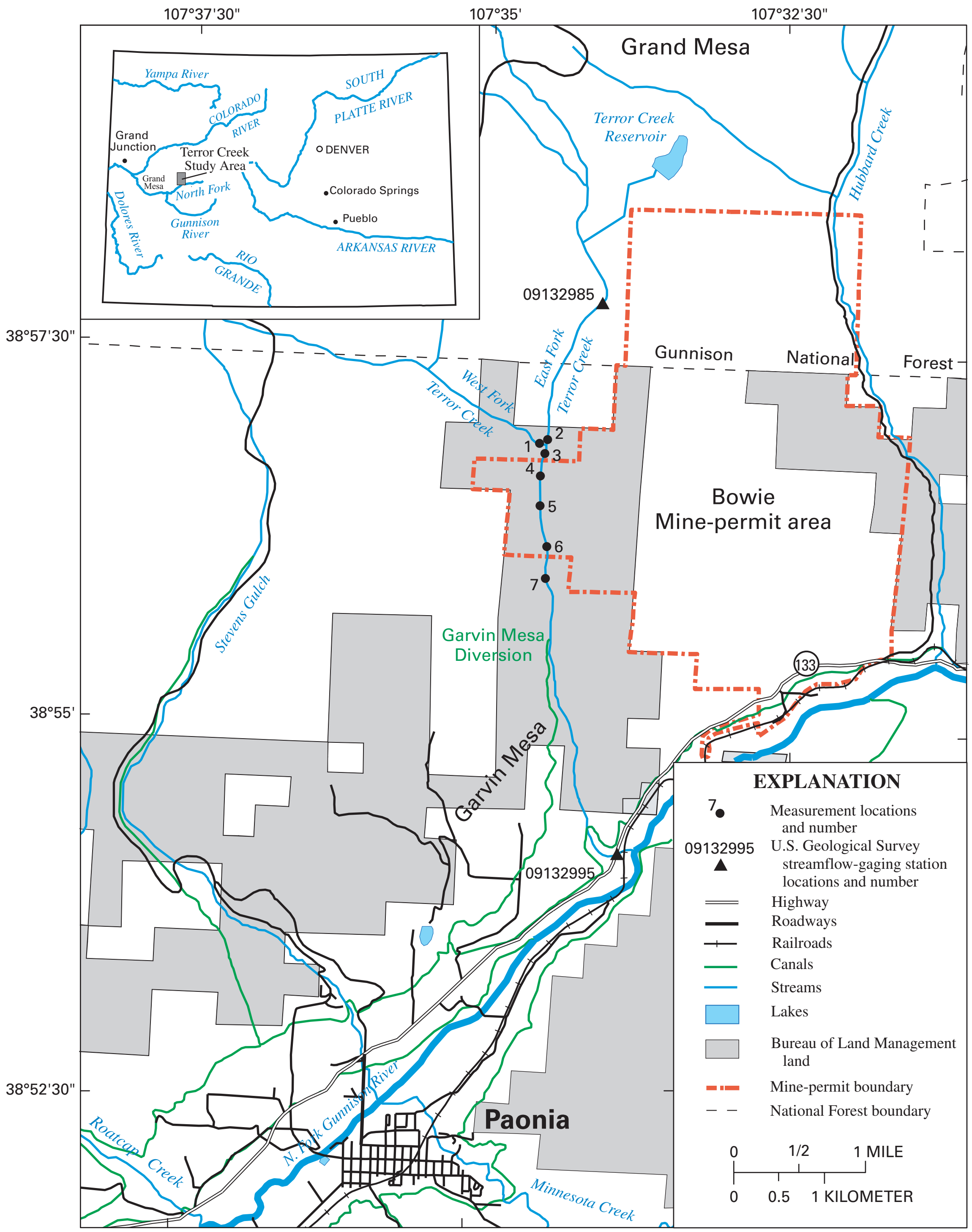

Figure 1. Location of Terror Creek study area, measurement locations, and mine-permit area.

could be affected by ground-water losses from the alluvium along and under Terror Creek into the fractures. Streamflow loss through recharge to the Mesa Verde Formation of Cretaceous age within the mine-permit area near Terror Creek also may occur. Information is needed by interested parties to assess future changes in streamflow characteristics in Terror Creek. Irrigation companies, the Bureau of Land Management (BLM), and mine operators will use the information in this report, which was done by the U.S. Geological Survey (USGS) in cooperation with Delta County, as a baseline characterization of streamflow gain-loss in Terror Creek in the vicinity of the mine-permit area.

Purpose and Scope

The purpose of this report is to describe the methods and results for the study of streamflow gain-loss characteristics of Terror Creek in the vicinity of a mine-permit area scheduled for future coal mining, during reservoir-supplemented and base-flow hydrologic conditions. Reservoir-supplemented streamflow conditions were evaluated June 17–18, 2003, and base-flow conditions were evaluated September 16–17, 2003. Streamflow gain-loss characteristics were determined using tracer techniques following the constant-rate injection method. Streamflow was determined at seven measurement locations along Terror Creek over the course of the study. The study reach was about 1 mi in length and less than one-fourth of the total length of Terror Creek.

Description of Study Area

Terror Creek is a high mountain stream located on the southeast flank of the Grand Mesa in western Colorado and about 5 mi north of the town of Paonia. The headwaters of Terror Creek originate in the Gunnison National Forest (fig. 1). Terror Creek flows south from its headwaters (elevation about 10,200 ft) to its confluence with the North Fork Gunnison River (elevation about 5,700 ft). The upper boundary of the study reach is located at the confluence of the East and West Forks Terror Creek; the lower boundary is located just below the mine-permit area, approximately 0.5 mi upstream from a small irrigation diversion referred to locally as the Garvin Mesa Diversion (fig. 1).

The stream channel of Terror Creek is typical of a high mountain stream, characterized by a narrow channel with a steep gradient. The stream channel consists mostly of cobbles and boulders surrounded by gravels and sands. The stream channel is commonly braided by cobbles and boulders in areas of relatively flat gradient, and consists of one or more small riffles and cascades in areas of steeper gradient. The streambed material typically is alluvium, but an exposed bedrock channel exists intermittently in the study reach.

The study area is characterized by steep and rugged terrain primarily covered by oak brush and evergreen and deciduous forest. Precipitation ranges from 17 to 43 inches annually, most of which occurs as snow at higher elevations during late winter and early spring (Daly and Taylor, 1998). Primary land use in the area is cattle grazing and coal mining, with the majority of the basin managed by the U.S. Department of Agriculture (USDA) Forest Service and BLM (Colorado Department of Transportation, 2003). Underground coal-mining production near Terror Creek ranked within the top 50 for the United States in 2002 (based on quantity), with nearly 5.4 million short tons produced annually by one local mining company (Energy Information Administration, 2002).

Geology

The variations in the stream-channel gradient reflect the geology of the area with the combination of erosion-resistant sandstones and siltstones interbedded with more erosive shales producing the stairstep stream profile. The predominant geologic outcrop within the study reach is the Upper Cretaceous Mesa Verde Formation, which consists of interbedded sandstones, siltstones, and shales. The Cretaceous Mancos Shale is present along the lower part of the study area. Geologic formations in the area generally dip 5 degrees north into the Grand Mesa (Brooks, 1983; Ellis and others, 1987). Previous geologic investigations located a subsurface fault 3 mi north of Paonia, mapped along the profile of Terror Creek in the study reach (Brooks, 1983; Ellis and others, 1987; and Dunrud, 1976). The mapped subsurface fault along Terror Creek is related to regional tectonics occurring well before Terror Creek existed. Faulting and fracturing may have been exacerbated by mining and other anthropogenic activities over the last 100 years.

The study reach contains economic deposits of bituminous coal bound by layers of shale and sandstone within the Mesa Verde Formation. The deposits are present intermittently as much as 600 ft above the Rollins Sandstone Member, a 150-ft-thick basal sandstone unit of the Mesa Verde Formation (Brooks, 1983). The most likely coal bed to be mined in the study area (D-seam) is located more than 200 ft above the Rollins Sandstone (Brooks, 1983; Dunrud, 1976). The D-seam occurs locally within the mine-permit area along the Terror Creek study reach.

Hydrology

Terror Creek is a perennial stream comprised of the East and West Forks Terror Creek. Two USGS streamflow-gaging stations are currently active (2001–present) along Terror Creek and bracket the study reach (fig. 1). The upstream station is on East Fork Terror Creek (USGS 09132985, East Fork Terror Creek below Cottonwood Stomp near Bowie, Colo.). The downstream station is near the mouth of Terror Creek (USGS 09132995, Terror Creek at Mouth near Bowie, Colo.). No streamflow-gaging stations are located on West Fork Terror Creek. Streamflow conditions on East Fork Terror Creek are supplemented by Terror Creek Reservoir. Streamflow conditions on West Fork Terror Creek are more natural (not reservoir supplemented). The Garvin Mesa Diversion is downstream from the study reach and was actively diverting water during both measurement sets (fig. 1). This diversion structure provides water locally along the Garvin Mesa for irrigation needs. Approximately 6 ft^3/s of streamflow is diverted from Terror Creek from early spring to late fall. No actively flowing tributaries or diversions were present in the study reach during either measurement set.

Most of Terror Creek streamflow is derived from snowmelt runoff. The highest streamflows at the mouth occur during early spring, with peak streamflow generally occurring in late April or early May (fig. 2). Reservoir operations decrease peak streamflows in East Fork Terror Creek and attenuate the hydrograph (fig. 2*A*). Snowmelt runoff stored in Terror Creek Reservoir is released from early summer to late fall to augment streamflow available for diversion to Garvin Mesa. In 2003, releases from Terror Creek Reservoir augmented the stream

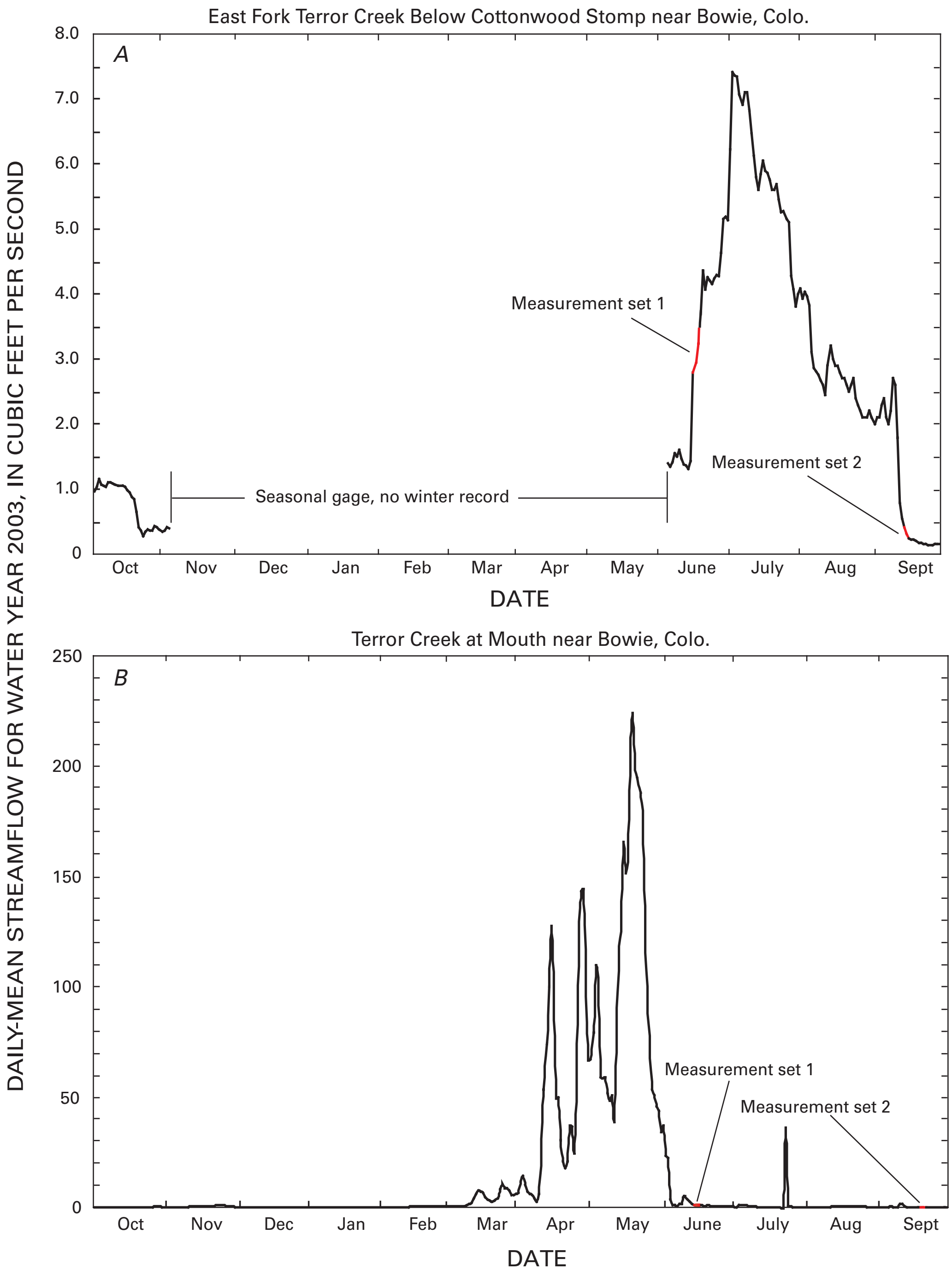

Figure 2. Daily-mean streamflow at USGS streamflow-gaging stations (*A*) East Fork Terror Creek Below Cottonwood Stomp near Bowie, Colo., and (*B*) Terror Creek at Mouth near Bowie, Colo., for water year 2003.

flow in East Fork Terror Creek with streamflows greater than 2.0 ft^3/s from early June to mid-September, whereas streamflow along Terror Creek at Mouth receded below 2.0 ft^3/s after May (fig. 2B). Numerous ephemeral tributaries also contribute to Terror Creek during spring runoff and the monsoon season of late summer.

Previous Studies

Previous published reports of interest regarding the Terror Creek area include a report by Brooks (1983) that describes the hydrology and subsidence potential of coal-lease tracts in Delta County and a report by Dunrud (1976) that describes geologic factors controlling coal-mine subsidence in Utah and Colorado. Maps of interest include a digital geologic map of Colorado by Green (1992) and a geologic coal map by Ellis and others (1987).

Acknowledgments

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Methods

A preliminary reconnaissance of the study area in October 2001 showed that the stream channel consists mostly of large cobbles and boulders. The stream channel is commonly braided in areas of relatively flat gradient and consists of one or more small riffles and cascades in areas of steeper gradient. These conditions preclude the use of traditional current-meter measurements that use the standard discharge techniques described by Rantz and others (1982) because of discrepancies in the theoretical and observed vertical velocity profile of the stream (Marchand and others, 1984). Larger sized bed material such as boulders, in combination with steep gradients (greater than 0.01 slopes), produce nonlogarithmic vertical velocity profiles. Under these conditions, traditional current-meter measurements tend to underestimate the true velocity and streamflow (Marchand and others, 1984). Therefore, the decision was made to measure streamflow in Terror Creek using tracers with the discharge by dilution method. This method uses the principle of conservation of mass to calculate streamflow (Rantz and others, 1982).

Two sets of measurements were made to determine the streamflow gain-loss characteristics of Terror Creek. Measurement set 1 was done June 17–18, 2003, during reservoir-supplemented streamflow conditions. Measurement set 2 was done September 16–17, 2003, during low base-flow conditions. These two time periods were selected to determine seasonal gain-loss (hydrologic condition) differences in the gain-loss characteristics of Terror Creek.

Streamflow Determination

A variety of methods are available to determine streamflow using the discharge by dilution method (Rantz and others, 1982). Two commonly used methods are the sudden-injection method (slug injection) and the constant-rate-injection method. The differences between these methods are based on the manner in which the tracer, or injectate, is introduced into the stream (see Rantz and others [1982] for a detailed comparison). The constant-rate-injection method was used for this investigation.

Discharge by Constant-Rate-Injection Method

Streamflow was determined in the Terror Creek study reach by using the constant-rate-injection method described in Rantz and others (1982) and Zellweger (1994). Preliminary assessment and previous investigations suggested that Terror Creek contains stream segments that are losing streamflow volume within the study reach; traditional discharge measurements by tracer-injection methods cannot indicate loss of streamflow volume (Zellweger, 1994). Therefore, a modified method of discharge determination was used to account for streamflow losses through the use of multiple-injection locations as suggested by Zellweger (1994) and hereinafter referred to as "the multiple-tracer method." Separate injections at seven measurement locations were coordinated throughout the length of the study reach along Terror Creek (fig. 1). A schematic diagram of the study reach is provided in figure 3. The streamflow determined at each measurement location will be construed as a point measurement for that location and time, which are comparable to streamflow measurements at other locations. It was assumed for this investigation that no decreases in streamflow volumes occurred in the mixing zones of each tracer-injection measurement.

A solution of sodium bromide was selected for the tracer injectate; changes in bromide concentrations were used to determine streamflow following the principle of conservation of mass. Bromide was selected as the tracer constituent because it is conservative and unique to the water chemistry of Terror Creek. The streamflow was computed, as shown in equation 1 (Rantz and others, 1982), which follows:

$$Q_B C_B + Q_I C_I = (Q_B + Q_I) C_2$$

or

$$Q_B = \frac{(C_I - C_2) Q_I}{(C_2 - C_B) K} \tag{1}$$

where

Q_B is the discharge of the stream, in cubic feet per second;

C_B is the background bromide concentration of the stream, in milligrams per liter;

Q_1 is the rate of flow of the injected tracer solution, in liters per minute;

C_1 is the bromide concentration of the tracer solution injectate, in milligrams per liter;

C_2 is the downstream bromide concentration, completely mixed with the stream, in milligrams per liter; and

K is a metric to standard units conversion factor (1.6992×10^3).

A solution of sodium bromide was prepared for use as the injectate for the tracers and was prepared for each tracer individually by combining about 4.34 lb of sodium bromide to about 1.3 gal of streamwater from each injection site. The applicable measurement procedures, such as tracer volume, injection rate, injection duration, and tracer-sampling location and timing, followed the methods prescribed in Kilpatrick and Cobb (1985) and in Kilpatrick and Wilson (1989). A log of specific conductance was collected at each measurement location to demonstrate that the bromide concentration had reached a plateau, indicating that complete mixing of the injectate solution had occurred before sampling.

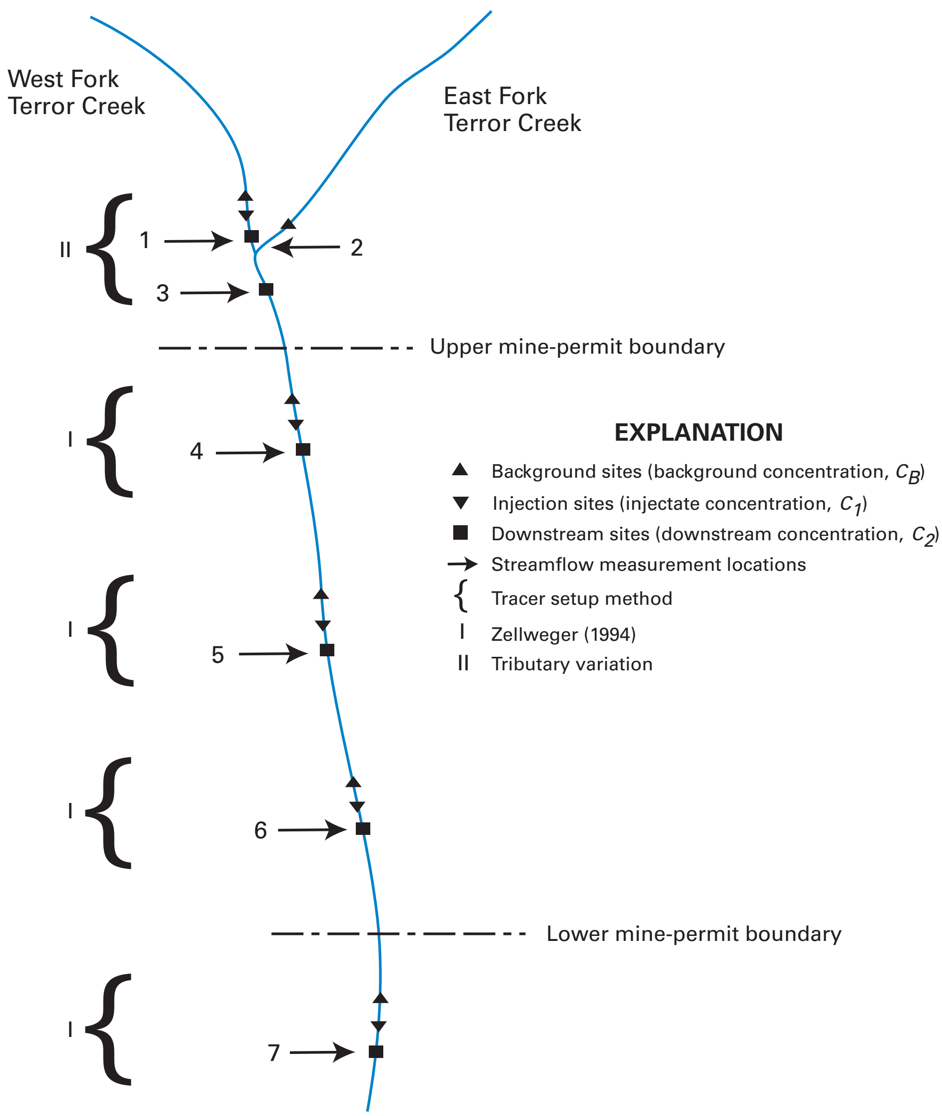

Figure 3. Tracer design schematic diagram modeled after (I) Zellweger (1994) and (II) tributary variation.

Measurement Location and Site Selection

Streamflow was determined at seven measurement locations in the study area: (1 and 2) immediately upstream from the confluence of East and West Forks Terror Creek; (3) immediately downstream from the confluence of East and West Forks Terror Creek, above the upstream boundary of the mine-permit area; (4, 5, and 6) at intermediate points within the mine-permit area; and (7) downstream from the downstream boundary of the mine-permit area, which is about 0.5 mi upstream from Garvin Mesa Diversion (figs. 1 and 3). The general positions of these measurement locations were selected at roughly equal spacing to best determine the gain-loss characteristics of the stream and to bracket gain-loss features controlled by tributaries and geology.

The specific position of each measurement location was selected in the field on the basis of discharge-measurement criteria and was mapped using a global positioning system. Streamflow values for each measurement location required three sampling sites and one injection site. The sampling sites were marked with flagging in the field, and the same sample and injection-site locations were used for both measurement sets. The arrangement of these sites follows the design of Zellweger (1994) and consists of a background site upstream from the injection site (background concentration), the injection site (injectate concentration), and a site downstream from the injection site (downstream concentration) (fig. 3I). The measurement-location position is coincident with the downstream sampling site. A variation of this design (tributary variation) was made at the uppermost tracer (measurement locations 1, 2, and 3), which allowed for the determination of streamflow at both East and West Forks Terror Creek through a single-tracer injection. To facilitate the determination of streamflow for each fork of Terror Creek, two background samples were collected (one upstream from the injection site on West Fork Terror Creek and one on East Fork Terror Creek), two downstream samples were collected (one downstream from the injection site and upstream from the confluence on West Fork Terror Creek, and one downstream from the confluence), and one injection sample is needed (fig. 3II). Streamflow in East Fork Terror Creek (measurement location 2) is assumed to be the difference between the streamflow downstream from the confluence (measurement location 3) and West Fork Terror Creek at the mouth (measurement location 1).

Accounting for Streamflow Variation

In order to understand the timing of streamflow, a preliminary assessment of the hydrologic conditions (before each measurement set) was done on discharge records for the two USGS streamflow-gaging stations located along Terror Creek: the upstream station (09132985) East Fork Terror Creek and the downstream station (09132995) Terror Creek at Mouth (fig. 1). The streamflow-gaging-station discharge record for East Fork Terror Creek was used to examine the hydrology upstream from the East and West Forks Terror Creek confluence. Interpretation is limited because the discharge record represents a reservoir-supplemented streamflow system controlled in part by Terror Creek Reservoir releases and does not match the more natural streamflow conditions in West Fork Terror Creek. The streamflow-gaging station discharge record for Terror Creek at Mouth was used to examine the hydrology of Terror Creek downstream from the confluence of East and West Forks Terror Creek; however, the Garvin Mesa Diversion structure downstream from the study area (but upstream from the Terror Creek at Mouth streamflow-gaging station) typically diverts a considerable portion of the streamflow during high-flow conditions and almost all of the streamflow during low-flow conditions. This diversion does not directly affect the gain-loss characteristics of the study reach on Terror Creek, but it does limit the usefulness of the streamflow record for purposes of examining hydrologic conditions during each measurement set.

Hydrologic conditions for measurement set 1 were evaluated for the period leading up to the measurement set. This information was needed so adjustments to pump rates and injection concentrations could be made just prior to the beginning of the injection to account for streamflow variations. A 10-day excerpt from the hydrograph bracketing the time period for measurement set 1 is shown in figure 4*A* for the East Fork Terror Creek streamflow-gaging station. Interpretation of the record for measurement set 1 shows substantial step increases in streamflow for the days immediately preceding measurement set 1, caused by increased releases from Terror Creek Reservoir. A 10-day excerpt from the hydrograph bracketing the time period for measurement set 1 is included in figure 4*B* for Terror Creek at Mouth streamflow-gaging station. Interpretation of the record for measurement set 1 shows substantial fluctuations of streamflow, probably resulting from a combination of increased releases from Terror Creek Reservoir and variable adjustments to the Garvin Mesa Diversion structure downstream from the study area.

Stairstep increases in streamflow observed in the 10-day period of gage record during measurement set 1 (caused by reservoir releases) precluded the direct comparison of the streamflow measurements at the seven measurement locations. This is because the variations in streamflow observed in the gage record due to the reservoir releases could indicate false increases or decreases in streamflow simply because of unresolved timing issues. To provide a better comparison of streamflow measurements among measurement locations for streamflow gain-loss analysis for measurement set 1, the multiple-tracer method was modified to include an estimate of traveltimes between measurement locations. This method was necessary to compensate for the reservoir release variations from East Fork Terror Creek and hereinafter will be referred to as the "modified multiple-tracer method."

The modified multiple-tracer method relies on the pairing of measurement locations to a reference measurement location (measurement location 3 was selected for this purpose), so adjustments to start times for tracer injections and sampling can coincide with the traveltime between reference measurement

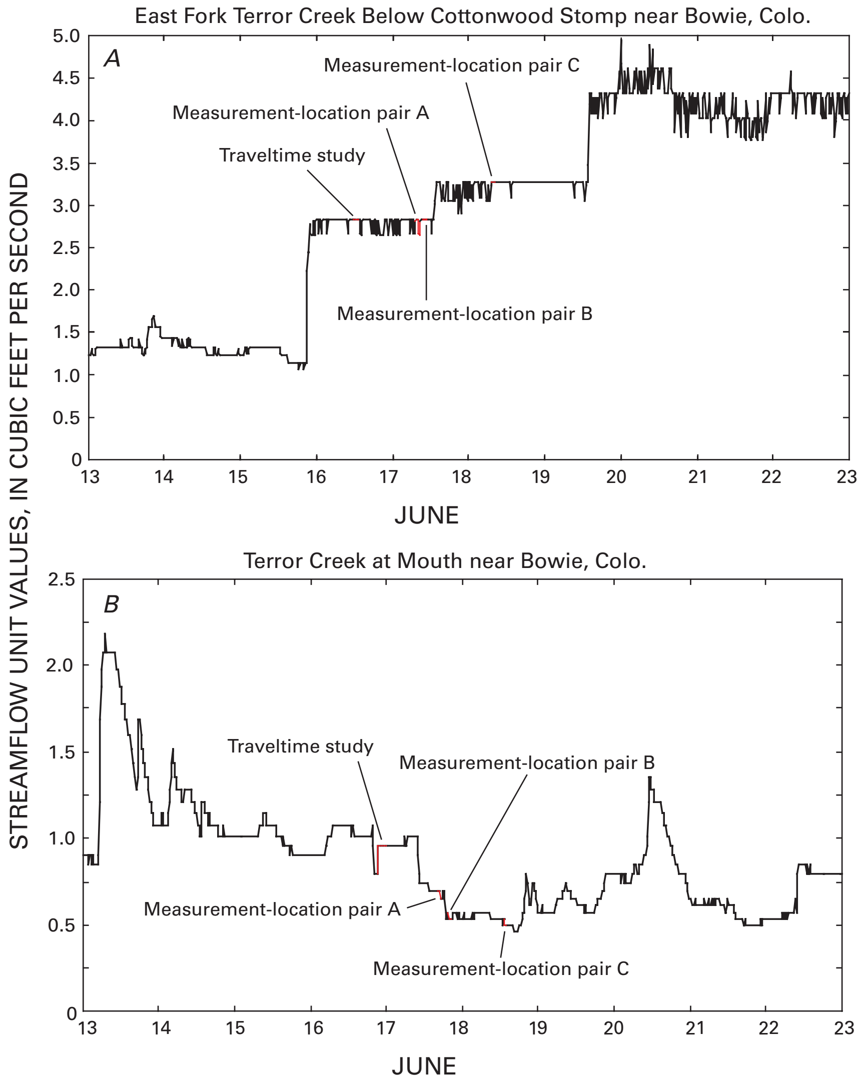

Figure 4. Streamflow unit values bracketing measurement set 1 at USGS streamflow-gaging stations (*A*) East Fork Terror Creek Below Cottonwood Stomp near Bowie, Colo., and (*B*) Terror Creek at Mouth near Bowie, Colo., for water year 2003.

location 3 and the downstream measurement locations. This modification to the multiple-tracer method facilitates the measurement of the same package of water at two different measurement locations (measurement-location pairs A–C) and determination of relative changes in streamflow volume between measurement locations associated with real streamflow gain-loss rather than reservoir-release variations.

A sodium chloride single-point slug injection was performed to determine streamflow traveltimes between measurement locations in the study reach on June 16, 2003. A single injection of concentrated sodium chloride was traced downstream from measurement location 3 to each measurement location included in measurement set 1using specific-conductance values. The traveltimes were defined by the difference in times between the arrivals of the sodium chloride between measurement locations (Hubbard and others, 1982; Kimball, 1996) (fig. 5) as indicated by specific conductance logs. Specific conductance was measured at measurement locations 4, 5, and 7 (table 1); traveltimes originated from measurement location 3. Measurement location 6 was not visited during measurement set 1.

Hydrologic conditions for measurement set 2 were evaluated for the days before the measurement set. This information was needed so adjustments to pump rates and injection concentrations could be made just prior to the beginning of the injection to account for streamflow variations. A 10-day excerpt from the hydrograph bracketing the time period for measurement set 2 is included in figure 6*A* for East Fork Terror Creek streamflow-gaging station. Interpretation of the record for measurement set 2 shows no substantial fluctuation of streamflow, and the stream appears to be at a steady-state hydrologic condition for the days immediately preceding measurement set 2. A 10-day excerpt from the hydrograph bracketing the time period for measurement set 2 is included in figure 6*B* for the Terror

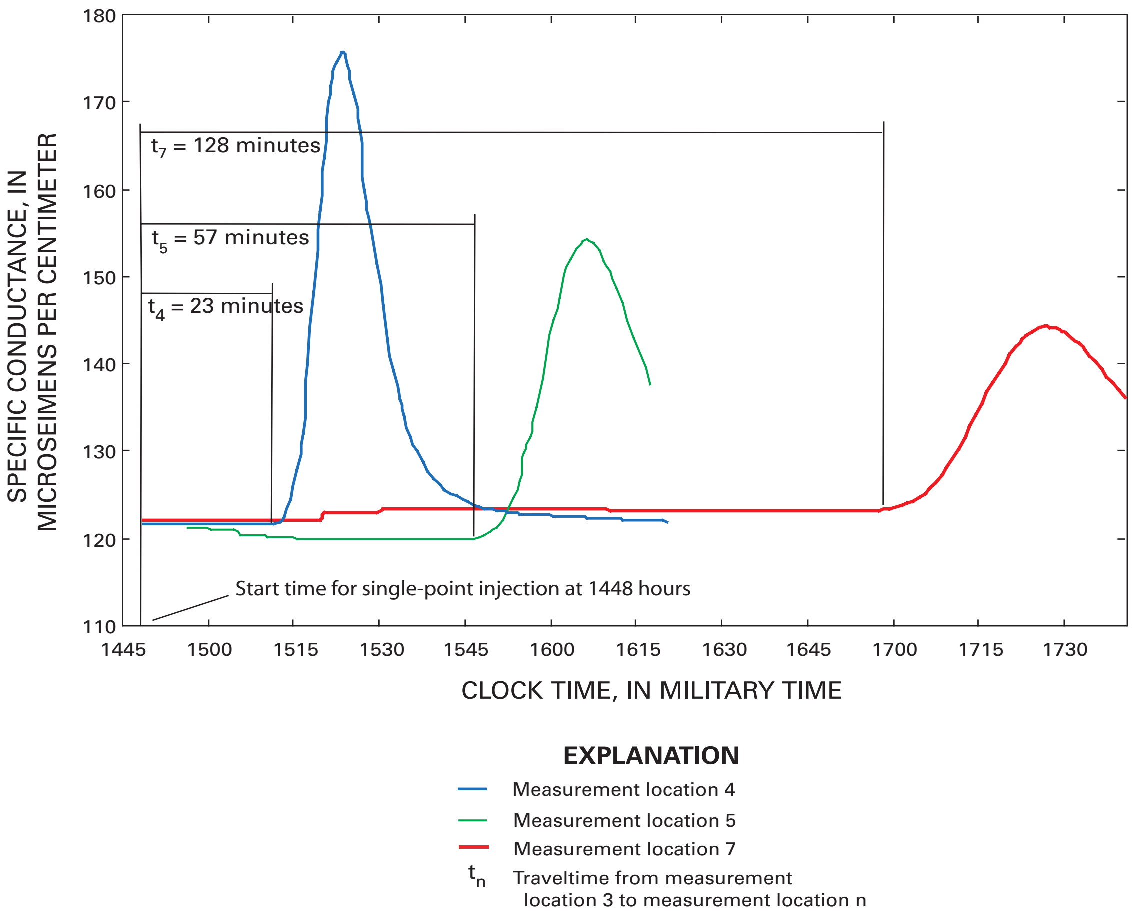

Figure 5. Specific-conductance log for traveltime determination following the single-point injection method for measurement set 1, Terror Creek, Colo.

Table 1. Relative traveltimes for use in the modified multiple-tracer method, measuremen t set 1, Terror Creek, Colo., water year 2003.

[--, not measured]

Streamflow measurement location or streamflow gaging station	Relative traveltimes, in minutes		
	[2]09132985	[1]3	[2]09132995
09132985	0	--	571
1	--	--	419
2	153	--	418
3	160	0	411
4	183	23	388
5	217	57	354
6	--	--	--
7	288	128	283
09132995	571	--	0

[1]Traveltimes measured using the single-point slug-injection method.

[2]Estimation of traveltimes using a combination of the average velocity from the single-point slug-injection method and the calculation of traveltimes measured using the single-point slug-injection method.

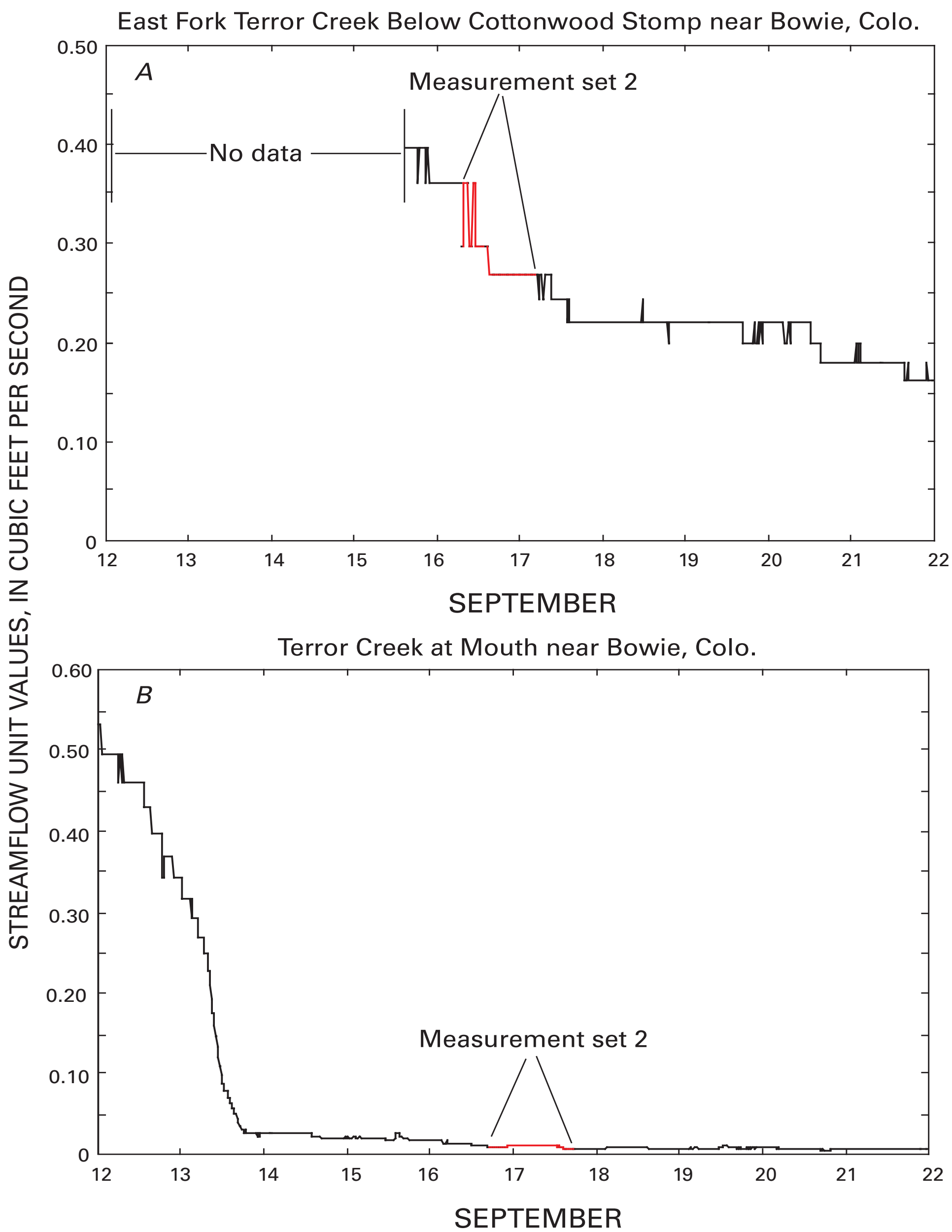

Figure 6. Streamflow unit values bracketing measurement set 2 at USGS streamflow-gaging stations (*A*) East Fork Terror Creek Below Cottonwood Stomp near Bowie, Colo., and (*B*) Terror Creek at Mouth near Bowie, Colo., for water year 2003.

Creek at Mouth streamflow-gaging station. Interpretation of the record for measurement set 2 shows no substantial fluctuation of streamflow; however, the Garvin Mesa diversion structure downstream from the study area was diverting most of the water in Terror Creek, preventing a more precise characterization of streamflow conditions present in West Fork Terror Creek. Based on available data, Terror Creek was assumed to be in a steady-state hydrologic condition, and no adjustments or modifications to the multiple-tracer method were necessary for measurement set 2.

Water-Sample Collection and Analysis

Water samples from each tracer measurement location were collected and analyzed for use in equation 1 of the constant-rate-injection method. The field methods used for the collection, processing, filtration, and preservation of inorganic constituents follow the guidelines listed in the USGS National Field Manual for the Collection of Water-Quality Data (Wilde and others, 2003).

Water-Sampling Techniques

Water samples were collected at each measurement location in areas where the stream was confined to a single-channel cascade or bedrock ledge to ensure maximum stream mixing. Samples were collected in 1-L high-density polyethylene bottles after being field rinsed with native streamwater at each measurement location. Owing to shallow depths, narrow widths, and turbulent conditions, collection of the samples was done by using the single-point grab method (Wilde and others, 2003). The samples were transported to a central processing location near measurement location 3 as soon after collection as possible. Samples were filtered through a 0.45-micron capsule filter into 250-mL high-density polyethylene bottles. Forty-one environmental samples were collected during the investigation: 24 samples were collected during measurement set 1 (table 2), and 17 samples were collected during measurement set 2 (table 3). In addition, five quality-assurance samples were collected during the investigation. Two quality-assurance field blanks were collected during the investigation, one during each measurement set. Three concurrent replicate pairs (two samples collected at the same time) were collected: two during measurement set 1, and one during measurement set 2. One sample was destroyed during shipping (measurement location 1, 06/17/03, 1211, C_2), which prevented the determination of one streamflow value each for measurement locations 1 and 2 during measurement set 1.

Quality assurance of field-method techniques was done for each measurement set. Field-blank samples of deionized water certified to be free of detectable amounts of trace elements were analyzed to determine if field methods contaminated the water sample with bromide. The blank samples were collected, pro

Table 2. Measurement set 1-Results for modified multiple-tracer method, Terror Creek, Colo., water year 2003.

[C_1, injectate bromide concentration; C_2, downstream bromide concentration; C_B, background bromide concentration; Q_1, rate of flow of the injectate; Q_B, measured streamflow; Q_B / $Q_{B\,3}$, measured streamflow expressed as percentage of streamflow at measurement location 3 within each measurement-location pair; S_{QB}, streamflow measurement error; mg/L, milligrams per liter; L/min, liters per minute; ft^3/s, cubic feet per second; --, no data or not applicable]

Streamflow measurement location	Tracer injections		Variables from equation 1						Error propagation	
	Date	Time	C_B (mg/L)	C_1 (mg/L)	Q_1 (L/min)	C_2 (mg/L)	Q_B (ft^3/s)	$Q_B / Q_{B\,3}$ (percent)	S_{QB} (ft^3/s)	S_{QB} (percent)
East and West Fork Terror Creek coincident with measurement-location pair A										
1	06/17/03	1107	0.00	268,300	0.0600	--[1]	--	--	--	--
2	06/17/03	1107	--	--	--	--	--	--	--	--
Measurement-location pair A										
3	06/17/03	1107	0.00	268,300	0.0600	1.61	5.90	100	0.186	3.2
4	06/17/03	1130	1.44	256,700	0.0910	3.72	6.04	102	0.136	2.3
East and West Fork Terror Creek coincident with measurement-location pair B										
1	06/17/03	1403	0.00	267,100	0.0838	4.15	3.17	48	0.046	1.5
2	06/17/03	1403	--	--	--	--	3.50	52	0.177	5.0
Measurement-location pair B										
3	06/17/03	1403	0.00	267,100	0.0838	1.97	6.67	100	0.170	2.6
5	06/17/03	1500	2.39	264,800	0.0825	3.62	10.47	157	0.413	3.9
East and West Fork Terror Creek coincident with measurement-location pair C										
1	06/18/03	1100	0.00	267,600	0.0860	4.80	2.82	40	0.038	1.3
2	06/18/03	1100	--	--	--	--	4.20	60	0.186	4.4
Measurement-location pair C										
3	06/18/03	1100	0.00	267,600	0.0860	1.93	7.02	100	0.183	2.6
7	06/18/03	1308	1.48	253,900	0.0840	3.36	6.65	95	0.177	2.7

[1]Sample destroyed during shipping.

Table 3. Measurement set 2-Results for multiple-tracer method, Terror Creek, Colo., water year 2003.

[C_I, injectate bromide concentration; C_2, downstream bromide concentration; C_B, background bromide concentration; Q_I, rate of flow of the injectate; Q_B, measured streamflow; Q_B / $Q_{B\,3}$, measured streamflow expressed as percentage of streamflow at measurement location 3; S_{QB}, streamflow measurement error; mg/L, milligrams per liter; L/min, liters per minute; ft^3/s, cubic feet per second; --, no data or not applicable]

Streamflow measurement location	Tracer injections		Variables from equation 1						Error propagation	
	Date	Time	C_B (mg/L)	C_1 (mg/L)	Q_1 (L/min)	C_2 (mg/L)	Q_B (ft^3/s)	Q_B / $Q_{B\,3}$ (percent)	S_{QB} (ft^3/s)	S_{QB} (percent)
1	09/16/03	1718	0.00	261,800	0.0713	4.96	2.21	81	0.031	1.4
2	09/16/03	1718	--	--	--	--	0.51	19	0.053	10.4
3	09/16/03	1718	0.00	261,800	0.0713	4.04	2.72	100	0.043	1.6
4	09/16/03	1406	0.00	267,800	0.0731	4.20	2.74	101	0.041	1.5
5	09/16/03	1138	0.00	265,600	0.0808	4.06	3.11	114	0.047	1.5
6	09/17/03	1340	0.00	271,800	0.0625	4.22	2.37	87	0.038	1.6
7	09/17/03	1137	0.00	270,100	0.0738	4.87	2.41	88	0.034	1.4

cessed, preserved, and transported using the same techniques and locations as the environmental samples. Analysis of the two blank samples determined that bromide concentrations of the blank samples were at or near the detection limit of the analysis method and considered to be insignificant as a bias to the results. The three concurrent replicate pairs were collected to determine the repeatability (precision) of the water-sampling methods. Analytical results for the concurrent replicates incorporate the variations inherent in sampling, processing, and preservation methods and allow an estimate of the precision of the streamflow measurements through error analysis. The use of the replicate results for error analysis is discussed in the Error Analysis section.

Analytical Techniques

Water samples were analyzed for bromide using two methods: (1) low-ionic-strength bromide detection was performed on stream samples (background and downstream concentrations) by the USGS National Water-Quality Laboratory (NWQL) in Denver, Colo., and (2) high-ionic-strength bromide detection was performed on the tracer-injectate solution by the USGS Colorado District Laboratory in Lakewood, Colo. Two separate methods are required to measure the bromide concentrations in this investigation based on the extreme differences of ionic strengths between the stream samples and the injectate solutions. The low-ionic-strength detection techniques for bromide are determined using colorimetric procedures (Fishman and Friedman, 1989). The high-ionic-strength detection techniques for bromide are determined using a gravimetric method to determine the residue on evaporation (Fishman and Friedman, 1989).

Quality assurance of analytical techniques was conducted for each measurement set. Replicate samples and standardized samples were analyzed for the low-ionic and high-ionic bromide detection methods. The low-ionic method is internally monitored at the USGS NWQL through in-house testing programs according to their quality-assurance plan (Michael Lewis, U.S. Geological Survey, written commun., 2004). The high-ionic bromide detection methods also were checked for precision by using replicate samples from the investigation. A comparison of the values reflects the repeatability (precision) of the procedures. Precision is used in the following section to estimate error associated with measuring streamflow by using the constant-rate-injection method.

Error Analysis

In order to determine the compounded effects of measurement error on the streamflow calculations from equation 1, error analysis was performed on each measurement set by using error-propagation techniques. Error introduced through field methods (sampling, processing, preservation, and shipping) as well as analytical methods (storage, processing, and analysis) are estimated on the basis of the standard deviation of the differences between replicate measurements for each variable in equation 1.

A correction factor was applied to the resulting standard deviations to compensate for the loss of degrees of freedom resulting from the calculations of the differences between replicate measurements and each mean for the sample. This correction factor is consistent with techniques used in analysis of variance techniques described by Helsel and Hirsch (2002) and Ott and Longnecker (2001) and is included in the calculation of the standard deviation. The equation used for the calculation of the standard deviation is shown in equation 2 (Helsel and Hirsch, 2002), which follows:

$$S = \sqrt{S^2} = \sqrt{\frac{\sum_{i=1}^{M}\sum_{j=1}^{N_i}(X_{ij} - \overline{X}_i)^2}{N - M}} \quad (2)$$

where

S is the standard deviation of the differences between replicate samples and their means,

S^2 is the variance of the differences between replicate samples and their means,

X_{ij} is the jth replicate for sample i,

$\overline{X}_i$ is the mean of the replicates for sample i,

N_i is the number of replicates for sample i,

M is the number of samples, and

N is the total number of replicates for all samples.

Sensitivity Analysis

Evaluation of the sensitivity of each parameter in equation 1 allows for the determination of the extent to which uncertainty in the variables results in uncertainty of the streamflow measurements. A comparison of these absolute sensitivities provides the error in streamflow for one unit of measure for the variable. The partial derivative of equation 1 is calculated with respect to each variable. The calculation of these values follows the forms:

$$\frac{\partial Q_B}{\partial C_B} = \frac{(C_1 - C_2)Q_1}{(C_2 - C_B)^2 K} \quad (3)$$

$$\frac{\partial Q_B}{\partial C_1} = \frac{Q_1}{(C_2 - C_B)K} \quad (4)$$

$$\frac{\partial Q_B}{\partial C_2} = \frac{(C_B - C_1)Q_1}{(C_2 - C_B)^2 K} \quad (5)$$

$$\frac{\partial Q_B}{\partial Q_1} = \frac{(C_1 - C_2)}{(C_2 - C_B)K} \quad (6)$$

where

$\frac{\partial Q_B}{\partial C_B}$ is the change in Q_B (cubic feet per second) relative to change in C_B (milligrams per liter),

$\frac{\partial Q_B}{\partial C_1}$ is the change in Q_B (cubic feet per second) relative to change in C_1 (milligrams per liter),

$\frac{\partial Q_B}{\partial C_2}$ is the change in Q_B (cubic feet per second) relative to change in C_2 (milligrams per liter),

$\frac{\partial Q_B}{\partial Q_1}$ is the change in Q_B (cubic feet per second) relative to change in Q_1 (liters per minute),

Q_B is the discharge of the stream (cubic feet per second),

C_B is the background bromide concentration of the stream (milligrams per liter),

C_1 is the bromide concentration of the tracer solution injectate (milligrams per liter),

C_2 is the downstream bromide concentration, completely mixed with the stream (milligrams per liter),

Q_1 is the rate of flow of the injected tracer solution (liters per minute), and

K is a metric to standard units conversion factor (1.6992×10^3).

Because the units of each variable are different, a relative sensitivity can be compared between variables in units of percent change in streamflow per percent change in each variable. The values now indicate a unitless percentage, which allows all of the variables to be directly compared. When these values are compared to the standard deviation of each variable, the level of error introduced from the measurement of each variable can be determined. Comparisons between variables can indicate field and analytical method improvements necessary to reduce the error of the calculations.

Error Propagation

The error inherent to the constant-rate-injection streamflow measurement method was quantified using error analysis. Following the rules of error propagation described in Bevington and Robinson (2003) and Taylor (1997), a Taylor Series was used to determine the error-propagation equation, which calculates the error in streamflow resulting from the error of the field and analytical methods. The calculation of the standard deviation of the streamflow error is based on the following equation:

$$S_{Q_B} = \sqrt{S^2{}_{Q_B}} = \sqrt{\left(\frac{\partial Q_B}{\partial C_B}\right)^2 S^2{}_{C_B} + \left(\frac{\partial Q_B}{\partial C_1}\right)^2 S^2{}_{C_1} + \left(\frac{\partial Q_B}{\partial C_2}\right)^2 S^2{}_{C_2} + \left(\frac{\partial Q_B}{\partial Q_1}\right)^2 S^2{}_{Q_1}} \quad (7)$$

where

S_{Q_B} is the standard deviation of error in Q_B (cubic feet per second),

$S^2{}_{Q_B}$ is the variance of the error in Q_B (cubic feet per second) squared,

$S^2{}_{C_B}$ is the variance of the error in C_B (milligrams per liter) squared,

$S^2{}_{C_1}$ is the variance of the error C_1 (milligrams per liter) squared,

$S^2{}_{C_2}$ is the variance of the error C_2 (milligrams per liter) squared,

$S^2{}_{Q_1}$ is the variance of the error Q_1 (liter per minute) squared,

$\frac{\partial Q_B}{\partial C_B}$ is the change in Q_B (cubic feet per second) relative to change in C_B (milligrams per liter),

$\frac{\partial Q_B}{\partial C_1}$ is the change in Q_B (cubic feet per second) relative to change in C_1 (milligrams per liter),

$\frac{\partial Q_B}{\partial C_2}$ is the change in Q_B (cubic feet per second) relative to change in C_2 (milligrams per liter),

$\frac{\partial Q_B}{\partial Q_1}$ is the change in Q_B (cubic feet per second) relative to change in Q_1 (liters per minute),

Q_B is the discharge of the stream (cubic feet per second),

C_B is the background bromide concentration of the stream (milligrams per liter),

C_1 is the bromide concentration of the tracer solution injectate (milligrams per liter),

C_2 is the downstream bromide concentration, completely mixed with the stream (milligrams per liter), and

Q_1 is the rate of flow of the injected tracer solution (liters per minute).

Error analysis is used as an indicator of the accuracy of the measured streamflow value. The error-analysis calculations provide a range of streamflow values and are depicted as error bars. These error bars provide context to the certainty of the streamflow values.

Streamflow Comparisons

Streamflow measurements were compared to determine the gain-loss characteristics of the Terror Creek study reach by using two methods: a graphical comparison and statistical testing. The graphical comparison was used to determine streamflow gain-loss characteristics among the seven measurement locations (upstream to downstream). The difference in the streamflow values among measurement locations indicates streamflow gains or losses during each measurement set and corresponding streamflow condition. A comparison of the two measurement sets and previous investigations was included in the interpretation of the overall streamflow gain-loss characteristics of the Terror Creek study reach. Statistical testing was used to evaluate the significance level associated with the overall streamflow gain or loss along the study reach within the mine-permit area; confidence intervals also were calculated for the gains or losses observed within the mine-permit area during measurement sets 1 and 2. Use of a combination of these methods allows the comparison of streamflow measurements within and between the two measurement sets.

Graphical Comparison

A graphical comparison of streamflow among measurement locations was used to determine the streamflow gain-loss characteristics of the Terror Creek study reach within the same hydrologic conditions. A graphical comparison of streamflow values and the corresponding error bars allows for an assessment of the likelihood that two streamflow values are discernibly different. For this investigation, a comparison of two streamflow values with overlapping error bars indicates that the two measurements are not discernibly different; a comparison of two measurements with error bars that are not overlapping indicates that the measurement values are discernibly different.

A direct comparison of streamflow values (comparison of streamflow between measurement locations, in cubic feet per second) was used to aid in the interpretation of streamflow gain-loss characteristics between measurement locations under the same hydrologic condition (measurement locations within the same measurement-location pairs A–C during measurement set 1, and all measurement locations within measurement set 2). This method does not allow for the quantification of gain-loss characterization between measurement locations under different hydrologic conditions.

An indirect comparison of streamflow values (comparison of streamflow between measurement locations, as a percentage of streamflow at measurement location 3) was used to aid in the interpretation of streamflow gain-loss characteristics among all measurement locations within the entire study reach, even under different hydrologic conditions and measurement sets. The streamflow values are normalized to a reference measurement location (measurement location 3), which removes the variations observed in the direct comparison of streamflow values. The indirect comparison between measurement locations is possible because each pairing of a new measurement location includes the same reference measurement location (measurement location 3). Therefore, any changes in streamflow between a specific measurement location and the reference measurement location can indicate a relative change among all the measurement locations. The units are expressed as percentages of the streamflow at measurement location 3 and can be compared across all measurement locations and measurement sets. This removes any erroneously perceived streamflow gains or losses, which actually are the result of variations in reservoir releases from Terror Creek Reservoir.

Statistical Comparison

Statistical tests are a second means by which a comparison of streamflow values is possible. Statistical testing was not done for each comparison of streamflow values, because the number of comparable streamflow values is insufficient for testing statistical significance (p-values <0.05) to be determined regardless of the magnitude of difference between streamflows. Statistical testing of streamflow values for the overall streamflow gain-loss (streamflow gain-loss indicated by the difference of streamflow values downstream and upstream from the mine-permit area) was performed, in addition to the graphical assessment previously described, because three sets of measurements are available for measurement locations 3 and 7 (including results of a previous study done by Brooks [1983]). Because of the small sample size available for statistical testing, a comparison of parametric (required assumptions: normality of distribution, independent sample pairs, and equal variance between data sets) and nonparametric (required assumptions: symmetric distribution about the median) methods was considered necessary. Under parametric assumptions, the paired t-test is appropriate for the comparison of streamflow for measurement locations 3 and 7 for measurement sets 1 and 2; under nonparametric assumptions, the exact Wilcoxon signed-rank test is appropriate for measurement sets 1 and 2, as well as the previous investigation by Brooks (1983), following guidelines described by Helsel and Hirsch (2002) and Ott and Longnecker (2001). Confidence intervals were calculated to quantify the certainty of the overall streamflow gain-loss observed for measurement sets 1 and 2. In this context, the comparison of streamflow measurements will be presented to determine the streamflow gain-loss characteristics of the Terror Creek study reach.

Evaluation of Streamflow Gain-Loss Characteristics

The determination of streamflow gain-loss characteristics for the study reach of Terror Creek included seven measurement locations and two measurement sets. A comparison of streamflow at measurement locations (from upstream to downstream) was used to quantify and locate gain-loss characteristics in the Terror Creek study reach. Quantification of the gain-loss characteristics was based on the direct (quantity) and indirect (percentage normalized to measurement location 3) comparison of streamflow measurements at the seven measurement locations visited during the study, as well as a statistical assessment of the difference in streamflow within the mine-permit area for available measurements.

Measurement Set 1, Streamflow Gain-Loss Characteristics

Measurement set 1 began June 17, 2003, and included three measurement-location pairs (A–C) following the modified multiple-tracer method (to account for variations in the reservoir releases to East Fork Terror Creek) (table 1). Measurements were made at measurement locations 1, 2, 3, 4, 5, and 7 over a 2-day period. Details concerning tracer operation and other tracer-injection information are included in the supplemental table at the back of this report (see table 5). Bromide concentrations, calculated values for streamflow, and error analysis are presented in table 1.

The streamflow gain-loss characteristics of the Terror Creek study reach for measurement set 1 was based on the direct comparison of the streamflows within each measurement-location pair (fig. 7). The first measurement-location pair (A), measurement locations 3 and 4, shows no discernible streamflow gain or loss; the error bars for both values overlap. The second measurement-location pair (B), measurement locations 3 and 5, shows a streamflow gain of 3.80 ft^3/s. The third measurement-location pair (C), measurement locations 3 and 7, shows a moderate streamflow loss of 0.37 ft^3/s. The indicated

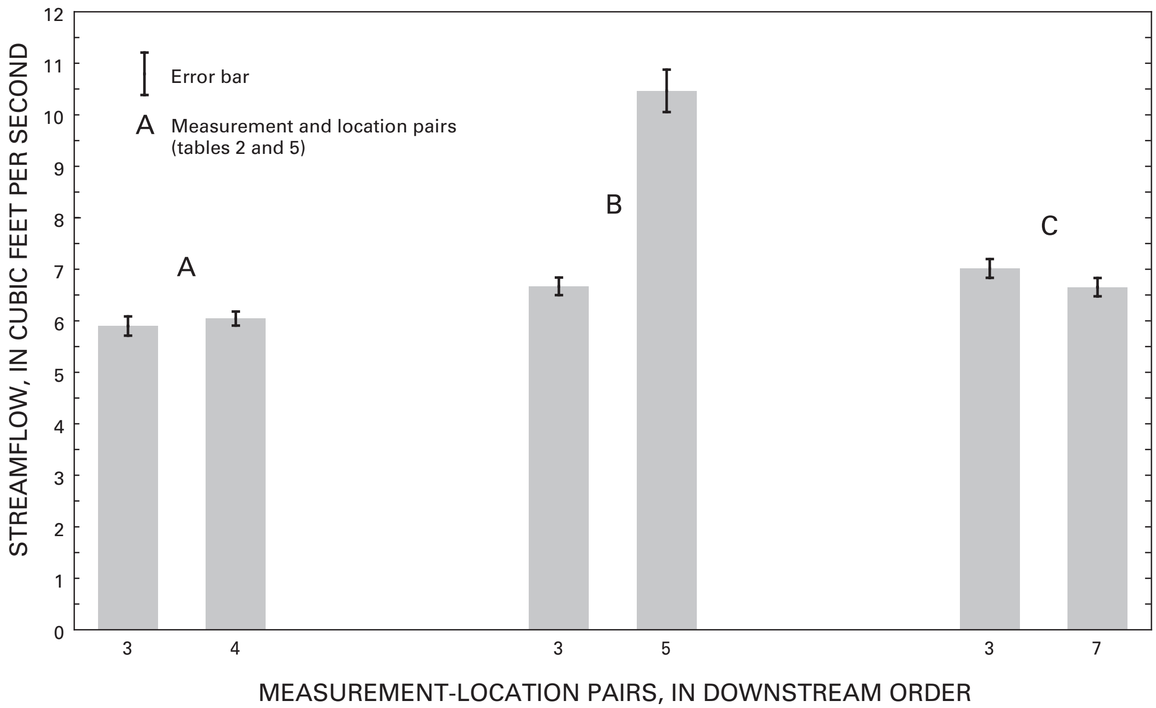

Figure 7. Comparison of streamflow between measurement-location pairs during measurement set 1, June 17–18, 2003, Terror Creek, Colo., water year 2003.

loss between measurement locations 3 and 7 is interpreted as the overall streamflow loss within the mine-permit area for measurement set 1.

In order to determine any discernible gains or losses among all measurement locations, an indirect comparison of the streamflow gain-loss (comparison of streamflow between measurement locations, normalized as a percentage of streamflow at measurement location 3) is necessary because of the stairstep increase in streamflow derived from Terror Creek Reservoir releases during measurement set 1. An indirect comparison of measurement locations 3 and 4 shows no discernible streamflow gain or loss within the precision of the measurements (fig. 8). A streamflow gain was shown between measurement locations 4 and 5, with an increase in streamflow of 55 percent normalized to measurement location 3. A streamflow loss was shown between measurement locations 5 and 7, with a decrease in streamflow of 62 percent normalized to measurement location 3.

Measurement Set 2, Streamflow Gain-Loss Characteristics

Measurement set 2 began September 16, 2003, and included five tracer injections following the multiple-tracer method. Measurements were made at measurement locations 1, 2, 3, 4, 5, 6, and 7 over a 2-day period. Details concerning tracer operation and other tracer-injection information are included in a supplemental table at the back of this report (see table 5). Bromide concentrations, calculated values for streamflow, and error analysis are presented in table 3.

The streamflow gain-loss characteristics for measurement set 2 were based on the direct comparison of each measurement location due to the steady-state hydrologic condition (fig. 9). The streamflow gain-loss characteristics of the Terror Creek study reach for measurement set 2 also was based on the indirect comparison of the streamflows for each measurement location (fig. 10). Measurement locations 3 and 4 had no discernible streamflow gain or loss. A streamflow gain was shown between measurement locations 4 and 5, with an increase in streamflow of 0.37 ft^3/s. A streamflow loss was shown between measurement locations 5 and 6, with a decrease in streamflow of 0.74 ft^3/s. No discernible streamflow gain or loss was shown between measurement locations 6 and 7. Normalized to measurement location 3, a streamflow gain of 13 percent was shown between measurement locations 4 and 5, and a streamflow loss of 27 percent was shown between measurement locations 5 and 6.

For consistency between measurement sets, each measurement location for measurement set 2 also was compared to measurement location 3. Measurement locations 3 and 5 show a streamflow gain of 0.39 ft^3/s. A streamflow loss was shown between measurement locations 3 and 6, with a decrease in streamflow of 0.35 ft^3/s. A similar streamflow loss was shown

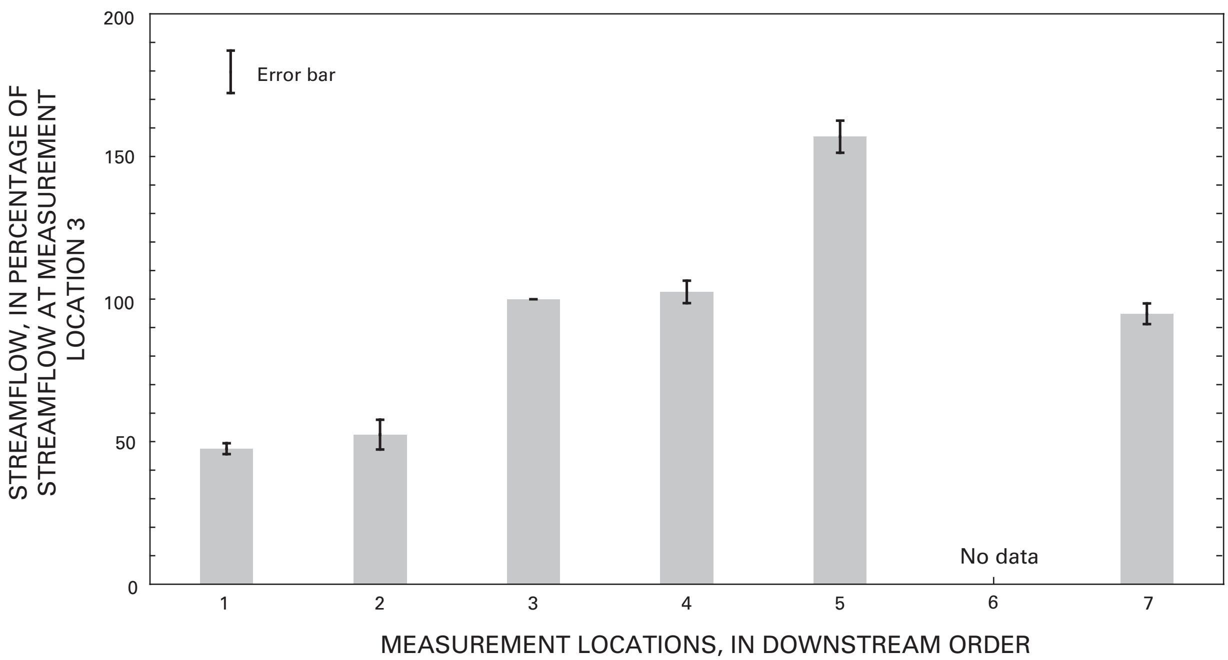

Figure 8. Comparison of relative streamflow among measurement locations during measurement set 1, June 17–18, 2003, Terror Creek, Colo., water year 2003.

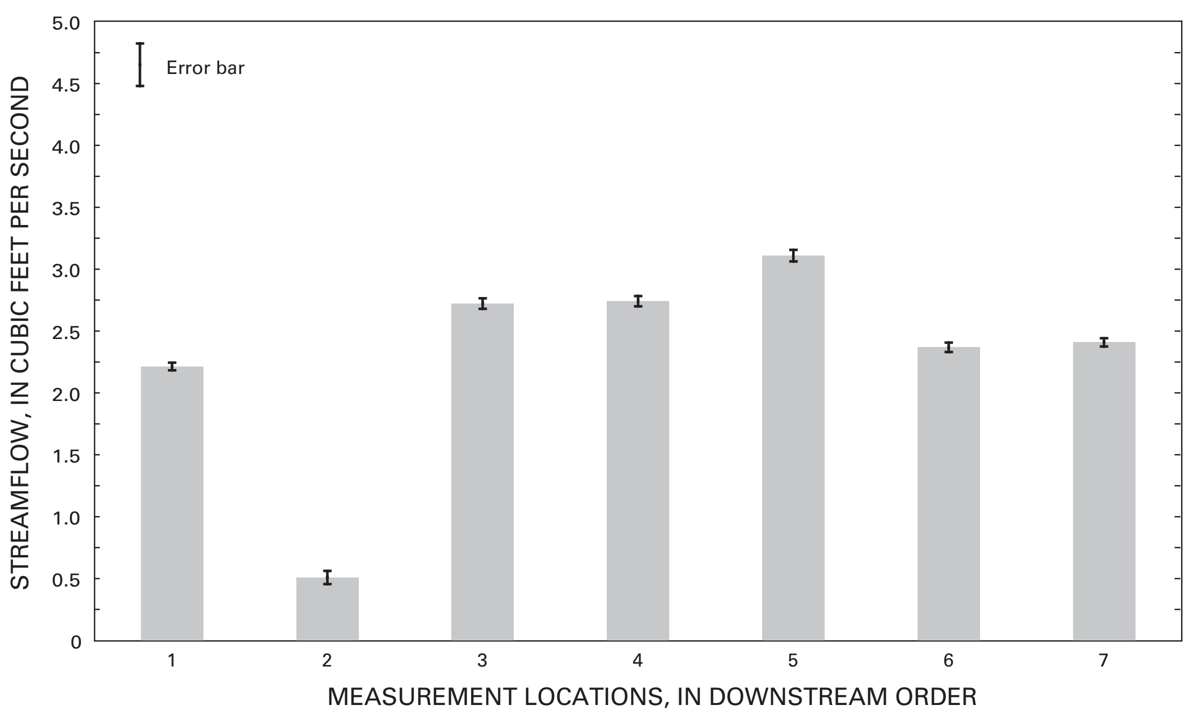

Figure 9. Comparison of streamflow among measurement locations during measurement set 2, September 16–17, 2003, Terror Creek, Colo., water year 2003.

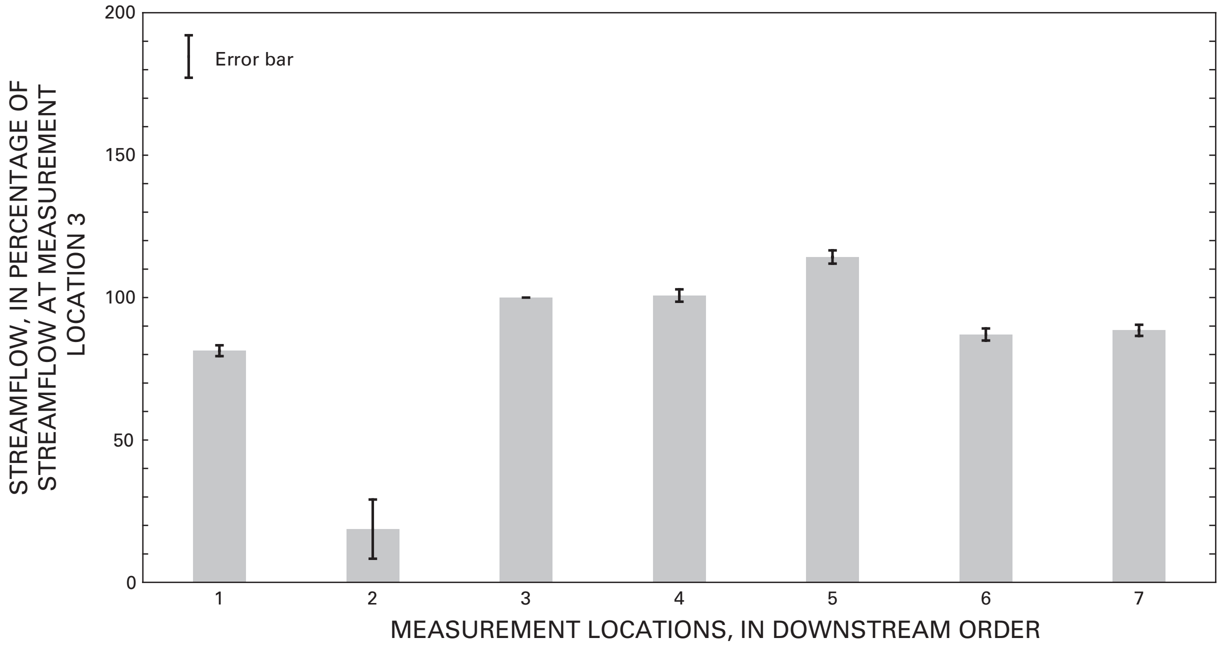

Figure 10. Comparison of relative streamflow among measurement locations during measurement set 2, September 16–17, 2003, Terror Creek, Colo., water year 2003.

between measurement locations 3 and 7, with a decrease in streamflow of 0.31 ft^3/s. The indicated loss between measurement locations 3 and 7 is interpreted as the overall streamflow loss within the mine-permit area for measurement set 2.

Interpretation of Findings

A comparison of the measurement sets indicates that the streamflow gain-loss characteristics of the Terror Creek study reach are consistent between time periods between the two hydrologic conditions evaluated: (1) reservoir-supplemented streamflow conditions of the summer during measurement set 1, and (2) the more natural base-flow conditions of early fall during measurement set 2 (fig. 11). A substantial streamflow gain is shown between measurement locations 4 and 5 in both measurement sets, but streamflow decreases between measurement locations 5 and 7 (measurement set 1, measurement location 6 not visited) and 5 and 6 (measurement set 2). During measurement set 1, the 55-percent streamflow gain between measurement locations 4 and 5, normalized to measurement location 3, is less than the 62-percent streamflow loss between measurement locations 5 and 7. During measurement set 2, the 13-percent streamflow gain between measurement locations 4 and 5, normalized to measurement location 3, is less than one-half the 27-percent streamflow loss observed between measurement locations 5 and 6. A comparison of the measurement sets for the measurement locations upstream and downstream from the mine-permit area (measurement locations 3 and 7) shows a consistent streamflow loss of 0.37 and 0.31 ft^3/s (representing 5- and 12-percent streamflow losses, normalized to measurement location 3) for measurement sets 1 and 2, respectively (tables 1 and 3). This result indicates that similar streamflow losses occur during both reservoir-supplemented and natural base-flow conditions, with a mean streamflow loss of 0.34 ft^3/s for measurement sets 1 and 2. The similarity in streamflow losses also indicates that the process controlling streamflow losses are the same between reservoir-supplemented and natural base-flow conditions.

Findings from a previous investigation (Brooks, 1983) to determine ground-water recharge in Terror Creek support the observed streamflow losses between measurement locations 3 and 7 for this investigation. The investigation in October 1982 compared current-meter style measurements at measurement locations 1 and 2 (the sum of which is equivalent to measurement location 3) with a measurement location 0.5 mi downstream from measurement location 7 (located directly upstream from the Garvin Mesa Diversion). Findings by Brooks indicate a 0.59-ft^3/s streamflow loss occurs between these measurement locations (fig. 12). The precision of the current-meter style discharge measurements made by Brooks was estimated for use

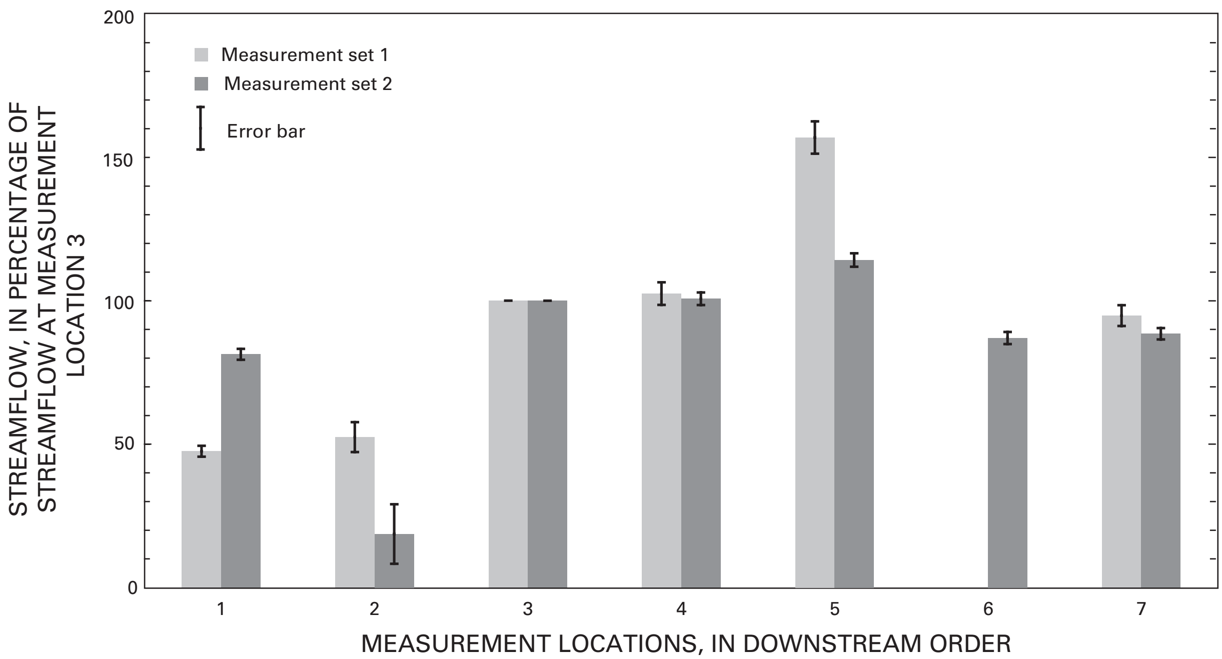

Figure 11. Comparison of relative streamflow among measurement locations during measurement set 1 (June 17–18, 2003) and measurement set 2 (September 16–17, 2003), Terror Creek, Colo., water year 2003.

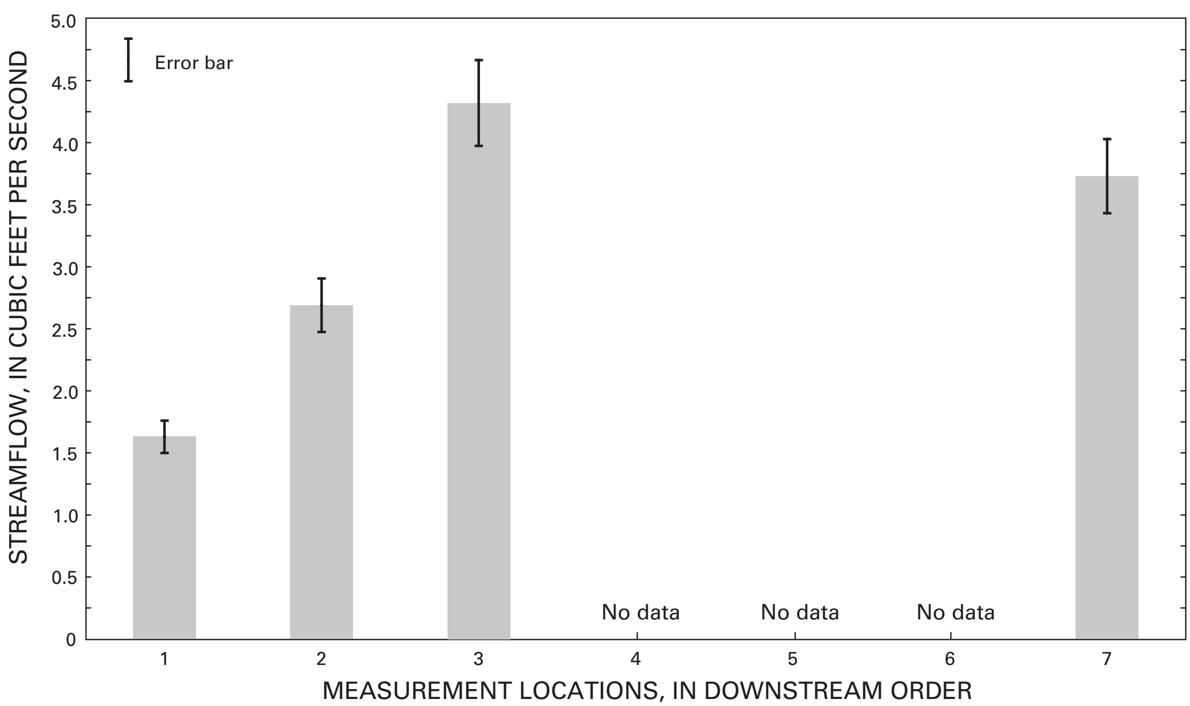

Figure 12. Comparison of streamflow among measurement locations from Brooks (1983), October 5, 1982, Terror Creek, Colo., water year 2003.

in this investigation at the USGS designation of fair (8-percent error), which is used to calculate the error bars in figure 12.

Statistical testing of the streamflow difference between measurement locations 3 and 7 was evaluated to determine the likelihood that the observed loss between the measurement locations truly represents the gain-loss characteristics of the study reach and to determine what level of certainty can be assigned to the findings. Calculations of the statistical tests were performed using S-Plus 2000 Professional software (Insightful Corporation, 2000), and the findings are presented in table 4.

The statistical testing of the differences in streamflow between measurement locations 3 and 7 indicates that the there is a discernible streamflow loss. The difference between measurement locations 3 and 7 for measurement set 1 is 0.37 ft^3/s with a standard deviation of the difference of 0.25 ft^3/s. The standard deviation of the difference for measurement set 1 indicates a confidence interval of about 92 percent (1.43 standard deviations from zero), indicating that there is about an 8-percent probability of observing a sample mean difference greater than or equal to 0.37 ft^3/s if the population mean is zero (that is, if there is no true difference in streamflow between these two locations). The difference between measurement locations 3 and 7 for measurement set 2 is 0.31 ft^3/s with a standard deviation of the difference of 0.05 ft^3/s. The standard deviation of the difference for measurement set 1 shows a confidence interval of approximately 100 percent (5.77 standard deviations from zero), indicating that there is almost no possibility of observing a sample mean difference greater than or equal to 0.31 ft^3/s if the population mean is zero. The standard deviation of the difference between measurement locations 3 and 7 for both measurement sets 1 and 2 is 0.34 ft^3/s for samples meeting parametric assumptions (measurement sets 1 and 2). The p-value of 0.0236 for the parametric paired t-test indicates that there is a 2.36-percent probability of observing a sample mean difference of 0.34 ft^3/s if the population mean is zero. This result is statistically significant at the standard 5 percent (p-value 0.05) generally accepted as the designation of a statistically significant result. The sample mean difference between measurement locations 3 and 7 is 0.42 ft^3/s for the samples meeting nonparametric assumptions (measurement sets 1 and 2, and Brooks (1983)). The p-value of 0.125 for the nonparametric exact Wilcoxon signed rank test indicates that there is a 12.5-percent probability of observing a sample mean difference this large if the population mean is zero. This level of significance is above the 5 percent (p-value 0.05) generally accepted designation of a statistically significant result. The lack of statistical significance in the nonparametric test is caused by the number of observations available for comparison being too few for a definitive assessment. The exact level of statistical significance is undetermined, but the incorporation of each of the available methods to detect a streamflow loss, including graphical interpretation, error analysis, repeatability of results, and two methods of testing of statistical significance, provides good evidence that there is a loss of about 0.34 ft^3/s within the mine-permit area (between measurement locations 3 and 7) for the hydrologic conditions investigated during measurement set 1 and 2.

Factors Affecting Streamflow Gain-Loss Characteristics

The observed streamflow gain-loss characteristics of the Terror Creek study reach are the result of two types of ground-water systems interacting with Terror Creek surface water. The first ground-water system is the shallow ground water that travels as hyporheic flow parallel to the stream channel or is stored seasonally in the adjacent alluvium of the stream channel. Water in the hyporheic system contributes to streamflow gains and losses in Terror Creek and has relatively short residence times. The second ground-water system is the deep ground-

Table 4. Summary of results from statistical tests of measured streamflow loss within the mine-permit area, Terror Creek, Colo., water year 2003.

[ft^3/s, cubic feet per second; n, number of sample pairs; df, degrees of freedom; p, probability that the true difference between streamflow values at measurement locations 3 and 7 is equal to or greater than zero]

Data source	Streamflow at measurement location (ft^3/s) 3	Streamflow at measurement location (ft^3/s) 7	Test type	Statistical diagnostics n	Statistical diagnostics df	Statistical diagnostics p
Paired t-test (one-sided)						
Measurement set 1	7.02	6.65	Parametric	2	1	0.0236
Measurement set 2	2.72	2.41				
Exact Wilcoxon signed-rank test (one-sided)						
Measurement set 1	7.02	6.65	Nonparametric	3	2	0.1250
Measurement set 2	2.72	2.41				
Brooks (1983)	4.32	3.73				

water system that receives recharge from the stream channel and transmits it out of the basin through fractures and bedrock aquifers, in turn causing a loss to the total surface water of the stream. This deeper ground water has substantially longer residence times and is not believed to return to Terror Creek.

Hyporheic Flow System

Investigation of the geology of the stream channel within the Terror Creek study reach indicates that alluvium is present throughout much of the study reach (Ellis and others, 1987). Hyporheic flow can occur throughout an alluvial setting and may contribute 20–25 percent of the total streamflow (Cleasby and Nimick, 2002; Nimick and Cleasby, 2000; and Zellweger and others, 1989). Variations in the proportions of streamflow that is transmitted as hyporheic flow or surface water along the Terror Creek study reach must be evaluated in order to fully interpret streamflow gain-loss characteristics.

Determination of the volume of hyporheic flow within the study reach with any certainty was beyond the scope of the investigation because the multiple-tracer method used to account for the losing subreaches of Terror Creek cannot include estimates of hyporheic flow volumes (Zellweger and others, 1989); however, some understanding of the proportion of streamflow transmitted as hyporheic flow at each measurement location is needed for interpretation of the relative streamflow values.

For this analysis, observed geologic and hydrologic characteristics identified onsite during this study and in previous investigations and analyses were used to indicate whether hyporheic flow is present. The thickness of alluvium adjacent to and below the stream channel at a given measurement location is related directly to the volume of hyporheic flow and available shallow ground-water storage. Variations in the thickness of these sediments can cause fluctuations in the amount of measurable surface water relative to the total surface water of the stream. In areas where these sediment deposits are thin or nonexistent, most of the total streamflow is present as surface water in the stream.

Measurement locations 3, 6, and 7, as well as the measurement location used by Brooks (1983) upstream from the Garvin Mesa Diversion, were located in areas where outcrops of sandstone decrease the amount of alluvium in the streambed. Ten yards downstream from measurement location 3, a sandstone outcrop was observed along the right bank. Five yards downstream from measurement location 6, the streambed of Terror Creek consisted of exposed sandstone bedrock. The bedrock channel continued on for 35 yards, before reverting to an alluvial channel. Extensive outcrops of sandstone were observed along the right bank of Terror Creek, approximately 100 yards downstream from measurement location 7, with small cascades caused by exposed bedrock ledges located just upstream. Similar cascades were observed just downstream from measurement location 7, but no observable outcrops of sandstone were located. The Rollins Sandstone was observed at the Garvin Mesa Diversion with exposed bedrock adjacent to the right bank of Terror Creek, as well as intermittently upstream. Field observations of channel characteristics and geologic outcrops support the statement that measurement locations 3, 6, and 7, as well as the measurement section used by Brooks (1983) upstream from the Garvin Mesa Diversion, have minimal to no hyporheic flow. This characterization is based on the thickness of observed alluvium within the stream channel at these locations, and the presence of sandstone outcrops adjacent to the stream channel. Subsequently, the streamflow measurements made at these measurement locations should represent the total streamflow of Terror Creek at these locations.

Measurement locations 4 and 5 have characteristics that indicate that the measurements made at these locations also may represent the total surface water of Terror Creek. Dense vegetation and various Quaternary deposits along the flanks of Terror Creek Basin obstructed field observation of sandstone outcrops along measurement locations 4 and 5. Comparisons of the stream-channel characteristics of measurement locations 4 and 5 with areas known to have sandstone outcrops indicate that sandstone outcrops and near bedrock-channel conditions could be present at these locations. Field observations indicate that variations in the stream profile were related to the presence of sandstone outcrops. In areas where sandstone dominated the stream channel, step-pool sequences and exaggerated rock-ledge cascades were common. Large, flat tracts of slower water also were common upstream from these sandstone outcrops due to the inability of the stream channel to downcut through these more resistant layers (as observed at measurement location 6). These stream characteristics also were observed at measurement locations 4 and 5.

Longitudinal consistency of streamflow-measurement values indicates similar channel and alluvial characteristics. The nearly identical streamflow values between measurement locations 3 and 4 within each measurement set indicate that the channel conditions are similar between the two measurement locations (nearly bedrock channels). Therefore, the assumption that total streamflow was measured at measurement location 4 is further supported. A more complex relation exits between measurement location 5 and measurement locations 4 and 6 and is not as readily apparent.

The streamflow gain observed between measurement locations 4 and 5 is followed by a proportional streamflow loss between measurement locations 5 and 6. If hyporheic flow occurs at measurement location 5 at the 20–25 percent typical of some mountain streams (Cleasby and Nimick, 2002; Nimick and Cleasby, 2000; and Zellweger and others, 1989), then the indicated gain between measurement locations 4 and 5 the and loss between measurement locations 5 and 6 would be even greater than previously estimated. Quantification of the amount of hyporheic flow at measurement location 5 is not possible without further investigation; however, based on channel characteristics, the assumption will be made for this analysis that the streamflow values from measurement location 5 include the total streamflow of Terror Creek at this location.

Based on field observations and measurement analysis, the volume of hyporheic flow within the Terror Creek study reach is considered to be negligible at all measurement locations. However, indicated gains between measurement locations 4 and 5 may be related to hyporheic flow from tributaries that were dry during the study between measurement locations 4 and 5. No other obvious surface-water sources were identified during the investigation.

Deep Flow System

Other factors that could affect the streamflow gain-loss characteristics of the Terror Creek study reach are fractures and bedrock aquifers that are part of the deep flow system. Investigation of the geology of the stream channel within the Terror Creek study reach indicates that such losses may occur through fractures associated with a mapped subsurface fault along the profile of Terror Creek (Brooks, 1983; Ellis and others, 1987). Secondary streamflow losses also may occur as recharge to bedrock aquifers and coal seams of the Mesa Verde Formation (Brooks, 1983). Most of the total streamflow loss within the Terror Creek study reach appears to occur between measurement locations 5 and 7. The loss in streamflow between measurement locations 5 and 7 exceeds the gain in streamflow between measurement locations 4 and 5 for both measurement sets. With the addition of measurement location 6 in measurement set 2, streamflow comparisons indicate that the losses are likely limited to the stream reach between measurement locations 5 and 6. The comparability in overall streamflow loss between measurement locations 3 and 7 (overall loss within the mine-permit area) for both measurement sets demonstrates that the mean overall-streamflow loss is approximately 0.34 ft^3/s.

The exact cause for the loss between measurement locations 5 and 6 is unknown but may be related to a combination of factors. The location of the loss is coincident with the D-seam coal bed, based on interpretation of a local Mesa Verde Formation geologic cross section located a few miles to the east in the Bear Creek drainage (Dunrud, 1976). The D-seam coal bed may act as an aquifer, enhanced by local faults and fractures transmitting ground water to the north, following the structural dip of the area. The mapped subsurface fault present along Terror Creek could act as a conduit for ground water to move between strata in the Mesa Verde Formation, as well as to the north, following the structural dip of the area. Further complication of the structural geology of the area may be the result of collapse structures and dewatering processes related to the past 100 years of coal mining in the area (Dunrud, 1976; Brooks, 1983). A combination of factors is most likely the reason for the observed streamflow losses along the Terror Creek study reach.

Summary

In 2003, the U.S. Geological Survey, in cooperation with Delta County, initiated a study to characterize streamflow gain-loss in a reach of Terror Creek, in the vicinity of a mine-permit area planned for future coal mining. This report describes the methods of the study and includes results from a comparison of two sets of streamflow measurements determined using tracer techniques following the constant-rate injection method. Characterization of streamflow gain-loss for the Terror Creek study reach included seven measurement locations and two measurement sets (measurement location 6 not visited during measurement set 1): measurement set 1, June 17–18, and measurement set 2, September 16–17, 2003.

Streamflow at measurement locations in each measurement set was compared graphically by using direct and indirect methods. A graphical comparison of streamflow values among measurement locations allows for an assessment of the likelihood that two streamflow values are discernibly different. The difference in the streamflow values between measurement locations indicates streamflow gains or losses. A direct comparison of streamflow values (in cubic feet per second) was used for steady-state hydrologic conditions (measurement-location pairs (A–C) for measurement set 1, and all measurement locations for measurement set 2). An indirect comparison of streamflow values (the comparison of streamflow values as a percentage of streamflow at measurement location 3) was used to account for variations in streamflow resulting from Terror Creek Reservoir during measurement set 1 and to normalize streamflow between measurement sets. In addition to the graphical comparison, a comparison of the two measurement sets and previous investigations of the study area was included in the interpretation of the streamflow gain-loss characteristics of the Terror Creek study reach and includes statistical testing of the overall streamflow losses within the mine-permit area.

The streamflow gain-loss characteristics of the Terror Creek study reach for measurement set 1, using the direct comparison of the streamflows in each measurement-location pair, indicate that there is no discernible streamflow gain or loss between measurement locations 3 and 4. There is a 3.80-ft^3/s streamflow gain between measurement locations 3 and 5. There is a 0.37-ft^3/s streamflow loss between measurement locations 3 and 7. The indicated loss between measurement locations 3 and 7 is interpreted as the overall streamflow loss within the mine-permit area for measurement set 1.

An indirect comparison of the streamflows for each measurement location during measurement set 1 also was done because of the stairstep increase in streamflow from Terror Creek Reservoir. Measurement locations 3 and 4 had no discernible streamflow gain or loss within the precision of the measurements. There was a 55-percent streamflow gain, normalized to measurement location 3, between measurement locations 4 and 5 and a 62-percent streamflow loss between measurement locations 5 and 7.

The streamflow gain-loss characteristics for measurement set 2 allowed for direct (cubic feet per second) and indirect (percentage difference normalized to measurement location 3) methods of comparison of the streamflows for each measurement location due to the steady-state hydrologic condition. Measurement locations 3 and 4 show no discernible streamflow gain or loss. There was a 0.37-ft^3/s (13 percent) streamflow gain between measurement locations 4 and 5. There was a 0.74-ft^3/s (27 percent) streamflow loss between measurement locations 5 and 6. No discernible streamflow gain or loss was shown between measurement locations 6 and 7.

In order to determine the overall streamflow gain or loss within the mine-permit area for measurement set 2, the streamflow value from measurement location 3 was paired with the streamflow value from measurement location 7, using the direct method. A 0.31-ft^3/s streamflow loss was shown between measurement locations 3 and 7. The streamflow loss between measurement locations 3 and 7 is interpreted as the overall streamflow loss within the mine-permit area for measurement set 2.

A comparison of the measurement sets indicates that the streamflow gain-loss characteristics of the Terror Creek study reach are consistent between time periods for the overall mine-permit area but differ in magnitude between individual measurement locations for the two hydrologic conditions evaluated. A substantial streamflow gain is shown between measurement locations 4 and 5 in both measurement sets, and streamflow decreases between measurement locations 5 and 7 (measurement set 1, measurement location 6 not visited) and 5 and 6 (measurement set 2). A comparison of the measurement sets above and below the mine-permit area (measurement locations 3 and 7) shows a consistent streamflow loss of 0.37 and 0.31 ft^3/s, representing 5- and 12-percent streamflow losses for measurement sets 1 and 2, respectively, normalized to streamflow at measurement location 3. This result indicates that similar streamflow losses occur during reservoir-supplemented and during natural base-flow conditions.

Findings from a previous investigation support a streamflow loss between measurement locations 3 and 7 observed in this study. The findings indicate that a 0.59-ft^3/s streamflow loss occurs between these measurement locations.

Statistical testing of the differences in streamflow between measurement locations 3 and 7 indicates that there is a discernible streamflow loss. The p-value of 0.0236 for the parametric paired t-test indicates that there is a 2.36-percent probability of observing a sample mean difference of 0.34 ft^3/s if the population mean is zero (that is, if there is no true difference in streamflow between these two locations). This level of significance is below the standard 5 percent (p-value 0.05) generally accepted as the designation of a statistically significant result. The p-value of 0.125 for the nonparametric exact Wilcoxon signed rank test indicates that there is a 12.5-percent probability of observing a sample mean difference this large if the population mean is zero. The lack of statistical significance in the nonparametric test is caused by the number of observations available for comparison being too few for a definitive assessment. The exact level of statistical significance is undetermined, but the incorporation of all the available methods to detect a streamflow loss, including graphical interpretation, error analysis, repeatability of results, and two methods of testing of statistical significance, provides good evidence that there is a loss of about 0.34 ft^3/s between measurement locations 3 and 7 for the hydrologic conditions investigated.

The similarity in streamflow gain-loss between measurement sets indicates that the process controlling streamflow may be the same between the two hydrologic conditions evaluated. Indicated gains between measurement locations 4 and 5 may be related to hyporheic flow from tributaries that were dry during the investigation. No other obvious sources of surface water were identified during the investigation. The cause for the observed streamflow loss between measurement locations 5 and 6 is unknown but may be related to mapped local faulting, 100 years of coal mining in the area, and aquifer recharge.

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Supplemental Information

Table 5. Supplemental information for the modified multiple-tracer method, measurement set 1, and multiple-tracer method, measurement set 2, Terror Creek, Colo., water year 2003.

[M.S.T., Mountain Standard Time; TC_1, time of sample for injectate bromide concentration; TC_2, time of sample for downstream bromide concentration; TC_B, time of sample for background bromide concentration; Q_1, rate of flow of the injectate; L/min, liters per minute; min, minutes; --, no data or not applicable]

Streamflow measurement location	Date	Tracer injection and sample times (M.S.T.)					Q_1 (L/min)	Duration of injection (min)
		Pump start	Pump stop	TC_1	TC_2	TC_B		
Measurement set 1								
East and West Fork Terror Creek coincident with measurement-location pair A								
1	06/17/03	1107	1213	1212	1211[1]	1206	0.0600	66
2	06/17/03	1107	1213	1212	--	1203	--	66
Measurement-location pair A								
3	06/17/03	1107	1213	1212	1157	--	0.0600	66
4	06/17/03	1130	1225	1224	1220	1215	0.0910	55
East and West Fork Terror Creek coincident with measurement-location pair B								
1	06/17/03	1403	1507	1506	1455	1450	0.0838	64
2	06/17/03	1403	1507	1506	--	1515	--	64
Measurement-location pair B								
3	06/17/03	1403	1507	1506	1503	--	0.0838	64
5	06/17/03	1500	1601	1600	1600	1552	0.0825	61
East and West Fork Terror Creek coincident with measurement-location pair C								
1	06/18/03	1100	1158	1157	1152	1147	0.0860	58
2	06/18/03	1100	1158	1157	--	--[2]	--	58
Measurement-location pair C								
3	06/18/03	1100	1158	1157	1200	--	0.0860	58
7	06/18/03	1308	1408	1407	1408	1406	0.0840	60
Measurement set 2								
1	09/16/03	1718	1818	1817	1812	1806	0.0713	60
2	09/16/03	1718	1818	1817	--	1830	--	60
3	09/16/03	1718	1818	1817	1822	--	0.0713	60
4	09/16/03	1406	1449	1448	1448	1442	0.0731	43
5	09/16/03	1138	1227	1226	1223	1220	0.0808	49
6	09/17/03	1340	1429	1428	1425	1418	0.0625	49
7	09/17/03	1137	1222	1221	1218	1211	0.0738	45

[1]Sample destroyed during shipping.

[2]C_B for this site measured during previous tracer injection.