Using the Tracer-Dilution Discharge Method to Develop Streamflow Records for Ice-Affected Streams in Colorado

By Joseph P. Capesius, Joseph R. Sullivan, Gregory B. O’Neill, and Cory A. Williams

Prepared in cooperation with the Colorado Water Conservation Board

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Contents

Figures

Tables

Conversion Factors

Multiply	**By**	**To obtain**
mile (mi)	1.609	kilometer (km)
foot (ft)	0.3048	meter (m)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
milliliters per minute (mL/min)	0.03785	gallon per minute (gal/min)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F–32)/1.8$$

Abbreviations

mg/L milligrams per liter
µS/cm microsiemens per centimeter at 25 degrees Celsius

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Abstract

Accurate ice-affected streamflow records are difficult to obtain for several reasons, which makes the management of instream-flow water rights in the wintertime a challenging endeavor. This report documents a method to improve ice-affected streamflow records for two gaging stations in Colorado. In January and February 2002, the U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, conducted an experiment using a sodium chloride tracer to measure streamflow under ice cover by the tracer-dilution discharge method. The purpose of this study was to determine the feasibility of obtaining accurate ice-affected streamflow records by using a sodium chloride tracer that was injected into the stream. The tracer was injected at two gaging stations once per day for approximately 20 minutes for 25 days. Multiple-parameter water-quality sensors at the two gaging stations monitored background and peak chloride concentrations. These data were used to determine discharge at each site. A comparison of the current-meter streamflow record to the tracer-dilution streamflow record shows different levels of accuracy and precision of the tracer-dilution streamflow record at the two sites. At the lower elevation and warmer site, Brandon Ditch near Whitewater, the tracer-dilution method overestimated flow by an average of 14 percent, but this average is strongly biased by outliers. At the higher elevation and colder site, Keystone Gulch near Dillon, the tracer-dilution method experienced problems with the tracer solution partially freezing in the injection line. The partial freezing of the tracer contributed to the tracer-dilution method underestimating flow by 52 percent at Keystone Gulch. In addition, a tracer-pump-reliability test was conducted to test how accurately the tracer pumps can discharge the tracer solution in conditions similar to those used at the gaging stations. Although the pumps were reliable and consistent throughout the 25-day study period, the pumps underdischarged the tracer by 5.8–15.9 percent as compared to the initial pumping rate setting, which may explain some of the error in the tracer-dilution streamflow record as compared to current-meter streamflow record.

Introduction

Accurate wintertime streamflow records are difficult to obtain for several reasons. First, ice cover changes the stage-discharge relation by causing a variable backwater condition, which can introduce error to the stage-discharge record during the weeks between discharge measurements. Second, ice cover may interfere with accurate gage-height measurement, especially on small streams with thick ice and snow cover. Third, wintertime weather makes current-meter measurements more difficult to make and potentially less accurate. These reasons, along with travel hazards, cause hydrographers to estimate large portions of the wintertime streamflow records at some sites in Colorado.

The inaccuracy of ice-affected streamflow records is particularly troublesome for streams where Instream-Flow (ISF) water rights exist. ISF water rights are administered by the State of Colorado for protection of the natural environment in support of the Instream Flow and Natural Lake Level Program. As part of this program, the State of Colorado acquired ISF water rights for more than 8,000 miles of streams and 475 natural lakes in the State. Water-use activities such as snowmaking at ski resorts can infringe on the amount of water needed to maintain the natural environment to a reasonable degree as stated in the Colorado Senate Bill 97, which was signed into law in 1973 (*http://cwcb.state.co.us/isf/Programs/Docs/ISFQuantPolicy.pdf*). To balance the demands of water users with ISF water rights, water-resource managers need more accurate wintertime streamflow records.

One alternative to an estimated streamflow record is to increase the frequency of streamflow measurement, either with a current meter or by using the tracer-dilution discharge method. Increased current-meter measurement frequency is costly and generally not used except for specific short-term studies. Tracer-dilution discharge methods are a potentially cost-effective alternative. This method has been used to determine discharge in studies conducted in Wyoming (Kilpatrick and Cobb, 1985) and Iowa (Soenksen, 1990; Melcher and Walker, 1990). These studies used a fluorescent dye, rhodamine-WT, to determine discharge for streams. None of these studies, however, attempted to develop a streamflow record determined exclusively by the tracer-dilution discharge measurements.

In 2002, the U.S. Geological Survey (USGS), in cooperation with the Colorado Water Conservation Board, began a study to assess the feasibility and accuracy of the tracer-dilution discharge method to develop streamflow records at two streamflow-gaging stations: Keystone Gulch near Dillon, Colorado, and Brandon Ditch near Whitewater, Colorado (fig. 1). In addition, the study also examined a key piece of equipment for the study, the tracer-injection pumps, to determine their reliability and accuracy in discharging the tracer into the stream over a period of weeks.

Purpose and Scope

The purpose of this report is to describe the results of a study to determine the feasibility and accuracy of ice-affected streamflow records using the tracer-dilution discharge method. Data were collected from January 9 through February 12, 2002. This study expanded upon the methods used in previous tracer-dilution discharge-measurement studies (Kilpatrick and Cobb, 1985; Soenksen, 1990; Melcher and Walker, 1990; J.E. Vaill, U.S. Geological Survey, written commun., 1999) by incorporating automated tracer injection and near-continuous (3-minute interval) tracer-concentration measurements to determine discharge in conjunction with conventional current-meter measurements to produce a streamflow record. The tracer-dilution streamflow and estimated streamflow determined by straight-line interpolation methods were compared to streamflow determined from current-meter measurements. For simplicity of terminology, "tracer gage" refers to a system of equipment set up to automatically inject a tracer into a stream for which streamflow can be measured using the tracer-dilution discharge method. In addition, a separate test was conducted to measure the reliability and accuracy of the tracer pumps over a period of 25 days.

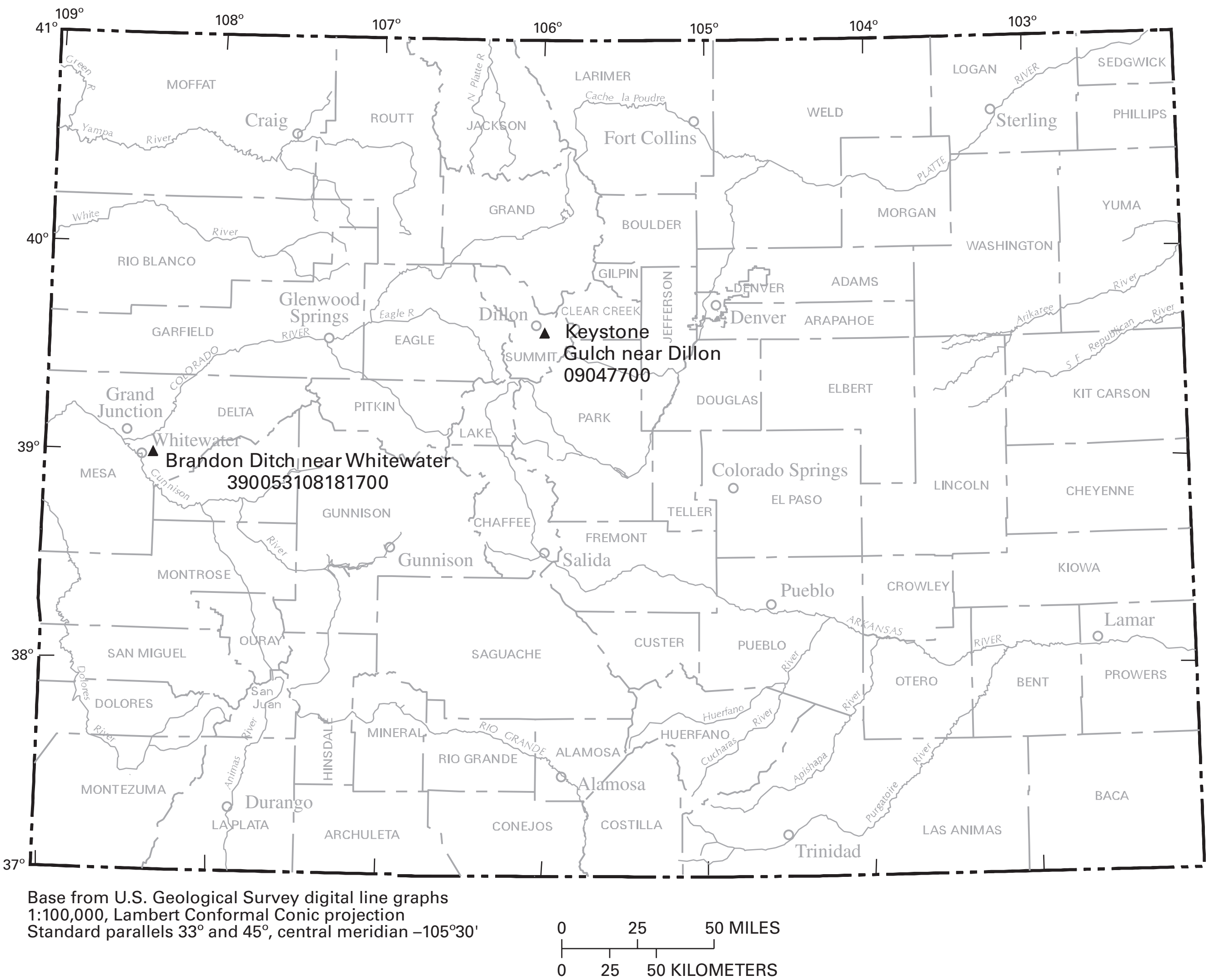

Figure 1. Location of study sites in Colorado.

Background

The equipment for the tracer gages was installed at two sites with conventional streamflow-gaging stations (fig. 1): Brandon Ditch near Whitewater, Colorado (gaging station number 390053108181700), and Keystone Gulch near Dillon, Colorado (gaging station number 09047700). The Brandon Ditch gage was chosen because of a Parshall flume at the site that, when covered with insulating materials, was reported to remain free from ice during the winter. After the project had begun, however, it was noted that there was enough ice formation along the sides of the flume to prevent accurate discharge measurement using the Parshall flume. Therefore, current-meter measurements were used to determine discharge at this site.

A tracer gage also was installed at Keystone Gulch. This site was chosen because it had an ISF water right (Case Number 5–86CW092) and a wintertime water user in close proximity (Keystone Ski Resort). Also, the site is located at an elevation of 9,350 ft on the northwest side of Keystone Mountain (11,935 ft). The Keystone Gulch site is subject to extremely cold wintertime temperatures, with overnight lows commonly reaching below 10° Fahrenheit. This site represented a field application of the tracer-gage methodology on a natural stream at high elevation, as it is noted that many of the streams with both an ISF water right and a substantial wintertime water user are located at high elevations (more than 7,500-ft elevation) in Colorado.

The tracer pumps were tested after the tracer gage was tested. It was noted from a previous tracer-gage experiment conducted at the Western Slope (Grand Junction, Colorado) office of the USGS (J.E. Vaill, U.S. Geological Survey, written commun., 1999) that the pumping rate was the only variable that could not be verified because the tracer-injection lines were buried and frozen in place. Therefore, a tracer-pump evaluation was conducted in an attempt to replicate onsite field conditions while accurately measuring the tracer volumes. This test was run for approximately 25 days.

Methods of Streamflow Measurement

The following is a brief summary of the two streamflow-measurement methods used in this study: the current-meter discharge-measurement method and the tracer-dilution discharge-measurement method. Those interested in further explanation of these or other streamflow-measurement methods are referred to Rantz and others (1982).

Current-Meter Discharge Measurements

Current-meter discharge measurements are the most commonly used method to determine streamflow by the USGS (Rantz and others, 1982). Streamflow is measured by subdividing a stream cross section and measuring water velocity by using a current meter. The product of the width and depth of the subsections and the velocity in the middle of the subsection is the subsection discharge. The subsection discharges are added to determine total discharge or streamflow.

Most discharge measurements are given a measurement rating or an evaluation of the accuracy of the measurement. Current-meter discharge measurements are rated from Excellent to Poor, depending on percentage of total flow in any one subsection. Ideally, no one subsection should have more than 5 percent of the total streamflow. Measurements rated Poor have over 8 percent of the total discharge in a single subsection, although the measurement rating may be downgraded based on site conditions such as changes in flow or possible meter malfunction. There are instances when a Poor current-meter discharge measurement is the best that can be obtained. For example, the stream cross section may be too narrow to allow for an adequate number of velocity measurements. Current-meter discharge measurements at sites with ice cover are commonly rated Poor. Current-meter discharge measurements were made daily at the two tracer gages from January 9 through February 12, 2002.

Tracer-Dilution Discharge Measurements

Streamflow also may be measured using tracers. Tracer-dilution discharge measurements rely on the conservation of mass law. A tracer of known concentration is injected into a stream at a constant rate for a predetermined period of time upstream from the site of interest, which usually is a gaging station. Concentrations of the tracer are measured before, during, and after the tracer passes the site. Typically, the tracer concentrations rapidly increase, remain steady, and then decline rapidly at the downstream section. This form of tracer-dilution discharge measurement is called the constant-rate method (Rantz and others, 1982). Discharge is determined by using the following equation, modified from Soenksen (1990):

$$Q_s = 5.89\times10^{-7} \frac{(c_i Q_i)}{(c_g - c_b)} \qquad (1)$$

where

Q_s is the discharge of the stream, in cubic feet per second (ft^3/s);

c_i is the concentration of the tracer injected, in milligrams per liter (mg/L);

Q_i is the rate of tracer injection, in milliliters per minute (mL/min);

c_g is the concentration of tracer at the gaging station, in milligrams per liter (mg/L);

and

c_b is the background concentration of the tracer at the gaging station, in milligrams per liter (mg/L).

Discharge determined by the tracer-dilution method is total discharge or streamflow. Use of the constant-rate tracer-dilution discharge-measurement method also assumes that the tracer is uniformly mixed throughout the cross section and that there is no loss of the tracer due to sorption or a chemical reaction (Rantz and others, 1982). There is no assigned rating of the quality of the tracer-dilution discharge measurement. Tracer-dilution discharge measurements were made concurrently with the current-meter measurements from January 9 through February 12, 2002.

Conventional Streamflow-Record Computation

Normally, stage is measured continuously at a stream site and discharge is measured periodically to develop a stage-discharge relation. In an ideal situation, this relation is constant and the amount of streamflow can be determined for all ranges in stage and discharge throughout the year. A daily-mean discharge is determined by averaging the individual values of discharge measured throughout the day to develop a streamflow record.

At many sites subject to subfreezing temperatures, ice can affect the stage-discharge relation. The formation of ice causes a variable backwater condition that changes the stage-discharge condition. The variable nature of the backwater condition introduces error to the stage-discharge relation, but the amount of change is unknown during the periods between discharge measurements. During periods of ice, hydrographers try to minimize the uncertainty within the streamflow record by using climatologic information such as overnight low temperature and periods of precipitation or streamflow at hydrologically similar sites that are not affected by ice to estimate the streamflow record. Unfortunately, it is difficult to estimate streamflow record on a real-time basis at sites that become ice covered.

Another, although less preferred, method to estimate streamflow under ice cover is to assume a constant change in base flow between discharge measurements (Rantz and others, 1982). This method is only used at sites with complete ice cover in very cold conditions where temperature remains below freezing during long periods of time and when there are no comparable sites on which to base streamflow estimates.

Methods of Tracer-Gage Operations

The tracer-dilution discharge method was implemented at two tracer gages: Brandon Ditch near Whitewater, Colorado, and Keystone Gulch near Dillon, Colorado. The approach at the two sites was the same. A sodium chloride solution (greater than 100,000 mg/L) was injected with a piston-driven pump once per day, and a multiple-parameter water-quality sensor downstream from the gaging station measured chloride ion concentrations, water temperature, specific conductance, and pH.

One assumption of using the tracer-dilution discharge method is that the tracer is uniformly mixed in the streamflow. To ensure uniform mixing, the water-quality sensor must be placed at a sufficiently long distance downstream from the injection point. The mixing reach can be shortened by using multiple tracer-injection ports to help disperse the tracer more quickly (Rantz and others, 1982). At Brandon Ditch, the mixing reach between tracer injection and tracer measurement was about 300 ft along a relatively uniform channel where flow was expected to remain below 1 ft^3/s. At Keystone Gulch, which consists of many pools and riffles, only a 100-ft reach immediately downstream from the gage was suitable for placement of the water-quality sensor. To ensure complete mixing of the tracer, several injection ports were used to inject the tracer and, before the site was covered with ice, small cobbles were moved to further help mix the tracer.

To test for the assumption of complete mixing, specific conductance of the stream water was measured in the stream at the same location as the chloride probe, both before and during the study period at Keystone Gulch. Specific conductance was measured at several points across the stream to ensure the chloride tracer was uniformly mixed. Specific conductance ranged from 131 to 137 µS/cm across the stream where the probe was located during an initial test run in November 2001 and also during the initial setup on January 2002. Given the consistency of the two tests, the tracer was assumed uniformly mixed and further measurements were not made. At Brandon Ditch, no specific-conductance measurements were made due to an oversight; however, the chloride probe was located at the mouth of the Parshall flume, which was about 300 ft downstream from the injection point for a channel that was less than 3 ft wide. Therefore, the tracer was assumed to have been uniformly mixed, which is plausible given the long mixing reach and small amounts of water at Brandon Ditch.

One tracer injection per day was used at each site so as to limit the time between refills of the tracer reservoir and to reduce tracer loading into the streams. Both sites were visited daily to make current-meter discharge measurements through an opening in the ice cover and to ensure that the equipment was working properly. The tracer pump was activated automatically by the data-collection platform at Brandon Ditch. At Keystone Gulch, electrical problems in the data-collection platform prevented automatic injection, so the pump was activated manually. In addition, a 200-hour candle was placed inside the shelter containing the tracer pump to add a small heat source to prevent the tracer from freezing and causing damage to the pump. The two tracer gages were operated from January 9 through February 12, 2002, in an effort to record 25 days of data. At the end of the data-collection period, the tracer-gage equipment was removed from both sites.

Methods of the Pump-Reliability Test

Upon completion of the tracer-gage portion of the study, the equipment was used in the pump-reliability test. The objective of this test was to determine the reliability and accuracy of the pumps to inject the sodium chloride tracer solution for the specified period. The tracer-pump-reliability test was conducted from February 23 through March 19, 2002, at the Western Slope office of the USGS in Grand Junction, Colorado. Table 1 lists the properties of each pump setup: Setup #1 was intended to determine the consistency of the pumping rates for field conditions without a heat source. Setup #1 represents the most basic tracer-gage setup. In setup #2, a heat source was added to determine if the heat source improved the consistency of the pumping rate, noting that a heat source (200-hour candle) was used at the Keystone Gulch site. Setup #3 was used to determine what effect a 200-ft electrical line and relay switch had on the pumping rate. This option was chosen because it was observed that battery voltage varied considerably during pumping, as recorded on the data-collection platforms; but there was less variation between the two streamflow-measurement methods at Brandon Ditch, where a relay switch and 200-ft electrical line were used to activate the pump. A heat source also was added to setup #3. Each pump setup was placed inside a small shelter, similar to those used at the two field sites.

Table 1. Setup properties for the tracer-pump test.

[mL/min, milliliters per minute; <, less than; ft, feet]

	Setup #1	Setup #2	Setup #3
Pumping rate	500 mL/min	450 mL/min	490 mL/min
Heat source	No	Yes	Yes
Length of electrical wire	<5 ft	<5 ft	200 ft
Solar panel	Yes	Yes	Yes
Relay switch	No	No	Yes

Each pump was set to a pumping rate similar to that used at the gaging stations (450–500 mL/min). In an attempt to mimic how the tracer pumps were installed at the tracer gages, the pumps were set for a consistent rate within this range, rather than setting the pump rates to a specific value. The final pumping rate for each setup was determined at the beginning of the tracer-pump evaluation by filling a graduated cylinder with the sodium chloride solution for 1 minute. Once the pump rate was between 450 and 500 mL/min, three additional rate tests were done to ensure consistency in the pump rates. This initial pump rate was used for comparison with the actual volume of solution pumped for 10 minutes during the 25 days of the tracer-pump evaluation.

Using the Tracer-Gage Method to Develop Streamflow Records

The months of October 2001 through January 2002 were unusually dry and warm for much of Colorado. Therefore, it was decided to implement the tracer-gage portion of the study during the coldest months of the year to ensure complete ice cover at the two gaging stations and the tracer-pump evaluation would be conducted afterward. The site locations for the tracer gages were determined in October 2001, and the tracer-gage equipment was installed in early January 2002. During the tracer-gage study, the background chloride concentrations in the streams were generally low (less than 5 mg/L) and rose rapidly due to injection of the tracer solution, and then fell rapidly after the tracer pumping stopped (fig. 2). The tracer-dilution discharge measurements were compared with current-meter measurements. For the comparison, 24 tracer-dilution discharge measurements were made at Brandon Ditch near Whitewater and another 23 measurements were made at Keystone Gulch near Keystone. One measurement at Brandon Ditch and two at Keystone Gulch were not used due to equipment failures or the depletion of the tracer reservoir part way through the pumping cycle. The tracer-pump-reliability test was done from February 23 through March 19, 2002, at the Western Slope office of the USGS in Grand Junction, Colorado.

Discharge-Measurement Comparison

The tracer-dilution discharge measurements had varying levels of comparability with the current-meter discharge measurements at the two sites. At the Brandon Ditch gage, the tracer-dilution discharge measurements overestimated streamflow by an average of 14 percent (fig. 3 and table 2). However, the standard deviation between the two types of measurement was 49 percent and a 25-percent trimmed mean (mean of the central 50 percent of data) of –2 percent, which indicates the differences between the two methods was strongly biased by a few outliers.

At Keystone Gulch, the tracer-dilution discharge method was compared to the current-meter discharge by an average of 52 percent with a standard deviation of 13 percent (fig. 4 and table 3). Unlike the Brandon Ditch site, the average and standard deviation at the Keystone Gulch site were not greatly influenced by outliers as the 25-percent trimmed mean of percent differences between the two methods is –55 percent.

Streamflow-Record Computation

The ultimate goal of the tracer-dilution discharge method is to improve the accuracy of wintertime streamflow records. Normally, much of the ice-affected streamflow record for high-elevation sites in

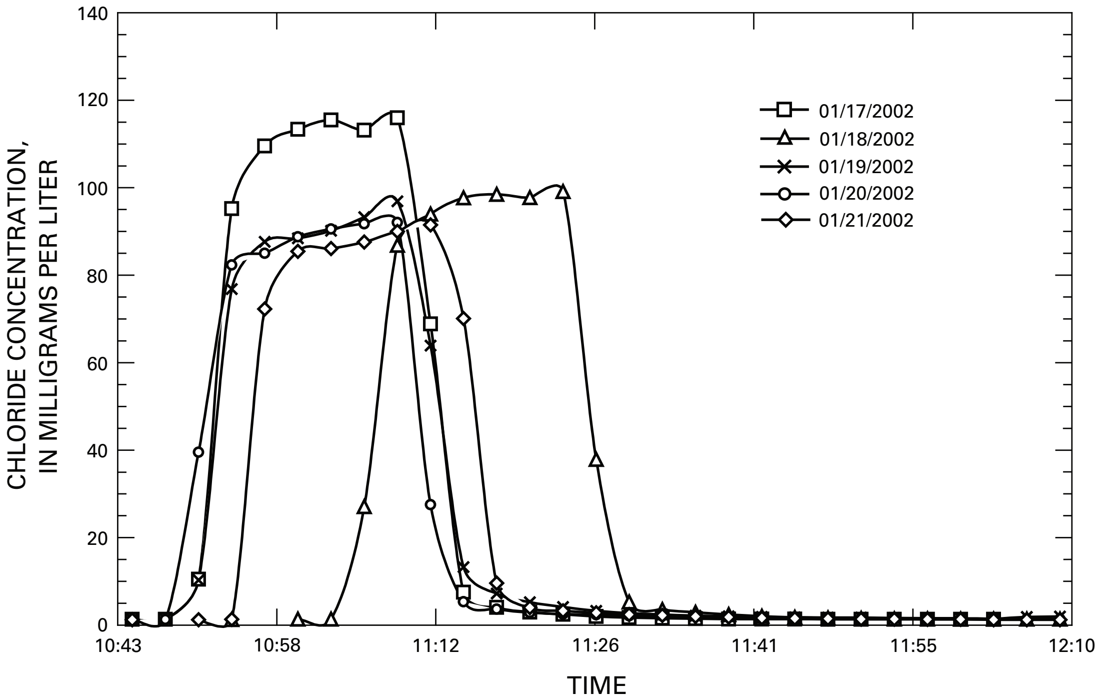

Figure 2. Concentration of chloride ions during a tracer-injection study in the stream water at Brandon Ditch near Whitewater, Colorado.

Colorado is estimated. The estimated streamflow record at a site often involves using a combination of the streamflow record of a nearby site with a more reliable streamflow record and measurements of climatic variables such as air temperature. Unfortunately, the Keystone Gulch site is subject to such cold temperatures (similar to arctic conditions) that air-temperature variations have little effect upon streamflow because the stream is covered with ice and a heavy layer of snow. Because midwinter air temperatures have little effect on the amount of streamflow at the Keystone Gulch gage, a slow and uniform recession in streamflow was assumed, and a straight-line interpolation between the first (January 9) and last (February 4) current-meter discharge measurements was used to determine the estimated streamflow record.

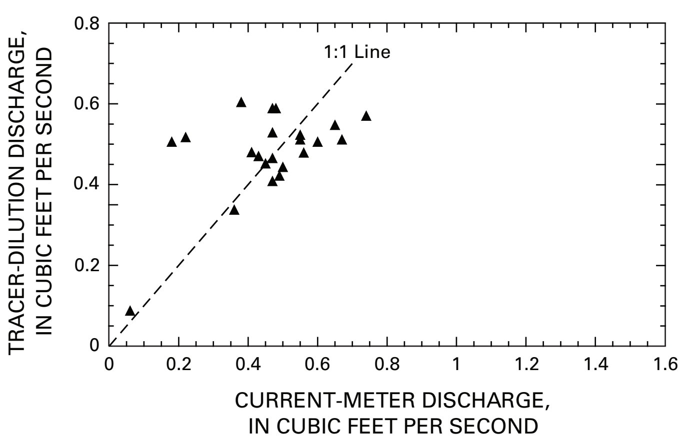

Figure 3. Comparison of current-meter and tracer-dilution discharge measurements at Brandon Ditch near Whitewater, Colorado.

At Brandon Ditch, the amount of streamflow was controlled by a ditch headgate upstream from the site, and a relatively constant discharge also was assumed. Because wintertime record is not computed at Brandon Ditch and a straight-line interpolation between current-meter measurements was used at Keystone Gulch to determine the estimated streamflow record, the estimated streamflow record for this study was interpolated between the first and last current-meter discharge measurements made on January 19 and February 12, respectively. Although this interpolation may not be the most desired method to determine wintertime streamflow record, it does provide a point of reference that can be used to compare the current-meter and tracer-gage methods of record computation. Each discharge measurement during the study is treated as the daily-mean discharge, and the three methods of record determination—tracer dilution, current meter, and straight-line interpolation (estimated)—were examined. Although multiple tracer-dilution measurements per day would be more useful for monitoring the ISF water right, this study used daily measurements due to the developmental nature of the methodology.

Table 2. Tracer-gage and current-meter discharge measurements, Brandon Ditch near Whitewater, Colorado.

[conc., concentrations; mg/L, milligrams per liter; mL/min, milliliters per minute; ft^3/s, cubic feet per second. c_i, Q_i, c_g, and Q_s are variables in equation 1]

Date	Tracer properties		Chloride concentration		Discharge		
	Tracer conc., mg/L, c_i	Injection rate, mL/min, Q_i	Peak conc., mg/L, c_g	Background, mg/L, c_b	Stream discharge, ft^3/s, Q_s	Measured, ft^3/s	Percent difference
01/09/02	146,000	450	94	2	0.42	0.49	–14
01/11/02	146,000	450	117	2	0.34	0.36	–6
01/12/02	146,000	450	83	2	0.48	0.56	–14
01/13/02	146,000	450	70	2	0.57	0.74	–23
01/14/02	146,000	450	450	2	0.09	0.06	50
01/15/02	146,000	540	100	1	0.47	0.43	9
01/16/02	146,000	540	106	1	0.44	0.50	–12
01/17/02	146,000	540	115	1	0.41	0.47	–13
01/18/02	146,000	540	98	1	0.48	0.41	17
01/19/02	146,000	540	93	1	0.50	0.18	178
01/20/02	146,000	540	92	1	0.51	0.67	–24
01/21/02	146,000	540	90	1	0.52	0.55	–5
01/22/02	146,000	540	93	1	0.50	0.60	–17
01/23/02	146,000	540	101	1	0.46	0.47	–2
01/24/02	146,000	540	104	1	0.45	0.45	0
01/25/02	146,000	540	91	1	0.52	0.22	136
01/26/02	146,000	540	86	1	0.55	0.65	–15
01/27/02	146,000	540	78	1	0.60	0.38	58
01/28/02	146,000	540	92	1	0.51	0.55	–7
01/29/02	146,000	540	89	1	0.53	0.47	13
02/01/02	146,000	540	80	1	0.59	0.47	26
02/02/02	146,000	540	80	1	0.59	0.48	23
02/03/02	146,000	540	78	1	0.60	0.66	–9
02/04/02	146,000	505	74	1	0.59	0.70	–16
				Average	0.49	0.48	14
Chloride concentration accuracy limit is ±2 mg/L				Standard deviation	0.11	0.16	49

Streamflow-Record Comparison

Results of the three methods for determining streamflow records for Brandon Ditch and Keystone Gulch were compared. Current-meter measurements are typically the standard by which other streamflow-measurement methods are judged; therefore, the tracer-dilution and estimated records were compared to the current-meter record (tables 4 and 5). The daily-mean streamflow record based on current-meter discharge measurements, tracer-dilution discharge measurements, and estimated record, percent difference from the current-meter record, and averages of both the streamflow record and the percent differences are listed in tables 4 and 5.

At Brandon Ditch (fig. 5 and table 4), the average current-meter streamflow for the period of daily measurements was 0.48 ft^3/s. By comparison, the average for the same period using the tracer-dilution method was 0.49 ft^3/s, overestimating streamflow by an average difference of 14 percent. Most of the overestimation of streamflow occurred during three particular measurements for which the streamflows were different by 50 percent or more. The estimated (straight-line interpolation) record at the site averaged 0.59 ft^3/s, overestimating streamflow by an average of 64 percent.

The Keystone Gulch site had vastly different results compared to the Brandon Ditch site. The average current-meter discharge was 2.8 ft^3/s (fig. 6 and table 5). The average tracer-dilution discharge was 1.3 ft^3/s with an average of 52 percent underestimation of streamflow. The estimated record (straight-line interpolation) was closer to the current-meter record, averaging 3.2 ft^3/s, overestimating streamflow by an average of 20 percent.

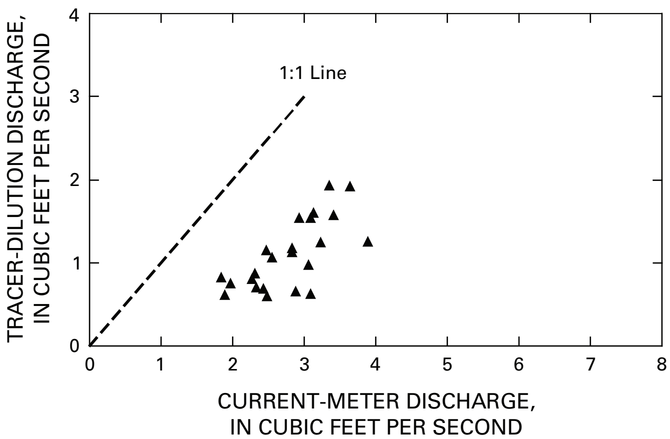

Figure 4. Comparison of current-meter and tracer-dilution discharge measurements at Keystone Gulch near Dillon, Colorado.

The results of the streamflow-record comparison using the available data are somewhat inconclusive; however, the inaccuracy of the Keystone Gulch tracer-dilution record is apparent. The inaccuracy at this site could be due more to equipment problems related to partial freezing of the tracer rather than to shortcomings of the methods. The results from the Brandon Ditch site show how streamflow records may be improved using the tracer-dilution method compared to using an estimated (straight-line interpolation) record. At most ice-affected sites, the additional data collection by the current-meter method cannot be justified due to the cost of visiting a site once per day. At sites where ISF water rights and wintertime water users come in conflict, however, the tracer-dilution method may provide improved streamflow record to help water-resource managers equitably distribute water.

Table 3. Tracer-gage and current-meter discharge measurements, Keystone Gulch near Dillon, Colorado.

[conc., concentrations; mg/L, milligrams per liter; mL/min, milliliters per minute; ft³/s, cubic feet per second. c_i, Q_i, c_g, and Q_s are variables in equation 1]

	Tracer properties		Chloride concentration		Discharge		
Date	Tracer conc., mg/L, c_i	Injection rate, mL/min, Q_i	Peak conc., mg/L, c_g	Background, mg/L, c_b	Stream discharge, ft³/s, Q_s	Measured, ft³/s	Percent difference
01/17/02	108,000	560	30	2	1.3	3.9	–67
01/18/02	108,000	560	20	2	2.0	3.4	–41
01/19/02	108,000	560	60	2	0.61	1.9	–68
01/20/02	108,000	560	33	1	1.1	2.8	–61
01/21/02	108,000	560	30	1	1.2	3.2	–63
01/22/02	108,000	560	20	1	1.9	3.6	–47
01/23/02	108,000	560	32	2	1.2	2.8	–57
01/24/02	108,000	560	49	1	0.74	2	–63
01/25/02	108,000	560	38	1	0.96	3.1	–69
01/26/02	108,000	560	24	1	1.6	3.4	–53
01/27/02	108,000	560	24	2	1.6	3.1	–48
01/28/02	108,000	560	25	2	1.6	3.1	–48
01/29/02	108,000	560	25	2	1.6	2.9	–45
02/01/02	108,000	560	45	2	0.83	1.8	–54
02/02/02	178,000	670	62	2	1.2	2.3	–48
02/04/02	178,000	640	65	3	1.1	2.9	–62
02/05/02	178,000	510	30	2	1.9	2.5	–24
02/06/02	178,000	480	30	2	1.8	2.6	–31
02/07/02	178,000	620	66	3	1.0	3.1	–68
02/09/02	178,000	280	28	2	1.1	2.4	–54
02/10/02	178,000	250	20	2	1.5	2.3	–35
02/11/02	178,000	260	22	2	1.4	2.3	–39
02/12/02	178,000	210	24	2	1.0	2.5	–60
				Average	1.3	2.8	–52
Chloride concentration accuracy limit is ±2 mg/L				Standard deviation	0.38	0.54	13

Table 4. Comparison of current-meter, tracer-gage, and estimated streamflow record, Brandon Ditch near Whitewater, Colorado.

[ft^3/s, cubic feet per second; --, no data]

Date	Measured, ft^3/s	Tracer, ft^3/s	Percent difference	Estimated, ft^3/s	Percent difference
01/09/02	0.49	0.42	–14	0.49	0
01/10/02	--	--	--	0.50	--
01/11/02	0.36	0.34	–6	0.51	41
01/12/02	0.56	0.48	–14	0.51	–8
01/13/02	0.74	0.57	–23	0.52	–29
01/14/02	0.06	0.09	50	0.53	783
01/15/02	0.43	0.47	9	0.54	25
01/16/02	0.50	0.44	–12	0.55	9
01/17/02	0.47	0.41	–13	0.55	18
01/18/02	0.41	0.48	17	0.56	37
01/19/02	0.18	0.50	178	0.57	217
01/20/02	0.67	0.51	–24	0.58	–14
01/21/02	0.55	0.52	–5	0.59	7
01/22/02	0.60	0.50	–17	0.59	–1
01/23/02	0.47	0.46	–2	0.60	28
01/24/02	0.45	0.45	0	0.61	36
01/25/02	0.22	0.52	136	0.62	181
01/26/02	0.65	0.55	–15	0.63	–4
01/27/02	0.38	0.60	58	0.63	67
01/28/02	0.55	0.51	–7	0.64	17
01/29/02	0.47	0.53	13	0.65	38
01/30/02	--	--	--	0.66	--
01/31/02	--	--	--	0.67	--
02/01/02	0.47	0.59	26	0.67	43
02/02/02	0.48	0.59	23	0.68	42
02/03/02	0.66	0.60	–9	0.69	5
02/04/02	0.70	0.59	–16	0.70	–0
Average	0.48	0.49	14	0.59	64

Tracer-Pump Evaluation

The reliability and accuracy of the piston-driven tracer pumps were evaluated during a test done from February 23 through March 19, 2002 (table 6). The pumps were evaluated because there was no practical method of independently measuring the output from the tracer pump, such as using a flow meter or volumetric measurements, because the injection lines were frozen in place. Also, this pump evaluation examined the consistency of three identical pumps to determine the pump reliability in a simulated field environment.

The three pumps were set up to automatically discharge a sodium chloride tracer solution for 10 minutes once per day. The setups were numbered in sequential order as setup #1, setup #2, and setup #3, and the specifications of each pump setup are given in table 1. Table 7 shows the air temperatures outside and inside the shelters while the pump test was in progress as an indication of how well the heat source helped to regulate the air temperature inside the structure. For the pump test, a propane pilot light was used as a heat source.

Each pump setup underdischarged the tracer as compared to the initial setting (see table 6). Setup #1 underdischarged the tracer by an average of –10.4 percent, setup #2 by –15.9 percent, and setup #3 by –5.8 percent. However, each pump setup was consistent in the volume of tracer discharged. Setup #1 had a standard deviation of the percent differences of 5.0 percent, setup #2 a standard deviation of 2.8 percent, and setup #3 a standard deviation of 3.6 percent.

These results from the tracer-pump evaluation support the assumption that the tracer pumps can consistently discharge the tracer solution for short time periods. However, to properly gage the tracer-injection rate, the results of this study also show that care must be taken when determining the pump rate before the pump is allowed to function automatically.

Table 5. Comparison of current-meter, tracer-gage, and estimated streamflow record, Keystone Gulch near Dillon, Colorado.

[ft^3/s, cubic feet per second; --, no data]

Date	Measured, ft^3/s	Tracer, ft^3/s	Percent difference	Estimated record	Percent difference
01/17/02	3.9	1.3	–67	3.9	0
01/18/02	3.4	2.0	–41	3.8	12
01/19/02	1.9	0.61	–68	3.8	100
01/20/02	2.8	1.1	–61	3.7	32
01/21/02	3.2	1.2	–63	3.7	16
01/22/02	3.6	1.9	–47	3.6	0
01/23/02	2.8	1.2	–57	3.6	29
01/24/02	2.0	0.74	–63	3.5	75
01/25/02	3.1	0.96	–69	3.5	13
01/26/02	3.4	1.6	–53	3.4	0
01/27/02	3.1	1.6	–48	3.4	10
01/28/02	3.1	1.6	–48	3.3	6
01/29/02	2.9	1.6	–45	3.2	10
01/30/02	--	--	--	3.2	--
01/31/02	--	--	--	3.1	--
02/01/02	1.8	0.83	–54	3.1	72
02/02/02	2.3	1.2	–48	3.0	30
02/03/02	--	--	--	3.0	--
02/04/02	2.9	1.1	–62	2.9	0
02/05/02	2.5	1.9	–24	2.9	16
02/06/02	2.6	1.8	–31	2.8	8
02/07/02	3.1	1.0	–68	2.8	–10
02/08/02	--	--	--	2.7	--
02/09/02	2.4	1.1	–54	2.6	8
02/10/02	2.3	1.5	–35	2.6	13
02/11/02	2.3	1.4	–39	2.5	9
02/12/02	2.5	1.0	–60	2.5	0
Average	2.8	1.3	–52	3.2	20

Equipment and Error Analysis

Probably the largest source of unquantifiable error in the tracer-dilution method is how the equipment works under extremely cold conditions. Although the pump-evaluation test examined the pump reliability to automatically inject the tracer during cold temperatures, the temperatures were not as cold as those at the Keystone Gulch gaging station. The tracer-gage results at Keystone Gulch showed that the tracer gage underestimated discharge at this site. It was noted during the study that the tracer pump had difficulty discharging the tracer solution, and partial freezing of the tracer solution in the injection lines was observed. Any reduction in the discharge of the tracer would cause an underestimation of discharge using the tracer-dilution method. In addition, a subsequent tracer-gage study (David Clow, U.S. Geological Survey, oral commun., 2003) experienced difficulty in accurately measuring the instream tracer concentration at a nearby site while the same probe performed well at a lower elevation, warmer site. Future work in the tracer-dilution method will need to focus on improving the reliability of the equipment at very cold temperatures.

There are additional sources of error that are quantifiable that also may have introduced error in the accuracy analysis of the tracer-dilution method. First, there are accuracy limitations to the equipment that was used during the study. The chloride ion probes had a 2-mg/L accuracy limit. This accuracy limit may have introduced an error ranging from less than 1 percent to 3 percent for the flows at Brandon Ditch and an error ranging from 3 to 10 percent at Keystone Gulch, based on peak-chloride concentrations. A lower peak-chloride concentration was used at Keystone Gulch compared to Brandon Ditch because high sodium chloride concentration could be potentially harmful to the ecosystem of the stream. A higher concentration, however, would have helped reduce any probe-accuracy errors.

The use of chloride as the tracer has limited application in Colorado. One requirement for a tracer is that the background concentrations of the tracer are low. Because sodium

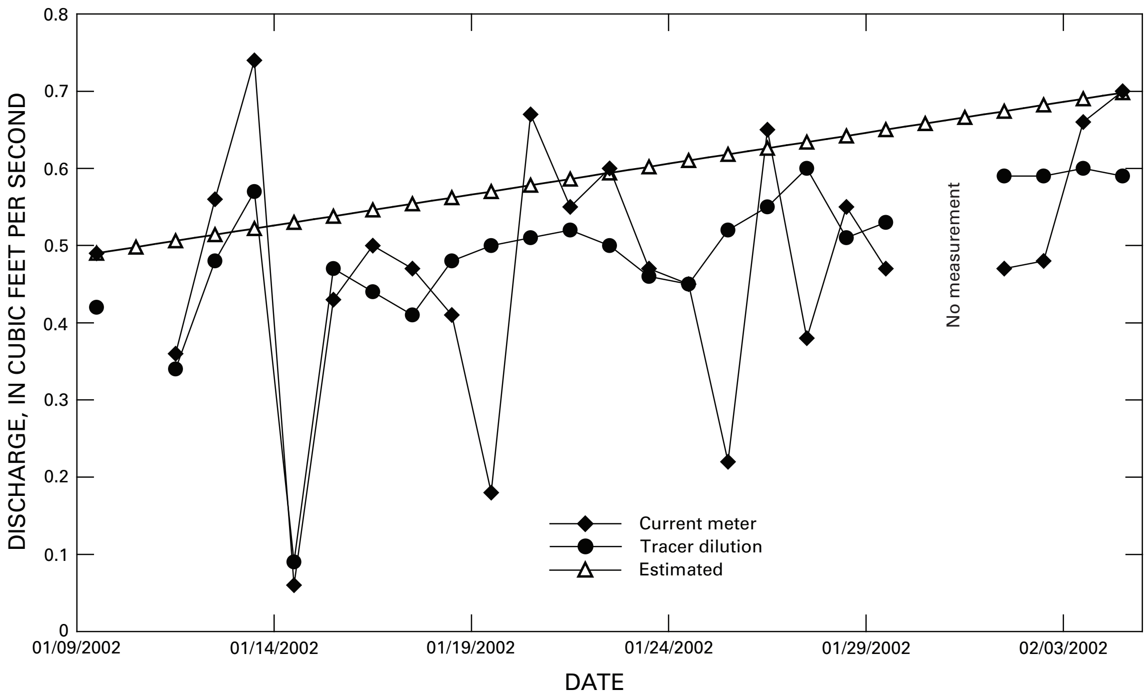

Figure 5. Streamflow-record comparison between estimated, current-meter, and tracer-dilution methods, Brandon Ditch near Whitewater, Colorado.

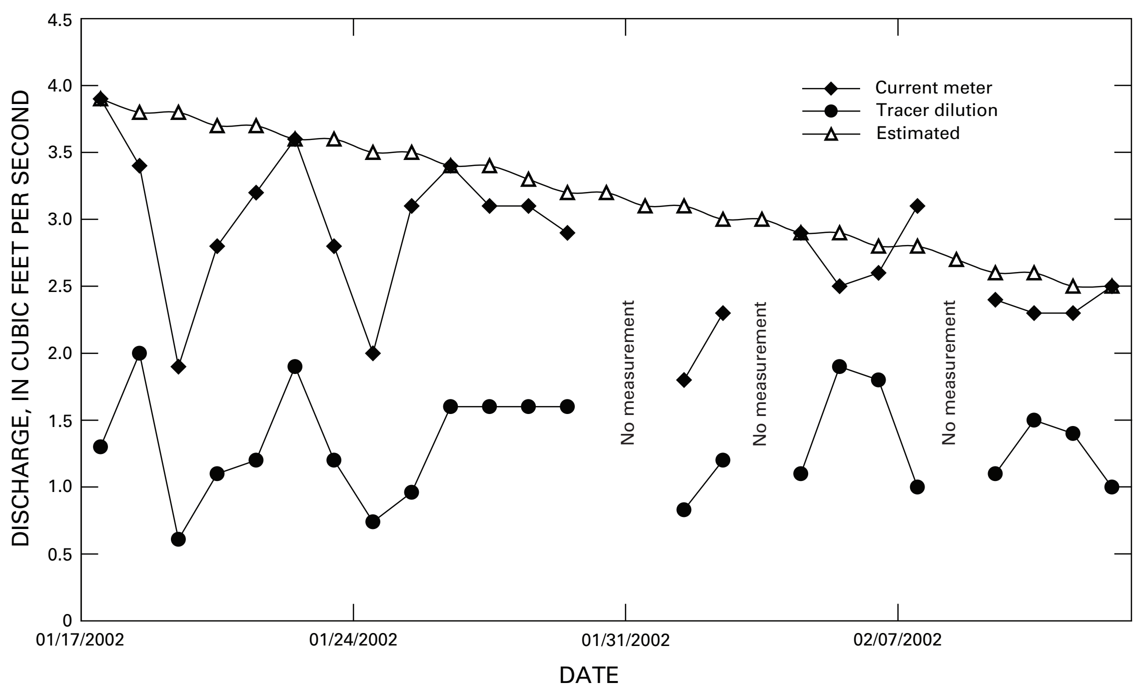

Figure 6. Streamflow-record comparison between estimated, current-meter, and tracer-dilution methods, Keystone Gulch near Dillon, Colorado.

Table 6. Results from the tracer-pump evaluation.

[%, percent; mL, milliliters; --, no data]

Date	Pump setup #1: 5,000 mL		Pump setup #2: 4,500 mL		Pump setup #3: 4,900 mL	
	Volume	% difference from 4,800 mL	Volume	% difference from 4,500 mL	Volume	% difference from 4,900 mL
02/23/2002	4,930	–1.4	--	--	4,738	–3.3
02/24/2002	4,820	–3.6	--	--	4,659	–4.9
02/25/2002	4,210	–15.8	--	--	4,040	–17.6
02/26/2002	4,029	–19.4	--	--	4,536	–7.4
02/27/2002	--	--	--	--	--	--
02/28/2002	4,376	–12.5	--	--	4,396	–10.3
03/01/2002	--	--	--	--	--	--
03/02/2002	4,622	–7.6	4,000	–11.1	4,500	–8.2
03/03/2002	4,148	–17.0	3,876	–13.9	4,548	–7.2
03/04/2002	4,216	–15.7	3,746	–16.8	4,425	–9.7
03/05/2002	4,288	–14.2	3,844	–14.6	4,503	–8.1
03/06/2002	4,396	–12.1	3,902	–13.3	4,652	–5.1
03/07/2002	4,559	–8.8	3,648	–18.9	4,712	–3.8
03/08/2002	4,720	–5.6	3,734	–17.0	4,693	–4.2
03/09/2002	4,594	–8.1	3,897	–13.4	4,805	–1.9
03/10/2002	4,364	–12.7	3,560	–20.9	4,550	–7.1
03/11/2002	4,590	–8.2	3,728	–17.2	4,724	–3.6
03/12/2002	4,498	–10.0	3,860	–14.2	4,744	–3.2
03/13/2002	4,210	–15.8	3,784	–15.9	4,722	–3.6
03/14/2002	4,104	–17.9	3,904	–13.2	4,810	–1.8
03/15/2002	4,574	–8.5	3,734	–17.0	4,714	–3.8
03/16/2002	4,656	–6.9	3,876	–13.9	4,784	–2.4
03/17/2002	4,704	–5.9	3,794	–15.7	4,670	–4.7
03/18/2002	4,688	–6.2	3,726	–17.2	--	--
03/19/2002	4,716	–5.7	3,512	–22.0	4,670	–4.7
Mean	4,479	–10.4	3,785	–15.9	4,618	–5.8
Standard deviation	248	5.0	126	2.8	176	3.6
Minus first 2 days						
Mean	4,441	–11.2	3,766	–16.3	4,610	–5.9
Standard deviation	224	4.5	118	2.6	182	3.7

chloride and magnesium chloride are used as road deicers throughout Colorado, the sites where chloride can be used as a tracer is limited to sites where few roads exist. In the mountains of Colorado, most roads follow at least portions of the stream valleys, thus limiting the use of chloride as a tracer to a few sites without roads that are used in the winter, such as Keystone Gulch.

Another limiting factor in the use of chloride as a tracer is the accuracy limitations of the in-situ water-quality probes. Most standard in-situ water-quality probes at present (2003) have an accuracy limit of 2 mg/L for the detection of chloride. Therefore, the peak concentration of chloride in the stream during the tracer-injection period should be at least 40–100 mg/L. Use of a tracer with a lower detection limit, such as rhodamine-WT dye, would allow for less tracer loading into the stream and a greater contrast between the background and peak tracer concentrations, which would reduce the error introduced by the accuracy limitations of the tracer probe. Another benefit of a lower detection limit of another tracer is the less frequent need to refill the tracer reservoir.

A second source of error in the equipment is the tracer pump. The pump-reliability test showed that the tracer pumps discharged less tracer solution as compared to the initial setting of the pumps. The pump-reliability test showed the pumps discharged 5.8–15.9 percent less tracer solution than was originally set. This decrease in the tracer discharge into the stream would cause an underestimation of discharge at the gaging stations by the same magnitude, but much of this error could be reduced with additional preparation of the tracer gage. One solution to this problem is to develop a better method to measure how much tracer is being discharged during a tracer-dilution study and to repeatedly check the pumping rate throughout the study without interfering with the operation of the tracer-injection equipment.

Table 7. Outside and inside air temperatures for the tracer-pump evaluation.

[°C, degrees Celsius; --, no data]

Date	Temperatures for pump test	
	Inside, °C	Outside, °C
02/23/2002	14	14
02/24/2002	20	5
02/25/2002	13.5	1.5
02/26/2002	6	–4
02/27/2002	–3	–4
02/28/2002	12	1
03/01/2002	--	--
03/02/2002	10	–4
03/03/2002	10	–6
03/04/2002	11.5	–4
03/05/2002	13	5
03/06/2002	17	8
03/07/2002	9	9
03/08/2002	14.5	3.5
03/09/2002	4	–4
03/10/2002	18	8.5
03/11/2002	23.5	11
03/12/2002	20	10.5
03/13/2002	27	15
03/14/2002	15.5	1
03/15/2002	22	11.5
03/16/2002	14	0.5
03/17/2002	17	7
03/18/2002	6.5	3.5

A third source of quantifiable error is the accuracy of the current-meter discharge measurements. At Brandon Ditch, most of the measurements made for this study are rated Poor or Fair, which indicates a greater than 8-percent accuracy limit and an 8-percent accuracy limit, respectively (Rantz and others, 1982). The measurement of any volume of water with a current meter has small amounts of potential error that, at small discharges, may become a larger portion of the total flow. At the Brandon Ditch gage, depth of flow did not exceed 0.9 ft during the study period, and 9 of the 25 current-meter measurements had more than 75 percent of the depth measurements less than 0.3 ft, which is the minimum depth of water needed for proper operation of a pygmy flow meter. Similarly at Keystone Gulch, all but one of the discharge measurements were rated Poor. While the error in the current-meter measurements was probably the least of the three error sources and likely the most difficult to remove, a combination of the unquantifiable error from equipment difficulties at very low temperatures and all three quantifiable error sources may help to explain some of the disagreement between the tracer-dilution and current-meter streamflow records.

Instream Flow Water Rights and Tracer-Gage Streamflow Records

Initially during the study, it was assumed that Keystone Gulch near Dillon, given the high elevation and cold temperatures at the site, maintained a slowly receding base flow throughout the winter. The current-meter measurements made at the site show that this slow recession does not occur. Part of the reason for the variable discharge at Keystone Gulch is an apparent return flow of water from snowmaking activities. The return flows enter Keystone Gulch about 500 ft upstream from the gaging station. It is acknowledged that the ISF water right for Keystone Gulch is 1.8 ft^3/s (ISF Program Database), and the current-meter measurements show that this minimal amount of streamflow was present in the stream throughout the study period (January 9–February 12).

Although the tracer-dilution method needs considerable improvement and refinement before it can help water-resource managers administer ISF water rights, future developments and technological improvements may provide unforeseen advancements. Development of in-situ water-quality probes to measure environmentally friendly tracers such as rhodamine-WT dye and the implementation of satellite or other telemetry could allow a water-resource manager to cost-effectively and accurately administer ISF water rights.

As the tracer-dilution method is improved and applied, consideration needs to be given to the compatibility of current-meter and tracer-dilution streamflow records. Water rights have been historically based upon streamflow records determined at gaging stations where current meters are used to measure flow. Studies using tracers have shown that tracer-dilution discharge measurements may overestimate flow in cobble-bed streams (Zellweger and others, 1989; Kimball, 1996) because the tracer can be diluted by water flowing through the cobble alluvium that cannot be measured with a current meter. The discrepancies between the two methods may lead to conflicting streamflow values.

Summary and Conclusions

The U.S. Geological Survey, in cooperation with the Colorado Water Conservation Board, conducted a study examining the feasibility and accuracy of ice-affected streamflow records using an automatically injected tracer and the constant-rate tracer-dilution discharge method to determine streamflow. This tracer-dilution study had two components. The first was to compare the accuracy of a current-meter ice-affected streamflow record with both tracer-dilution and estimated (straight-line interpolation) streamflow records. The second was to examine the reliability of the tracer pumps to consistently and accurately discharge a specified volume of the tracer solution.

The first component of the study had varying levels of comparability between the current-meter, the tracer-dilution, and the straight-line interpolation streamflow records. At the lower elevation and warmer site, Brandon Ditch near Whitewater, the tracer-dilution method overestimated the amount of streamflow by an average of 14 percent. This average overestimation was strongly biased by 3 days for which the streamflows were 50 percent, or more, different. For the 24 days where a successful tracer-dilution discharge measurement was made, the daily-mean flow was 0.49 ft^3/s, whereas the daily-mean flow using a current meter was 0.48 ft^3/s and the daily-mean flow using straight-line interpolation was 0.59 ft^3/s. At the higher elevation and colder site, Keystone Gulch near Dillon, the tracer-dilution method underestimated flow by an average of 52 percent. For the 23 days where a successful tracer-dilution discharge measurement was made, the daily-mean flow was 1.3 ft^3/s, whereas the daily-mean flow using a current meter was 2.8 ft^3/s and the estimated straight-line interpolation record was 3.2 ft^3/s.

Several factors contributed to the difficulties of developing streamflow records using the tracer-dilution discharge method. The first is the reliability of the equipment to work at a cold, high-elevation site as the tracer pump was less reliable at Keystone Gulch. Other factors that may have caused inaccuracies between the current-meter and tracer-dilution streamflow records are the tracer-probe accuracy limits and the accuracy of wintertime current-meter flow measurements that were mostly rated Poor. It appears that the performance of the equipment at cold, high-elevation sites is where most of the error exists between the current-meter and tracer-dilution discharge records.

The second component of the study showed that the piston-driven pumps can consistently discharge the tracer solution in a field environment with no adjustments after installation. Although the pump setups performed consistently throughout the study period, care must be exercised when setting the discharge rate of the pumps, as each pump setup underdischarged the tracer as compared to its original setting.

The use of the tracer-dilution method has great potential and utility where streams are subject to variable backwater conditions from ice or a constantly shifting streambed. It is expected that advances in technology will allow water-resource managers to have timely and accurate near-real-time streamflow records. Improvements in the ability of the tracer pumps to perform in extreme cold, development of in-situ water-quality probes with lower (less than 2 mg/L) tracer-detection limits, and the use of satellite telemetry are examples of where improved technology will enhance the tracer-dilution method.

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