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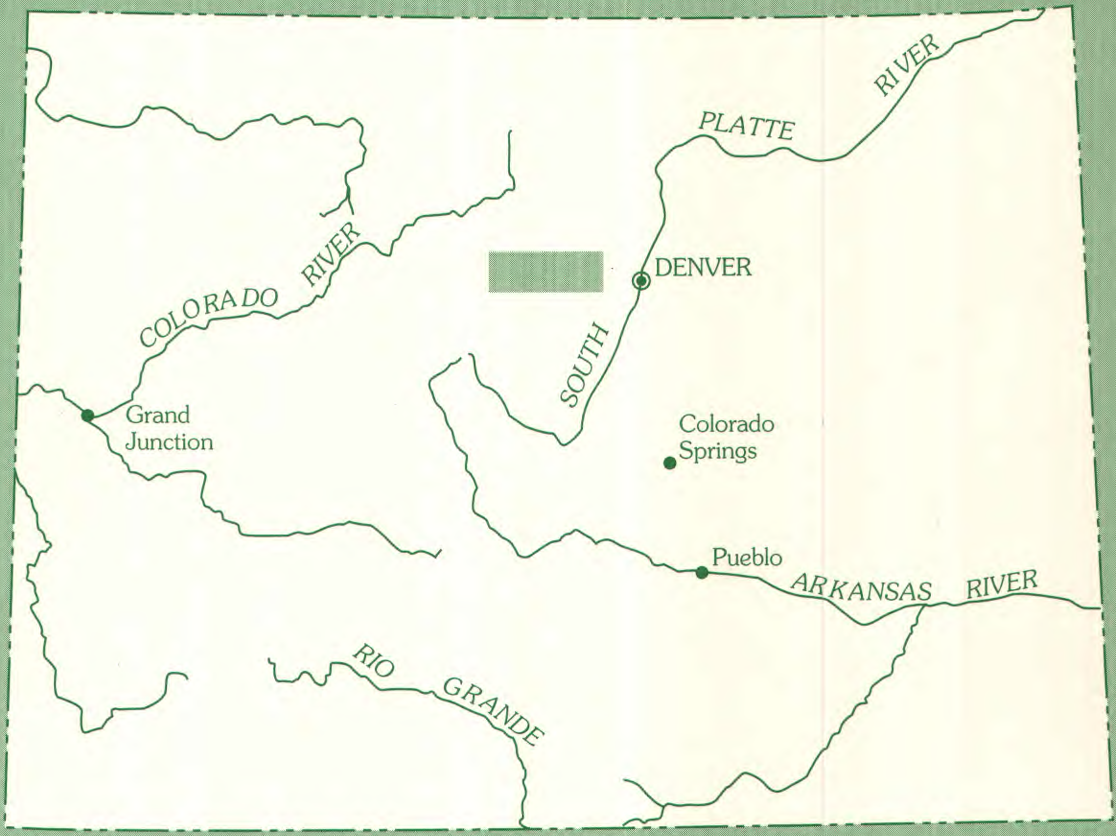
TRAVELTIMES ALONG CLEAR CREEK AND SELECTED TRIBUTARIES UPSTREAM FROM GOLDEN, COLORADO, 1996–97

U.S. GEOLOGICAL SURVEY



Water-Resources Investigations Report 98–4151

Prepared in cooperation with the
LACKHAWK

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By Sally M. Cuffin

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CITY OF BLACKHAWK

Denver, Colorado
1999

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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

For additional information write to:

District Chief
U.S. Geological Survey
Box 25046, Mail Stop 415
Denver Federal Center
Denver, CO 80225–0046

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286
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Denver, CO 80225

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CONVERSION FACTORS

Multiply	By	To obtain
cubic foot (ft^3)	0.02832	cubic meter
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon (gal)	3.785	liter
mile (mi)	1.609	kilometer
mile per hour (mi/hr)	1.609	kilometer per hour
square foot (ft^2)	0.09290	square meter

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = (1.8 \times °C) + 32$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A Geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

The following terms and abbreviations also are used in this report:

greater than (>)
less than (<)
microgram per liter (µg/L)
nanometer (nm)
plus or minus (±)

Traveltimes Along Clear Creek and Selected Tributaries Upstream from Golden, Colorado, 1996–97

By Sally M. Cuffin

Abstract

Increased traffic along mountainous stretches of Interstate Highway 70, U.S. Highway 40, and U.S. Highway 6 in Colorado has resulted in a corresponding increase in the movement of hazardous materials. The proximity of Clear Creek and its tributaries to these highways places downstream water users at risk in the event of an accidental hazardous-material release. A traveltime study was performed on two reaches of Clear Creek and two of its tributaries to provide the necessary information to allow downstream water managers to protect water supplies in the event of a hazardous-material release. The information also can be used by hazardous-material-response teams to intercept contaminants as they move downstream. This report summarizes the methods and findings of the traveltime study.

Traveltime measurements were made using rhodamine-WT dye as a tracer in two reaches of Clear Creek and two Clear Creek tributaries in Clear Creek and Jefferson Counties, Colorado. The reaches were Clear Creek from the town of Berthoud Falls to the city limits of Golden; Clear Creek from the eastern edge of the Loveland Basin Ski Area parking lot to the town of Georgetown; the headwaters of two Clear Creek tributaries near Loveland Pass to the Loveland Valley Ski Area; and two unnamed tributaries of Hoop Creek (a tributary of Clear Creek) near Berthoud Pass to the confluence with the West Fork of Clear Creek. Measurements were made at three times of the year to obtain data from different flow conditions.

Traveltime and average velocities were determined for each stream reach. During high flow, dye-cloud leading-edge traveltimes ranged from about 0.6 hour along the Loveland Pass to the Loveland Valley Ski Area drainage to about 8.8 hours between Berthoud Falls and Golden. During low flow, leading-edge traveltimes ranged from about 2.6 hours along the same drainage from Loveland Pass to about 28.6 hours between Berthoud Falls and Golden. Average velocity between the Loveland Pass sites ranged from about 1.3 miles per hour during high flow to about 0.3 mile per hour during low flow. Average velocities between Berthoud Falls and Golden ranged from about 4.4 miles per hour during high flow to about 1.3 miles per hour during low flow.

A curve-fitting program was used to fit Lorentz and Gaussian distributions to the data generated from the traveltime measurements. Because discrete (not continuous) traveltime measurements were made, an estimate of the actual time of the leading edge, peak, and trailing edge needed to be determined from the sample data. The curve-fitting program provided the means to calculate the timing of events (leading edge, peak, and trailing edge) that were not precisely measured. Calculated leading-edge, peak, and trailing-edge times were used to generate a series of graphs for each study reach.

Traveltime estimation tables were generated from the data for a range of Clear Creek discharges. Because of the high variability of discharge within the basin, the Lawson

surface-water gage located near the center of the basin was used as the reference location. Discharge measurements for the Lawson gage are available on the Internet, which can be accessed by most hazardous-material-team dispatchers. Traveltimes determined during the individual studies were plotted against the corresponding discharge at the reference location. A curve-fitting program was used to generate a series of curves, which were used to produce traveltime estimation tables.

INTRODUCTION

In mountainous areas of Colorado, major highways often follow stream valleys where grades are not so steep. The close proximity of streams and roads place these streams at risk of contamination in the event of a vehicular accident involving hazardous materials. Many of these "at risk" streams also supply water to downstream users.

Population growth along the Front Range of Colorado and in nearby mountain communities has resulted in increased traffic along the mountain highways and a corresponding increase in the movement of hazardous materials. In addition, mountain driving can be challenging because of winding roads and changeable weather conditions. These factors can contribute to traffic accidents and possible associated hazardous-material spills.

The population growth also is placing increasing demands on water supplies, and water suppliers need to be prepared if a stream becomes contaminated with hazardous materials. A water manager needs to know when to close intake valves to treatment plants and how long to keep them closed. Contaminants drawn through a water-treatment system can result in the potential distribution of contaminated water to the public and in the costly replacement of filters.

A stream traveltime study can provide water suppliers and water managers with necessary information in the event of a hazardous-material release. Soluble-tracer studies of streams can provide an effective and accurate method for the determination of traveltimes between a spill site and the intake for a domestic water supply or a temporary holding pond. In addition, the timing of the passage of the dye cloud provides useful information for determining the capacity of temporary holding ponds used to contain hazardous-material spills.

Mountain stream characteristics are variable (slope; streambed materials, such as gravel, cobbles, and boulders; obstructions, such as fallen trees; and discharge), making traveltime estimations through a long mountainous stream reach difficult.

Because Clear Creek is one of the "at risk" streams (fig. 1) in the Front Range of Colorado, the U.S. Geological Survey (USGS), in cooperation with the City of Blackhawk, began a study in 1996 to determine the traveltime for soluble contaminants between selected points along two reaches of Clear Creek and along two Clear Creek tributaries. The study stream reaches were: (1) The West Fork of Clear Creek from the town of Berthoud Falls to the Clear Creek confluence and continuing along Clear Creek to the city limits of Golden [potentially affected by spills from Interstate Highway 70 (I–70), U.S. Highway 40 (Hwy 40), and U.S. Highway 6 (Hwy 6)] (fig. 1); (2) the main channel of Clear Creek at the Loveland Basin Ski Area to the 6th Street bridge in Georgetown (potentially affected by spills from I–70) (fig. 1); (3) two unnamed tributaries near Loveland Pass to the western edge of the Loveland Basin Ski Area parking lot (potentially affected by spills from Hwy 6) (fig. 2), and (4) two unnamed tributaries flowing into Hoop Creek (a tributary of the West Fork of Clear Creek) near Berthoud Pass to the Hoop Creek crossing of Hwy 40 near its confluence with the West Fork of Clear Creek (potentially affected by spills from by Hwy 40) (fig. 3). The traveltime characteristics of the streams were measured using rhodamine-WT dye as a tracer. One objective for the study along the two Clear Creek tributaries was to provide information to the Colorado Department of Transportation for the design of detention ponds needed to capture hazardous-material spills prior to their introduction into the main stream channels. Traveltimes were determined at three times of the year during three different flow conditions: high flow (late spring); transitional flow (mid-summer); and low flow (early fall).

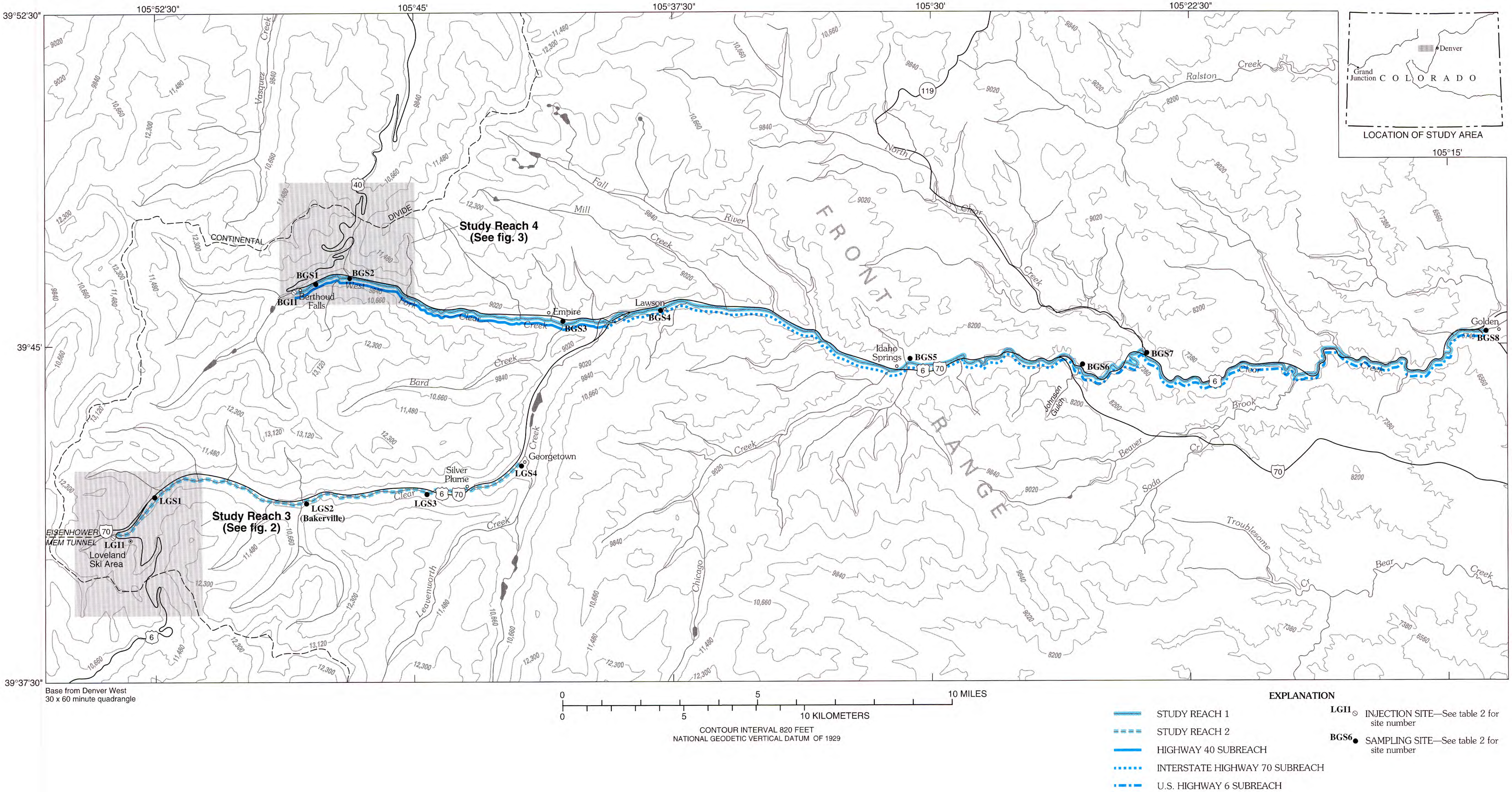

Figure 1. Location of Upper Clear Creek Basin, Study Reaches 1 through 4, and injection and sampling sites for Study Reach 1—Berthoud Falls to Golden and for Study Reach 2—Loveland Basin Ski Area to Georgetown, Front Range.

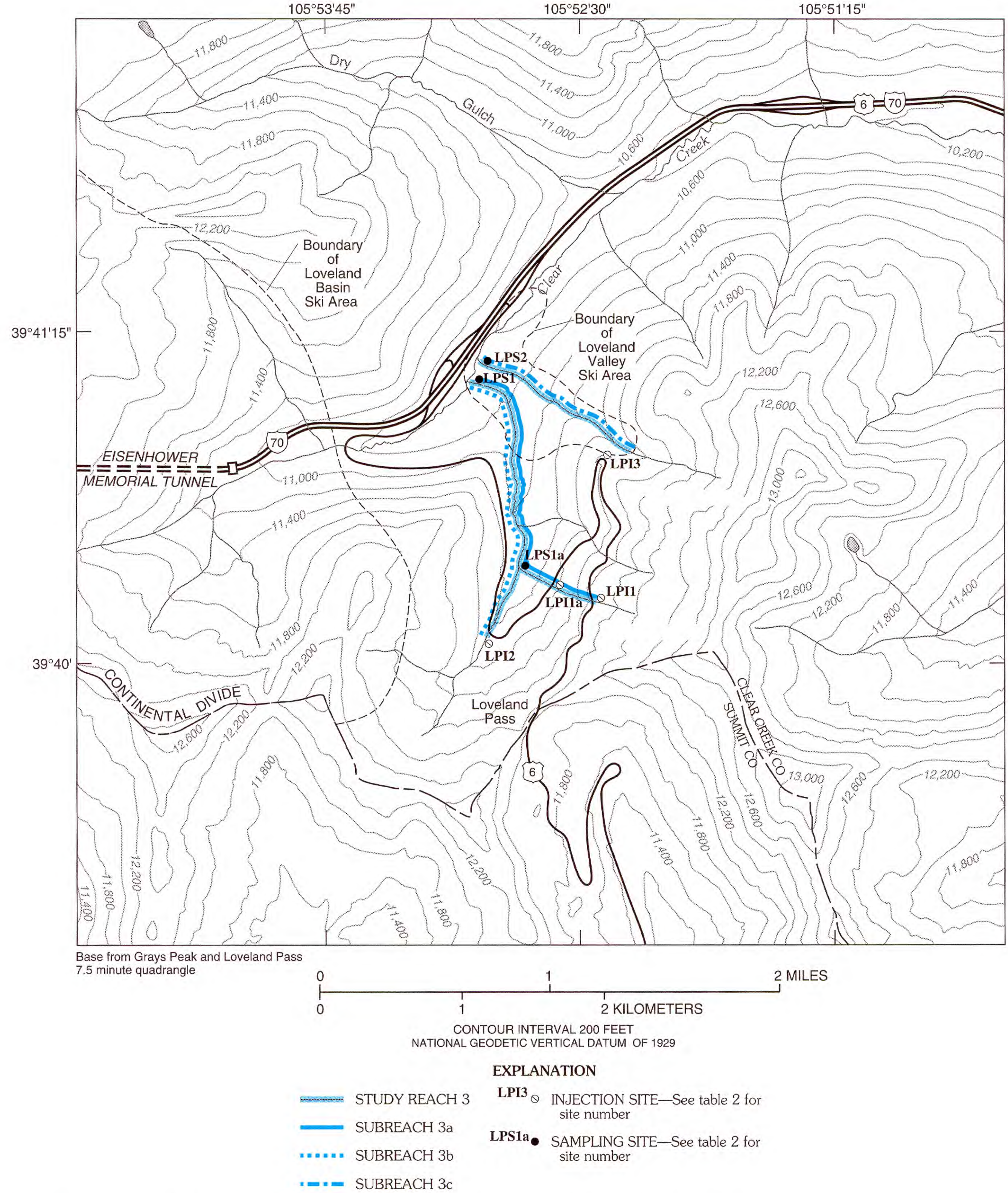

Figure 2. Location of Study Reach 3—Loveland Pass and associated injection and sampling sites.

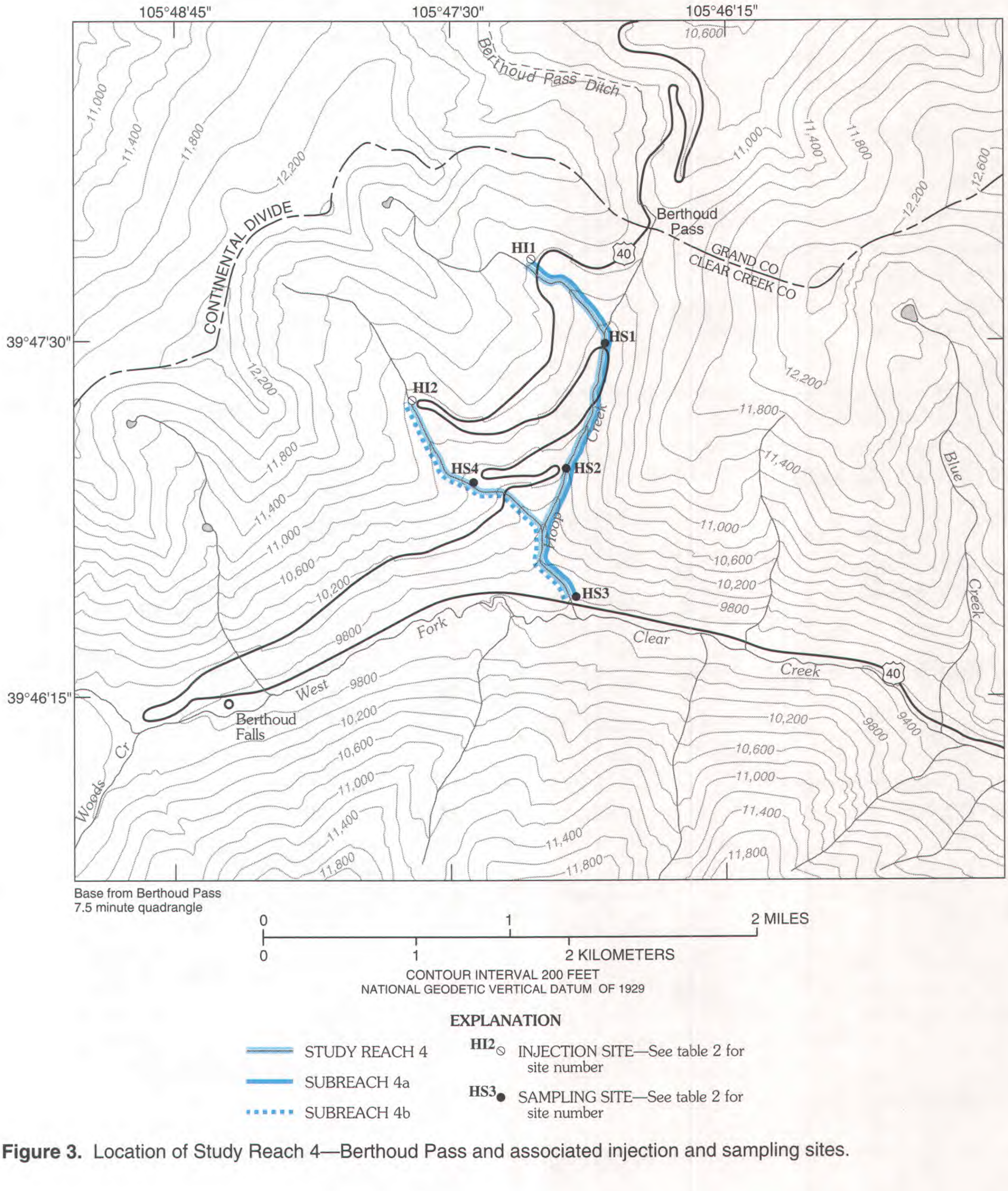

Figure 3. Location of Study Reach 4—Berthoud Pass and associated injection and sampling sites.

Purpose and Scope

This report presents the results of three sets of traveltime data collected for two reaches of Clear Creek and two of its tributaries. Traveltime measurements were made on all study reaches, except Hoop Creek, during the high flow (mid-June 1996); the transitional flow (mid-August 1996) when the stream transitions from high to low flow; and the low flow (early October 1996). The study was revised in

August of 1996 to include traveltime measurements for Hoop Creek during transitional flow and low flow of 1996 and high flow of 1997 (mid-June).

Acknowledgments

The author wishes to thank the members of the upper Clear Creek Watershed Association and the Colorado Department of Transportation for their assistance with this study. Special thanks are extended to Robert Jones who negotiated steep mountain roads with the 2,500-gal fire tanker truck used to simulate spills for this study. Special thanks also are extended to Don Smith who provided access to the West Fork of Clear Creek at Berthoud Falls. The author also appreciates the data-collection efforts of members of the Lakewood Field Office of the USGS.

LOCATION AND CHARACTERISTICS OF STUDY REACHES

Study Reach 1—Berthoud Falls to Golden

Study Reach 1 extends from Berthoud Falls (elevation 9,800 ft) along the West Fork of Clear Creek to the western city limits of Golden (elevation 5,695 ft) along Clear Creek (fig. 1). The study reach was divided into three subreaches: the Hwy 40 subreach that includes the West Fork of Clear Creek from Berthoud Falls to the confluence with the main channel of Clear Creek (about 1.6 mi east of Empire, elevation 8,230 ft); the I–70 subreach that includes the main channel of Clear Creek from the confluence with the West Fork of Clear Creek to the junction of I–70 and Hwy 6 (about 4.5 mi east of Idaho Springs, elevation 7,210 ft); and the Hwy 6 subreach that includes the main channel of Clear Creek from the junction of I–70 and Hwy 6 to the bottom of Clear Creek Canyon near the city limits of Golden (elevation 5,695 ft).

The Hwy 40 subreach begins (injection site BGI1) in a primarily undeveloped, forested area and descends into areas of mountain communities and historical mining operations. The West Fork of Clear Creek parallels Hwy 40 from Berthoud Falls to its confluence with the main channel of Clear Creek. Distances between the stream and the highway through this subreach vary from several yards, about 1 mi east of Berthoud Falls, to about 0.25 mi, near Empire.

The stream channel along the Hwy 40 subreach is characteristic of Colorado mountain streams, having streambeds consisting primarily of sands, gravels, cobbles, and boulders. Rock outcroppings and debris flows from steep mountain slopes have affected the stream channel along this subreach. The U.S. Fish and Wildlife Service has done extensive work along the western part of the Hwy 40 subreach to improve fish habitat by the use of small dams and rock structures. Because of limited anthropogenic effects in the western part of the subreach, the stream channel includes meanders, beaver ponds, channel vegetation (especially during high flow), and natural water falls. The stream channel was straightened along the eastern part of the Hwy 40 subreach to accommodate highway and residential construction and mining operations.

The I–70 subreach continues along the main channel of Clear Creek, paralleling I–70 from the highway junction near Empire to the junction with Hwy 6, about 4.5 mi east of Idaho Springs. Elevations along this reach decrease from about 8,230 to about 7,210 ft. The stream borders the highway along about 90 percent of this subreach. Along the remaining 10 percent of the subreach, the stream borders frontage roads or residential and business development.

Extensive straightening of the channel has occurred throughout the I–70 subreach because of highway, business, and residential construction. The streambed throughout this subreach consists primarily of cobbles and boulders.

The Hwy 6 subreach follows the main channel of Clear Creek through Clear Creek Canyon to Golden. The elevation decreases from about 7,210 ft at the junction of I–70 and Hwy 6 to 5,695 ft at the city limits of Golden (sampling site BGS8). Clear Creek Canyon is a narrow canyon that has steep rock walls that limit development in the area. The highway is located within 50 to 100 ft of the stream throughout most of the canyon.

The stream channel has been modified throughout much of this subreach to make room for the highway and mining operations. The streambed in the western part of the subreach consists primarily of cobbles and boulders. Channel vegetation affects stream velocities (primarily during high flow) in the eastern part of the subreach near Golden.

A limited amount of traffic data is provided to indicate the trends since the early 1990's. Traffic accident and volume information for the highways along the study reach are provided in table 1 (Colorado Department of Transportation, written commun., 1997). The traffic data include the 1991 through 1996 period. An arbitrary comparison was made between the first 2 years and the last 2 years of the period. The 2-year period was chosen because of the limited data and to reduce the effect of an abnormal accident year (such as a year with a multi-car pileup).

Study Reach 2—Loveland Basin Ski Area to Georgetown

Study Reach 2 includes the reach of Clear Creek from the eastern edge of the Loveland Basin Ski Area parking lot (elevation about 10,840 ft) to Georgetown (elevation 8,512 ft) (fig. 1). Interstate 70 follows the valley carved by Clear Creek along this reach, and the distance from the highway to the creek varies from 50 ft to about 0.25 mi. Study Reach 2 begins at the Loveland Basin and Valley Ski Areas (injection site LGI1), passes through mostly undeveloped, forested land, and descends into areas of mountain communities and historical mining operations. The final sampling site is at the 6th Street bridge in Georgetown (LGS4).

The western part of this reach passes through the Arapaho National Forest. Extensive work has been done to the Clear Creek stream channel by the U.S. Fish and Wildlife Service between the Loveland Basin Ski Area and Bakerville to improve fish habitat by the use of small dams and rock structures. Natural meanders, channel vegetation, and debris flows affect stream velocities in the western part of the reach. The I–70 construction and historic mining operations have resulted in major disturbance of the stream channel, primarily in the eastern part of this reach, with large sections of the stream being straightened and rerouted.

As in Study Reach 1, accidents and average daily traffic volume have increased along this stretch of highway (Colorado Department of Transportation, written commun., 1997) (table 1).

Study Reach 3—Loveland Pass

Study Reach 3 includes parts of two unnamed tributaries that flow into the main channel of Clear Creek near the western end of the Loveland Valley Ski Area parking lot (fig. 2). These tributaries drain the southern side of the Clear Creek Basin that is traversed by Hwy 6 through a series of steep grades and switch-back curves. The tributaries are intersected by Hwy 6 several times as the highway winds up to the pass. The headwaters of the tributaries are located along the

Table 1. Traffic accident and volume information for Study Reaches 1 and 2 (Colorado Department of Transportation, written commun., 1997)

Stretch of highway	Average number of accidents		Percent increase	Average daily traffic volume		Percent increase
	1991–92	1995–96		1991–92	1994–95	
Study Reach 1						
U.S. Highway 40, Berthoud Falls to Interstate 70 junction	13	23	76.9	4,691	5,553	18.4
Interstate 70, junction U.S. Highway 40 to junction U.S. Highway 6 (east of Idaho Springs)	137	[1]203	48.2	27,991	31,761	13.5
U.S. Highway 6, junction Interstate 70 to Golden city limits	144	180	25.0	7,178	12,058	68.0
Study Reach 2						
Interstate Highway 70, Eisenhower Memorial Tunnel to Georgetown	78	127	62.8	21,076	24,138	14.5

[1]Data not available for 1996; average number of accidents for 1994–95.

Continental Divide near Loveland Pass (elevation 11,992 ft). All of the study reach is located in the Arapaho National Forest. The study reach was divided into three subreaches to provide traveltime information from three potential accident sites.

Subreach 3a follows an intermittent drainage to the confluence with a perennial Clear Creek tributary (flow is minimal during the winter) (fig. 2). Subreach 3a starts at the entrance of a culvert that passes under Hwy 6 about 0.6 mi from the top of Loveland Pass (injection site LPI1). The reach begins in alpine tundra and then rapidly descends through forested land to the main tributary at the bottom of the valley (passing again under Hwy 6 through another culvert). The drainage channel mostly consists of a series of small alternating waterfalls and pools. The water essentially steps down the mountainside until it reaches a grass and willows wetland at the bottom of the slope. There are numerous small channels meandering through the wetland, but a large percentage of the water is absorbed and slowed by the vegetation. Once it reaches the main tributary, the water is again slowed by a meandering stream channel and extensive vegetation. The stream channel just upstream from the confluence with Clear Creek (sampling site LPS1) has been disturbed by activities at the Loveland Valley Ski Area.

Subreach 3b is a reach of the same perennial Clear Creek tributary that drains subreach 3a (fig. 2). Subreach 3b begins at a culvert under Hwy 6 about 2.8 mi from the top of Loveland Pass (injection site LPI2). Subreach 3b starts in forested land about 0.6 mi upstream from the confluence with subreach 3a, meandering through the same grass and willows wetland. The upper part of this subreach has been disturbed by debris generated by a test bore for the Eisenhower Tunnel. Sampling site LPS1 was used for the subreach 3b traveltime measurement.

Subreach 3c follows an intermittent drainage to the confluence with another perennial Clear Creek tributary (this tributary may completely freeze during some winters). Subreach 3c begins at a hairpin turn on Hwy 6, 1.2 mi from the top of Loveland Pass (injection site LPI3) (fig. 2). A small channel drains water that flows down the eastern side of the highway. The channel descends a steep mountainside to a valley containing the Clear Creek tributary and a Loveland Valley Ski Area chairlift. The subreach follows the valley passing through the Loveland Valley Ski Area parking lot (sampling site LPS2) to the confluence with Clear Creek. Although the area is primarily forest, some of the vegetation has been removed for the chairlift construction. Access roads and chairlift construction have disturbed parts of the stream channel for subreach 3c.

Interstate 70 is the major east/west transportation corridor in Colorado and, as such, is a common route for transporting hazardous material. Trucks hauling such materials usually are not allowed through the Eisenhower Memorial Tunnel as a safety precaution and normally are routed over Loveland Pass using Hwy 6. The Colorado Department of Transportation is exploring the possibility of locating a detention pond at the Loveland Valley Ski Area that would capture a hazardous-material release before the spill could reach the main stem of Clear Creek.

Study Reach 4—Berthoud Pass

Study Reach 4 includes two unnamed tributaries of Hoop Creek, a tributary of the West Fork of Clear Creek (fig. 3). Elevations in this study reach range from about 9,590 to 11,140 ft. The tributaries drain the northern side of the West Fork of Clear Creek Basin that is traversed by Hwy 40 through a series of steep grades and switchback curves. The headwaters for these tributaries are located along the Continental Divide near Berthoud Pass (elevation 11,315 ft). Study Reach 4 also is located in the Arapaho National Forest. All of the study reach is located in forested land. The study reach was divided into two subreaches to provide traveltime information from three potential accident sites.

Subreach 4a begins at a culvert that passes under Hwy 40 (injection site HI1) about 0.6 mi from the top of Berthoud Pass (fig. 3), continues downstream to the confluence with Hoop Creek, and crosses under Hwy 40 just upstream from the confluence with the West Fork of Clear Creek (sampling site HS3). The subreach alternates between a series of small waterfalls and pools through forest and one small reach of meanders through a meadow. The lower part of the subreach follows the main channel of Hoop Creek, which becomes a braided channel as it passes through debris fields near the confluence with the West Fork of

Clear Creek. Stream channel disturbances along the subreach primarily are the present Hwy 40 roadbed and an older, abandoned roadbed.

A major effect on subreach 4a is a diversion (Berthoud Pass ditch) that moves water from the northern side of the Continental Divide to the southern side, into Hoop Creek. The diversion generally begins flowing in late May or early June after snow has been cleared from the Hoop Creek channel. Flow continues through most of the summer until the water-rights allocations are satisfied. The gate to the diversion usually is shut sometime in late summer. Flows from the upper part of the subreach are decreased by about one-half when the gate is closed.

Subreach 4b begins at a hairpin turn on Hwy 40 about 1.7 mi from the top of Berthoud Pass (fig. 3). Most of the subreach is a series of small waterfalls and pools until the confluence with Hoop Creek where the stream channel becomes braided. As with subreach 4a, the stream channel disturbances primarily are the present Hwy 40 roadbed and an older, abandoned roadbed. Debris flows from the Hwy 40 roadcuts also are affecting this subreach.

DETERMINATION OF AND VARIATION IN TRAVELTIME

The traveltime in the two reaches of Clear Creek and two of its tributaries was determined by injecting a fluorescent dye, rhodamine-WT and measuring the dye concentrations in samples collected at downstream sites (site locations and numbers provided in table 2). In traveltime studies, as the dye moves downstream, dispersion of the dye mass elongates and dilutes the dye cloud (fig. 4). At a nearby downstream site, water samples analyzed with a fluorometer will show a low concentration of dye in the leading edge of the cloud, a rapid rise in concentration to a peak value, and a slightly slower decline in concentration as the trailing edge of the cloud passes (fig. 4). Farther downstream, the time between the leading edge and peak concentration lengthens, with the arrival of the trailing edge (defined as 10 percent of the peak concentration for this study) stretching out considerably (fig. 4). Samples for this study were collected at selected intervals, usually 1 to 10 minutes, depending on flow conditions, at each site to determine the arrival of the leading edge, peak, and trailing edge of the dye cloud. The dye-concentration measurements were used to generate a set of curves, which can be used to estimate the arrival times for two reaches of Clear Creek and two of its tributaries.

Average velocities between sampling sites were determined by dividing the distance between sites by the elapsed time for the dye-cloud leading edge to reach the downstream sampling site (these values are provided in the elapsed time tables for each study reach). Discharge and velocity were measured at several sampling sites for comparison to the average subreach velocity calculated by timing the dye cloud. Discharge was determined at the remaining sites from existing continuously recording surface-water gages or staff gages (table 2). A range of average velocities (from high to low flow) for each study reach was determined by dividing the total reach length by the elapsed time for the dye-cloud leading edge to reach the last sampling site (these values are provided in the text).

Rhodamine-WT Injection Procedures

A soluble dye injected into a stream assumes the flow characteristics of the water particles in that stream. Measuring the movement of the dye essentially measures the movement of water particles and their dispersion characteristics (Kilpatrick and Wilson, 1989, p. 2).

Rhodamine-WT is a highly soluble fluorescent dye with a specific gravity of 1.15 at 20°C. The standard form of rhodamine-WT used for traveltime studies is a 20-percent solution of the dye. Because the dye is very viscous (<25 centipoises at 25°C), slug-injection dye doses for this study were prepared by mixing a predetermined amount of dye into several gallons of water. The slug injection then could be made by rapidly pouring the mixed dye into the center of the stream, with a quick rinse of the container to remove the last of the rhodamine-WT. Without the initial dilution, several rinses of the container would be required, which would change the characteristics of what is intended to be a slug injection.

The amount of dye used for each injection was determined using the equation described by Kilpatrick (1970). The relation between the quantity of dye required and the concentration expected at the end sampling site is as follows:

Table 2. Injection and sampling-site locations, site numbers, elevations, average slopes between sites, and discharge at the time of sampling

[ft, feet; ft/ft, feet per foot; ft^3/s, cubic feet per second; mi, mile; --, no data; a, continuously recording surface-water gage; b, staff gage; c, stream-discharge measurement]

Location	Site number	Distance upstream from last sampling site (mi)	Elevation (ft)	Average slope between sites (ft/ft)	Average slope over reach (ft/ft)	Traveltime measurement discharge (ft^3/s)			Discharge measurement obtained from
						High flow	Transitional flow	Low flow	
Study Reach 1—Berthoud Falls to Golden (fig. 1)									
Berthoud Falls (injection site)	BGI1	38.5	9,800	--	--	--	--	--	--
Berthoud Falls staff gage (0.7 mi east of Berthoud Falls)	BGS1	37.8	9,690	0.030	--	317	40	21	b
Hoop Creek confluence (1.4 mi east of Berthoud Falls)	BGS2	37.1	9,600	0.024	--	--	--	--.	c
West Fork of Clear Creek gage (1.2 mi east of Empire)	BGS3	30.0	8,235	0.036	--	497	53	38	a
Lawson gage (at Lawson)	BGS4	27.8	8,080	0.013	--	1,010	135	88	a
Idaho Springs 23d Street bridge	BGS5	20.8	7,440	0.017	--	1,276	181	121	c
Clear Creek above Johnson Gulch (4.5 mi east of Idaho Springs)	BGS6	15.9	7,210	0.009	--	1,330	182	130	a
Junction of U.S. Highway 6 and State Highway 119	BGS7	12.6	6,910	0.017	--	--	--	--	--
Golden gage (100 ft downstream from U.S. Highway 6 bridge at west edge of Golden)	BGS8	0.0	5,695	0.018	0.020	1,250	138	90	a
Study Reach 2—Loveland Ski Area to Georgetown (fig. 1)									
Loveland Basin Ski Area (injection site)	LGI1	12.4	10,840	--	--	--	--	--	--
Loveland Valley Ski Area gage (east end of Loveland Valley Ski Area)	LGS1	11.5	10,615	0.047	--	80	8.3	5.3	a
Bakerville staff gage (I–70 Bakerville exit)	LGS2	6.5	9,710	0.034	--	321	40	23	b
Downstream from Silver Plume alluvial wells (0.5 mi west of Silver Plume)	LGS3	3.7	9,200	0.034	--	--	--	--	--
Georgetown 6th Street bridge	LGS4	0.0	8,512	0.035	0.036	389	44	26	c
[1]Study Reach 3—Loveland Pass (fig. 2)									
Subreach 3a—western injection site (0.6 mi)	LPI1	1.3	11,820	--	--	--	--	--	--
U.S. Highway 6 crossing downstream from injection site (2.1 mi) (injection site)	LPI1a	1.1	11,380	0.417	--	--	--	--	--
Confluence with main stem of stream (0.2 mi below LPI1a—not on road)	LPS1a	0.9	11,070	0.294	--	--	--	--	--
Upstream from west confluence with Clear Creek at Loveland Valley Ski Area	LPS1	0.0	10,640	0.090	0.172	19.2	1.7	1.3	c
Subreach 3b—western tributary main-stem injection site (2.8 mi)	LPI2	1.3	11,250	--	--	--	--	--	--
Upstream from west confluence with Clear Creek at Loveland Valley Ski Area	LPS1	0.0	10,640	0.089	0.089	19.2	1.7	1.3	c
Subreach 3c—eastern injection site (1.2 mi)	LPI3	0.8	11,620	--	--	--	--	--	--
Upstream from west confluence with Clear Creek at Loveland Valley Ski Area	LPS2	0.0	10,640	0.232	0.232	4.7	0.24	0.03	c
[2]Study Reach 4—Berthoud Pass (fig. 3)									
Subreach 4a—eastern injection site (0.6 mi)	HI1	1.6	11,140	--	--	--	--	--	--
Floral Park campground (2.7 mi)	HS1	1.1	10,710	0.163	--	--	--	--	--
Eastern switchback downstream from Floral Park campground (3.8 mi)	HS2	0.6	10,420	0.110	--	--	--	--	--
U.S. Highway 40 crossing upstream from confluence with West Fork of Clear Creek	HS3	0.0	9,590	0.262	0.183	38	4.1	1.2	c
Subreach 4b—western injection site (1.7 mi)	HI2	1.2	10,940	--	--	--	--	--	--
Western switchback upstream from Floral Park campground (3.5 mi)	HS4	0.7	10,540	0.152	--	--	--	--	--
U.S. Highway 40 crossing upstream from confluence with West Fork of Clear Creek	HS3	0.0	9,590	0.257	0.213	38	4.1	1.2	c

[1]Mileages refer to distance along U.S. Highway 6 from top of pass.

[2]All mileages refer to distance along U.S. Highway 40 from top of pass.

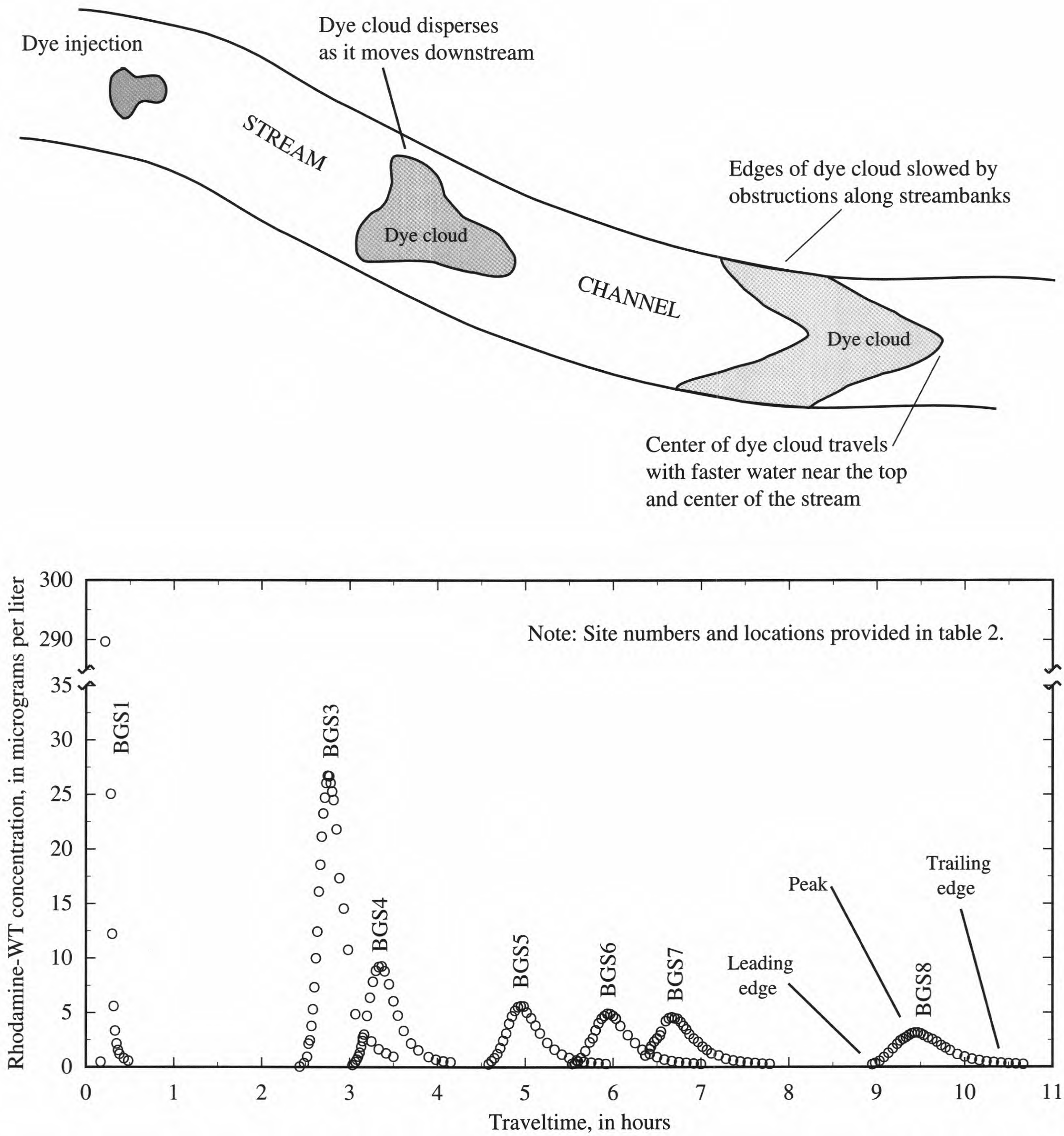

Figure 4. Diagram showing dye-cloud dispersion and graph showing actual dye concentrations during high-flow traveltime measurement, Berthoud Falls to Golden, June 11, 1996 (modified from Boyle and Spahr, 1985, fig. 3).

$$V_d = 3.4 \times 10^{-4}\left(\frac{Q_m L}{v}\right)^{0.93} C_p \qquad (1)$$

where

V_d is the volume of rhodamine-WT 20-percent dye required (gallons);

Q_m is the mean discharge of the reach (cubic feet per second);

L is the length of the reach (miles);

v is the mean stream velocity (feet per second); and

C_p is the peak concentration desired at the end of the reach (micrograms per liter).

Equation 1 is fairly easy to use in a reach of steady-state flow where discharge and velocity remain fairly constant; but the study reaches of Clear Creek start at high elevation, and the streams gain discharge and velocities vary as they descend the mountainous terrain. To properly use the equation, the mean velocity and corresponding mean discharge of the stream was estimated from historical records of several continuously recording surface-water gages.

For Study Reaches 1 and 2, the rhodamine-WT dye was injected into the stream at night to best reflect the actual high flow for the stream. Clear Creek has a strong diel variation in flow during spring runoff (high flow) with the highest flows occurring near the top of the drainage shortly after dark. This water volume moves down the basin during the night, typically arriving near Golden at dawn. During high flow, the discharge at Golden can vary by as much as 200 ft^3/s in 24 hours.

Rhodamine-WT Sampling Procedures

Rhodamine-WT is detected by a fluorometer that measures the luminescence of a fluorescent substance exposed to a light source of a given wavelength. Two Turner Designs Model 10 fluorometers were used for this study. The higher the fluorescent dye concentration, the more light is emitted for the fluorometer to detect. The optimum excitation wavelength for rhodamine-WT is about 556 nm, with an optimum analyzing wavelength of about 580 nm. The sensitivity of a fluorometer allows rhodamine-WT dye to be detected to concentrations of less than 0.1 μg/L. A detailed discussion of the use of fluorometers in dye tracing is in Wilson and others (1986).

Grab samples were collected at selected time intervals from the streamflow center at each sampling site, using the sampling equipment described by Kilpatrick and Cobb (1985). Sample collection times were recorded for comparison to the injection time. A small amount of each sample was analyzed with an onsite fluorometer to determine the arrival of the leading edge, peak, and trailing edge of the dye cloud. Because fluorescence is temperature sensitive, the remainder of the sample was taken to the USGS laboratory in Lakewood, Colorado, for analysis at a constant temperature. Samples were collected from the stream prior to the arrival of the dye cloud to determine any background fluorescence in the stream (Clear Creek background values varied from about 0.02 to 0.05 μg/L). Once the instream concentrations increased above the background levels, samples were kept for later analysis at the laboratory.

Study Reach 1 had one injection and eight sampling sites; Study Reach 2 had one injection and four sampling sites; Study Reach 3 had four injection (includes one alternative site) and two sampling sites; and Study Reach 4 had two injection and four sampling sites (figs. 1–3 and table 2).

Traveltime Data Analysis

Analysis of the rhodamine-WT by the USGS laboratory provided a dye concentration for each sampled time. Because it is not possible to collect discrete samples at the exact time of the arrival of the leading edge, peak, or trailing edge of the dye cloud, an initial estimate of the time of these events was determined using graphical methods. To further refine the estimate of the arrival times, a curve-fitting program was used.

A typical plot of the relation between time and dye concentration is shown in the graph in figure 4. The concentration values rise rapidly to the peak concentration and then trail off at a somewhat slower rate. The leading edge of the curve has the shape of a Gaussian distribution curve, but the trailing edge has a different distribution. A curve that fits the trailing-edge data best was a Lorentz distribution curve. To obtain the best mathematical representation of the data, the time/concentration curve was divided into two parts. Part one was the rise in concentration to the peak, and part two was the fall in concentration to the trailing edge (fig. 5). A curve-fitting program was used to fit each part of the curve (Gaussian distribution for part one and Lorentz distribution for part two) using a Monte Carlo algorithm. This process was repeated for each sampling site. Using the generated curves, arrival times of the leading edge, peak, and trailing edge of the dye cloud were calculated. The leading edge was defined as when the curve reached a value of 0.10 μg/L on the Gaussian distribution curve, the peak was the maximum value for the Gaussian curve, and the trailing edge was defined as 10 percent of the peak on the Lorentz curve.

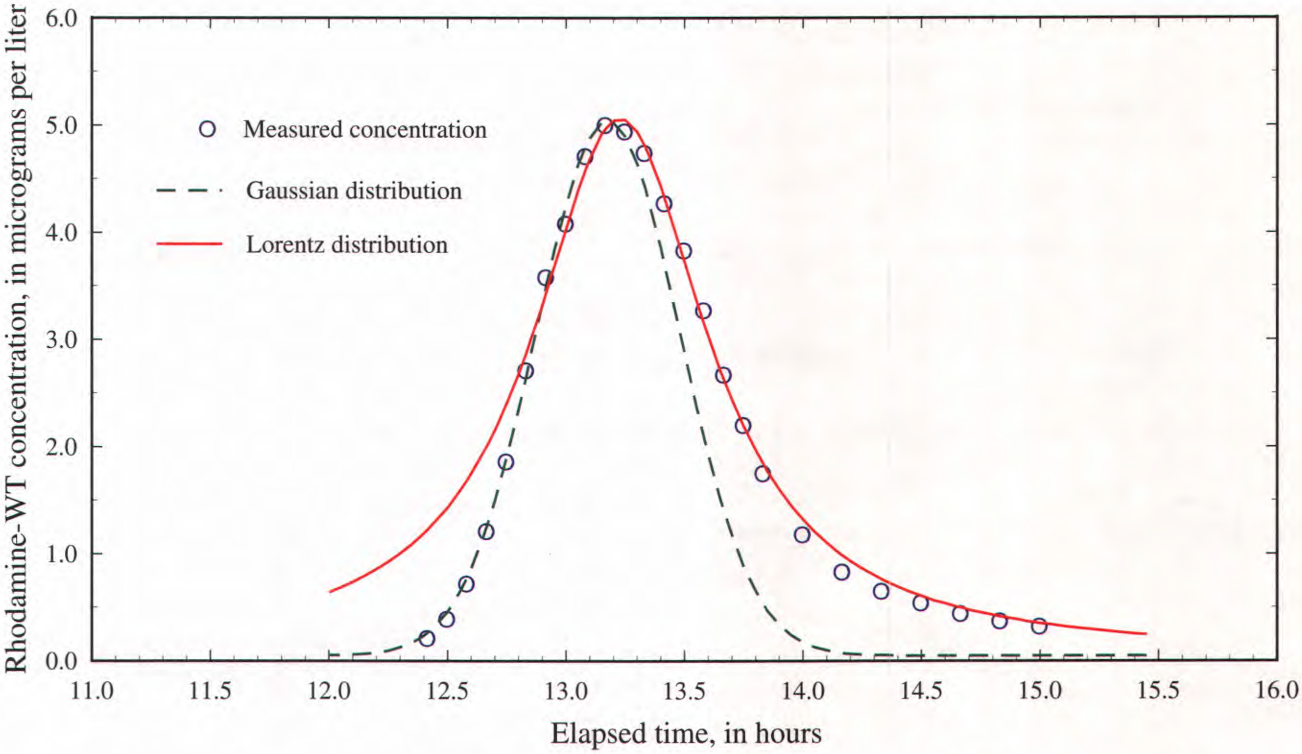

Figure 5. Rhodamine-WT concentration compared to time with curve fit of Gaussian and Lorentz distribution curves.

Variations in Traveltime in Mountain Streams

The hydrology of mountain streams is highly variable because of large changes in the topography of the stream channel and large fluctuations in stream discharge. Mountain stream discharge is affected by the weather-controlled release of water from mountain snowpacks and the yearly variation in the annual precipitation. One reason for measuring traveltimes at different times of the year was to determine the effect of some of these variations.

A mountain stream can be thought of as a series of rough channels (sometimes steep) connecting a series of storage areas. Stream velocities and discharge along these streams are affected by a number of variables. Stream velocity in uniform channels can be described by the Manning equation, and the effect of storage areas on discharge can be described by a combination of the continuity equation and a storage function. Because mountain streams are not uniform, the Manning equation normally is not directly applicable, but equation variables describe the factors affecting stream velocities.

The general form of the Manning equation is as follows:

$$v = \frac{1.5}{n}R^{2/3}S^{1/2} \quad (2)$$

where

- v is the velocity of flow (feet per second);
- n is the Manning roughness coefficient;
- R is the hydraulic radius of the channel [the cross-sectional area of the channel, A (square feet), divided by the wetted perimeter of the channel cross section, P (feet)]; and
- S is the channel-bed slope (feet per feet) (Ward and Elliot, 1995, p. 212).

In mountain streams, the roughness coefficient can range from 0.030 in reaches that have gravels, cobbles, and a few boulders to 0.070 in reaches that have cobbles and large boulders (Ward and Elliot, 1995, p. 217). Factors affecting n include streambed material (earth, rock, and gravel); degree of irregularity (smooth to severe); variations of channel cross section; relative effect of obstructions; vegetation; and degree of meandering (Ward and Elliot, 1995, p. 223). Channel-bed slopes (S) usually are larger in mountainous areas because of elevation changes. Although only minimal changes occur in the slope over a year, the roughness of the channel can be affected by the stream expanding into the flood plains during high discharge. Large changes in discharge also affect the hydraulic radius (the daily mean flow at surface-water gaging station in Golden can vary from about 20 to about 2,300 ft^3/s during the year).

Streamflow through a storage location can be described by the continuity equation:

$$\frac{dS}{dt} = I(t) - Q(t) \tag{3}$$

where

- dS is the change in storage (cubic feet),
- dt is the change in time (seconds),
- $I(t)$ is the input to the storage (cubic feet per second), and
- $Q(t)$ is the output from the storage (cubic feet per second).

The storage function

$$S = f\left(I, \frac{dI}{dt}, \frac{d^2I}{dt^2}, \ldots, Q, \frac{dQ}{dt}, \frac{d^2Q}{dt^2}, \ldots\right) \tag{4}$$

provides the relation between S, I, and Q, contributing the information necessary to solve the continuity equation (Chow and others, 1988, p. 242–243). Storage areas usually slow stream velocity because of increases in the hydraulic radius of the stream and the time required to fill the storage (dt). In addition, when storage is increasing, the discharge out of the storage area usually is less than the discharge into the storage area [$I(t) - Q(t) > 0$ if dS/dt is positive], which can slow the output velocity if the channel areas upstream and downstream from the storage area are the same ($Q = vA$). Large storage areas will affect traveltimes throughout the year, but the effect of small storage areas may only become apparent during low-flow conditions.

Water rushing down a steep mountain slope often is perceived as fast moving. On closer examination, the stream channel is not continuous, but involves a series of steps and pools (channels and storage). The step-pool sequence observed along the steep mountain slopes are characteristic of headwater streams (Leopold, 1997, p. 67–68). Studies have indicated that the morphology of step-pool streams evolves toward a condition of maximum flow resistance. The step pools are a result of the material moved during the high-flow conditions to a position of maximum stability (Abrahams and Li, 1995, p. 2593). The maximum flow resistance developed in the step pools results in decreased velocities and increased traveltimes for the stream reach.

To mathematically determine the stream velocity in a long mountain reach, a large number of stream subreaches would need to be characterized to estimate all of the necessary variables. The advantage of dye-tracer measurements becomes apparent when all of the variables affecting a mountain stream are considered.

UPPER CLEAR CREEK TRAVELTIME RESULTS AND DISCUSSION

Study Reach 1—Berthoud Falls to Golden

The results of the three traveltime measurements from Berthoud Falls to Golden are presented in table 3 and figure 6. Sampling-site locations and numbers are provided in table 2 and shown in figure 1. The measured traveltimes from the Berthoud Falls injection site (BGI1) to the various downstream sampling sites are listed in table 3. A graphical representation of the arrival of the dye-cloud leading-edge, peak, and trailing-edge data for high, transitional, and low flow is shown in figure 6.

Table 3. Elapsed time between injection and arrival of dye at sampling sites and average velocity between sites for Study Reach 1—Berthoud Falls to Golden

[Average velocity is determined by dividing reach length by traveltime between sites; measured velocity is the velocity determined by a discharge measurement at the site during traveltime sampling; **, no measurements were made at Hoop Creek during high flow of 1996; --, no data]

Sampling site	Site number	Distance upstream from Golden (miles)	Arrival of leading edge		Average velocity between sites (miles per hour)	Measured stream velocity (miles per hour)	Arrival of peak		Average velocity between sites (miles per hour)	Arrival of trailing edge		Average velocity between sites (miles per hour)
			(hours)	(hours: minutes)			(hours)	(hours: minutes)		(hours)	(hours: minutes)	
High-flow elapsed time and velocity												
Berthoud Falls (injection site)	BGI1	38.5	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Berthoud Falls staff gage	BGS1	37.8	0.14	00:08	5.00	--	0.21	00:12	3.33	0.28	00:16	2.50
Hoop Creek confluence	BGS2	37.1	**	**	--	--	**	**	--	**	**	--
West Fork of Clear Creek gage	BGS3	30.0	2.41	02:24	3.13	--	2.75	02:45	2.80	3.26	03:15	2.38
Lawson gage	BGS4	27.8	2.97	02:58	3.93	--	3.34	03:20	3.73	3.94	03:56	3.24
Idaho Springs 23d Street bridge	BGS5	20.8	4.48	04:28	4.64	6.75	4.95	04:57	4.35	5.66	05:39	4.07
Clear Creek above Johnson Gulch	BGS6	15.9	5.43	05:25	5.16	--	5.95	05:57	4.90	6.71	06:42	4.67
Junction Highways 6 and 119	BGS7	12.6	6.11	06:06	4.85	--	6.71	06:42	4.34	7.50	07:30	4.18
Golden gage	BGS8	0.0	8.80	08:48	4.68	--	9.44	09:26	4.62	10.59	10:35	4.08
Transitional-flow elapsed time and velocity												
Berthoud Falls (injection site)	BGI1	38.5	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Berthoud Falls staff gage	BGS1	37.8	0.44	00:26	1.59	--	0.60	00:36	1.17	0.78	00:47	0.89
Hoop Creek confluence	BGS2	37.1	1.08	01:04	1.09	--	1.40	01:24	0.87	1.71	01:42	0.75
West Fork of Clear Creek gage	BGS3	30.0	6.78	06:46	1.25	--	7.57	07:34	1.15	8.52	08:31	1.04
Lawson gage	BGS4	27.8	8.28	08:16	1.47	--	9.08	09:04	1.46	10.18	10:10	1.33
Idaho Springs 23d Street bridge	BGS5	20.8	12.26	12:15	1.76	2.41	13.18	13:10	1.71	14.66	14:39	1.56
Clear Creek above Johnson Gulch	BGS6	15.9	14.64	14:38	2.06	--	15.54	15:32	2.08	17.22	17:13	1.91
Junction Highways 6 and 119	BGS7	12.6	16.30	16:18	1.99	--	17.46	17:27	1.72	19.09	19:05	1.77
Golden gage	BGS8	0.0	23.27	23:16	1.81	--	24.56	24:33	1.77	26.78	26:46	1.64
Low-flow elapsed time and velocity												
Berthoud Falls (injection site)	BGI1	38.5	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Berthoud Falls staff gage	BGS1	37.8	0.51	00:30	1.37	--	0.76	00:45	0.92	0.99	00:59	0.71
Hoop Creek confluence	BGS2	37.1	1.33	01:20	0.85	--	1.85	01:51	0.64	2.39	02:23	0.50
West Fork of Clear Creek gage	BGS3	30.0	8.90	08:53	0.94	--	9.89	09:53	0.88	11.29	11:17	0.80
Lawson gage	BGS4	27.8	10.61	10:36	1.28	--	11.76	11:45	1.18	13.43	13:25	1.03
Idaho Springs 23d Street bridge	BGS5	20.8	15.58	15:34	1.41	2.15	16.84	16:50	1.38	18.96	18:57	1.27
Clear Creek above Johnson Gulch	BGS6	15.9	18.33	18:19	1.78	--	19.77	19:46	1.67	22.01	22:00	1.60
Junction Highways 6 and 119	BGS7	12.6	20.43	20:25	1.57	--	21.94	21:56	1.52	24.23	24:14	1.48
Golden gage	BGS8	0.0	28.62	28:37	1.54	--	30.40	30:24	1.49	33.46	33:27	1.37

The arrival of the leading edge at Golden varied from about 8.8 hours during high flow to about 28.6 hours during low flow. During the high-flow measurement, the dye cloud required about 0.1 hour to pass the first sampling site (BGS1), but required about 1.8 hours to pass the Golden sampling site (BGS8). The dispersion increased during low flow as the dye cloud required about 0.5 hour to pass the first sampling site (BGS1) and about 4.8 hours to pass site BGS8. Average velocities between sampling sites are provided in table 3. The average velocity of the leading edge of the dye for this study reach was about 4.4 mi/hr during high flow and about 1.3 mi/hr during low flow. The precision of the traveltime measurements varied from about 1 minute for the samples collected at site BGS1 to between ±2 minutes (high flow) and ±10 minutes (low flow) at site BGS8.

Although there are subtle changes in the gradient of the lines (fig. 6), the plots of the elapsed time, compared to the distance downstream, seem to be essentially linear from sampling site BGS5 (Idaho Springs) to BGS8 (Golden gage). The linear nature of this part of the plots indicates that the average velocities are relatively similar along this subreach of Study Reach 1. Average velocity data from table 3 indicates similar values along this subreach. The gradient of the plots change between each sampling site from BGS5 (Berthoud Falls staff gage) to BGS1, indicating more

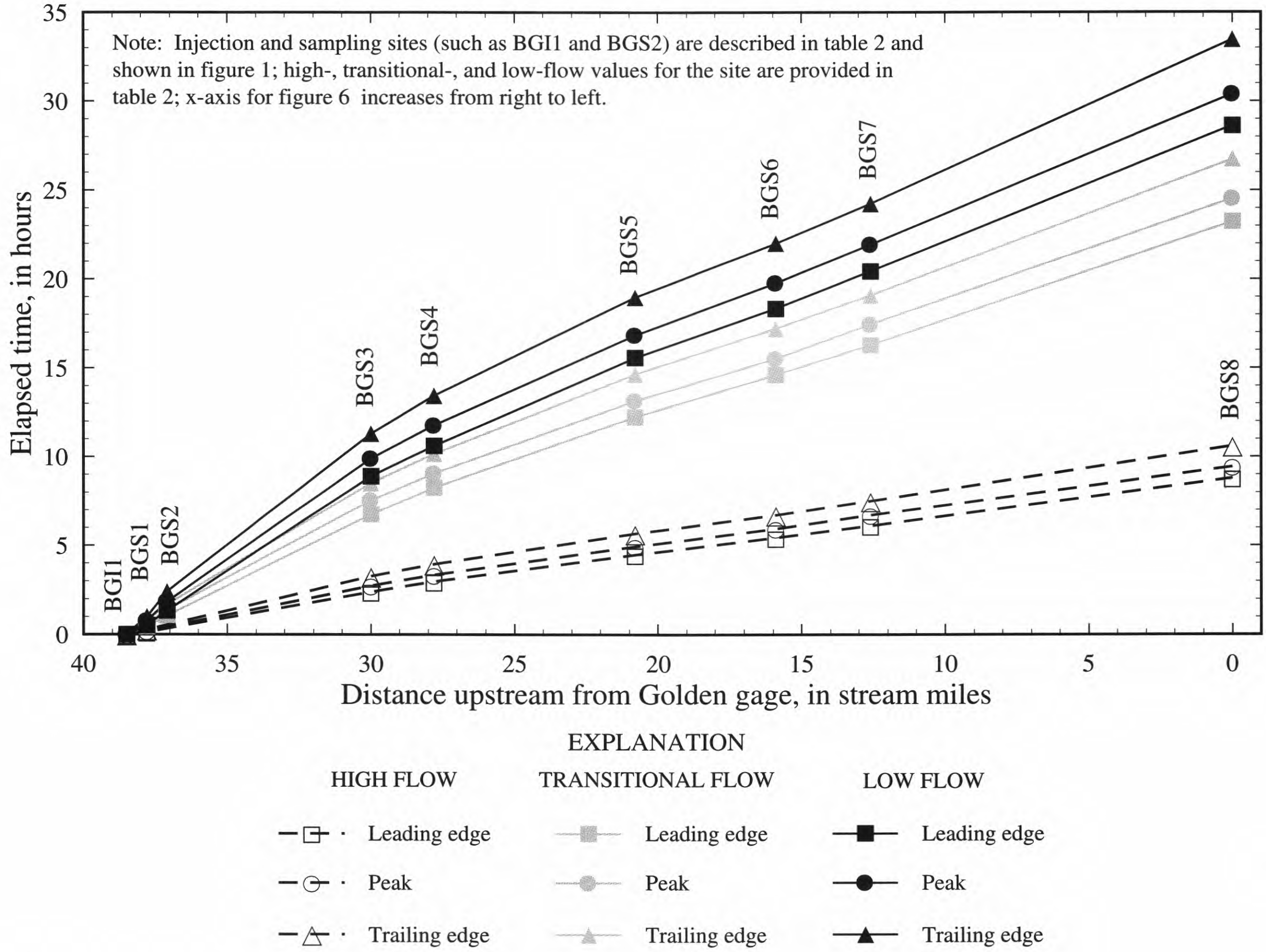

Figure 6. Study Reach 1—Berthoud Falls to Golden traveltimes for three flow conditions.

velocity variability in the upper part of the reach. The steeper the line (fig. 6), the slower the dye cloud passes through that subreach (lower velocity). Velocity variability is a function of the changes in discharge, channel characteristics, and storage-area effects.

The data in table 2 indicate that the slope, *S*, along the upper subreaches [excluding the subreach between the injection point (BGI1) and the first sampling site (BGS1) that has minimal stream channel obstructions] of the study reach is steeper than in the lower subreaches, but the actual dye velocities were slower in the upper subreaches. If only the slope were used, the Manning equation (eq. 2) would predict faster velocities (the *S* value would be greater). Although changes in the Manning roughness coefficient can account for some of the velocity decreases, storage-area effects (eqs. 3 and 4) probably were the primary cause of the decreased velocity and longer traveltime. Storage areas along the upper reach of Study Reach 1 include numerous beaver ponds and small, low dams used to produce pooling for improved fish habitat.

Study Reach 2—Loveland Basin Ski Area to Georgetown

The results of the three traveltime measurements from Loveland Basin Ski Area to Georgetown are presented in table 4 and figure 7. Sampling-site locations and numbers are provided in table 2 and shown in figure 1. The arrival of the dye-cloud leading edge, peak, and trailing edge for the three flow conditions is shown in figure 7. The arrival of the leading edge in Georgetown varied from about 3.5 hours during high flow to about 15.7 hours during low flow. The dye cloud passed the first sampling site (LGS1) in about 0.2 hour and the last sampling site (LGS4) in about 1.1 hours during high flow. During low flow, the dye cloud required about 0.7 hour to pass LGS1 and about 6.0 hours to pass LGS4. The average velocity of the leading edge of the dye through Study Reach 2 was about 3.5 mi/hr during high flow and about 0.8 mi/hr during low flow (average velocities between sampling sites are provided in table 4). The slope is steeper in Study Reach 1 than in Study Reach 2, but discharge, channel characteristics, and storage-area effects combine to result in slower movement of the dye cloud through Study Reach 2 compared to Study Reach 1. The precision of the traveltime measurements varied from about ±1 minute for the samples collected at site LGS1 to between 2 minutes (high flow) and ±20 minutes (low flow) at site LGS4.

The variability of the subreach characteristics in Study Reach 2 can be seen in the changes in the line gradients in figure 7. Although the plots of elapsed time compared to distance in figure 7 seem to be linear, closer examination shows distinct changes in gradient of the lines between sampling sites. The steeper the line, the slower the velocity and the longer the traveltime. In Study Reach 2, storage areas, meanders, and vegetation decrease stream velocities, but as discharge and slope increase, stream velocities increase. The largest change in average velocity between sites for Study Reach 2 occurred between the Silver Plume alluvial wells (LGS3) and Georgetown (LGS4) (table 4). This subreach includes an artificial widening of the stream, several abrupt changes in stream direction, and a series of waterfalls and pools.

Study Reach 3—Loveland Pass

The results of the three traveltime measurements for the three subreaches in Study Reach 3 are presented in table 5 and figures 8 through 10. Sampling-site locations and numbers are provided in table 2 and shown in figure 2. The precision of the traveltime measurements varied from about 2 minutes for the samples collected at site LPS1 during high flow to between ±10 minutes (subreach 3b) and ±30 minutes (subreach 3a) during low flow. Traveltime-measurement precision at site LPS2 for subreach 3c varied from about ±1 minute during high flow to ±20 minutes during low flow.

Because of the intermittent nature of flow in of subreaches 3a and 3c, the flow was supplemented with water from a fire tanker truck. Rhodamine-WT dye was added to 2,500 gal of water in the tanker. The tanker was driven to the two drainages, and about one-half of the tanker capacity was added to subreach 3a (LPI1) and the other one-half was added to subreach 3c (LPI3). The tanker provided the advantage of simulating a hazardous-material spill. A slug injection was used in the large tributary (LPI2) because sufficient instream flow was available year round.

Table 4. Elapsed time between injection and arrival of dye at sampling sites and average velocity between sites for Study Reach 2—Loveland Basin Ski Area to Georgetown

[Average velocity is determined by dividing reach length by traveltime between sites; measured stream velocity is the velocity determined by a discharge measurement at the site during traveltime sampling; --, no data]

Sampling site	Site number	Distance upstream from Georgetown (miles)	Arrival of leading edge		Average velocity between sites (miles per hour)	Measured stream velocity (miles per hour)	Arrival of peak		Average velocity between sites (miles per hour)	Arrival of trailing edge		Average velocity between sites (miles per hour)
			(hours)	(hours: minutes)			(hours)	(hours: minutes)		(hours)	(hours: minutes)	
High-flow elapsed time and velocity												
Loveland Basin Ski Area (injection site)	LGI1	12.4	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Loveland Valley Ski Area gage	LGS1	11.5	0.27	00:16	3.33	--	0.36	00:21	2.50	0.45	00:26	2.00
Bakerville staff gage	LGS2	6.5	1.79	01:47	3.29	--	2.00	02:00	3.05	2.38	02:22	2.59
Silver Plume alluvial wells	LGS3	3.7	2.64	02:38	3.29	--	2.93	02:55	3.01	3.57	03:34	2.35
Georgetown 6th Street bridge	LGS4	0.0	3.51	03:30	4.25	4.10	3.84	03:50	4.07	4.61	04:36	3.56
Transitional-flow elapsed time and velocity												
Loveland Basin Ski Area (injection site)	LGI1	12.4	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Loveland Valley Ski Area gage	LGS1	11.5	0.99	00:59	0.91	--	1.23	01:13	0.73	1.45	01:27	0.62
Bakerville staff gage	LGS2	6.5	6.02	06:01	0.99	--	6.59	06:35	0.93	7.60	07:35	0.81
Silver Plume alluvial wells	LGS3	3.7	8.62	08:37	1.08	--	9.37	09:21	1.01	10.73	10:43	0.89
Georgetown 6th Street bridge	LGS4	0.0	11.20	11:12	1.43	1.73	12.01	12:00	1.40	14.02	14:01	1.12
Low-flow elapsed time and velocity												
Loveland Basin Ski Area (injection site)	LGI1	12.4	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Loveland Valley Ski Area gage	LGS1	11.5	1.30	01:18	0.69	--	1.66	01:39	0.54	2.03	02:01	0.44
Bakerville staff gage	LGS2	6.5	8.51	08:30	0.69	--	9.41	09:24	0.65	11.80	11:47	0.51
Silver Plume alluvial wells	LGS3	3.7	12.18	12:10	0.76	--	13.25	13:15	0.73	16.59	16:35	0.58
Georgetown 6th Street bridge	LGS4	0.0	15.72	15:43	1.05	1.52	16.83	16:49	1.03	21.69	21:41	0.73

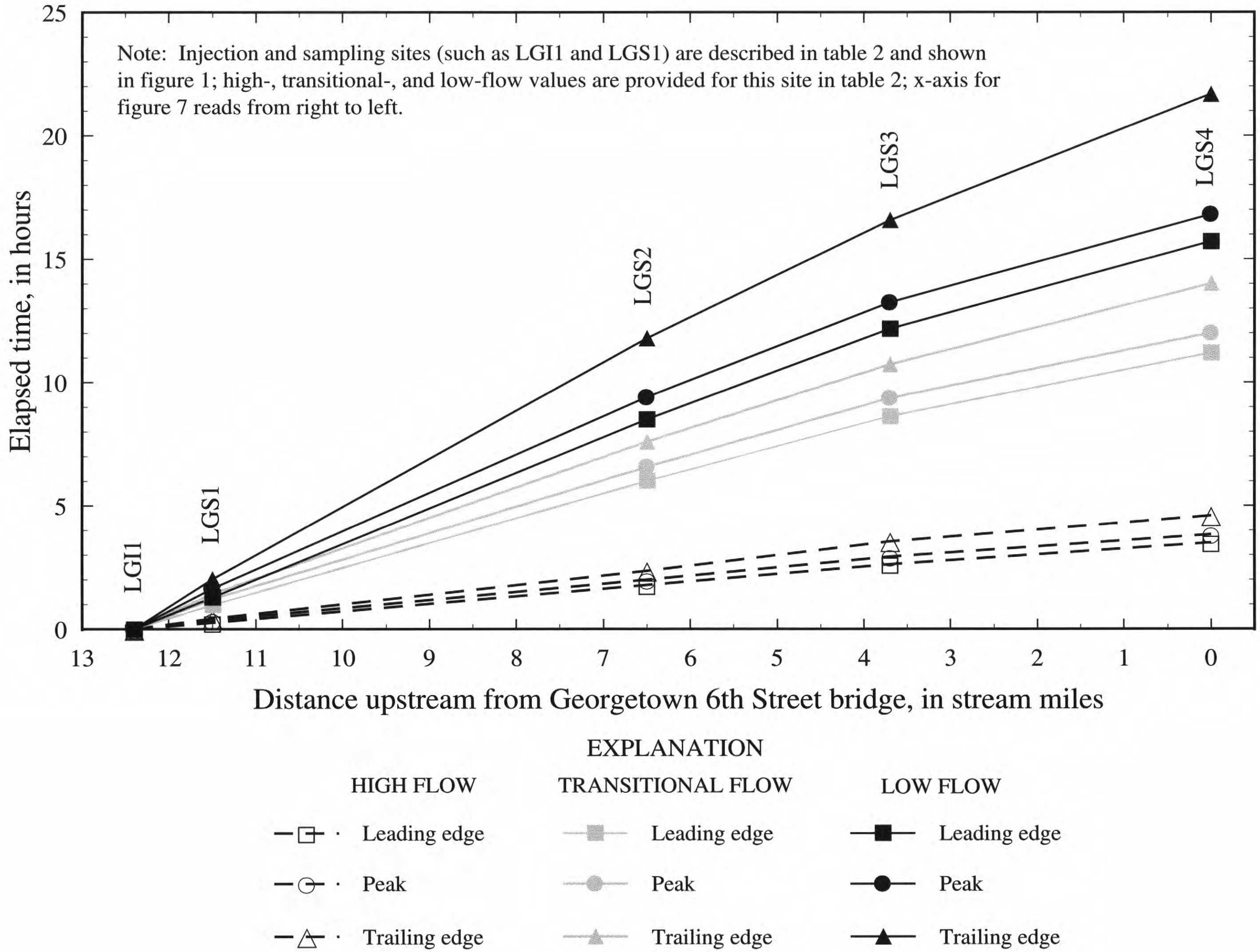

Figure 7. Study Reach 2—Loveland Basin Ski Area to Georgetown traveltimes for three flow conditions.

Table 5. Elapsed time between injection and arrival of dye at sampling sites and average velocity between sites for Study Reach 3—Loveland Pass

[Average velocity is determined by dividing reach length by traveltime between sites; measured velocity is the velocity determined by a discharge measurement at the site during traveltime sampling; --, no data]

Sampling site	Site number	Distance upstream from final sampling site[1] (miles)	Arrival of leading edge		Average velocity between sites (miles per hour)	Measured stream velocity (miles per hour)	Arrival of peak		Average velocity between sites (miles per hour)	Arrival of trailing edge		Average velocity between sites (miles per hour)
			(hours)	(hours: minutes)			(hours)	(hours: minutes)		(hours)	(hours: minutes)	
High-flow elapsed time and velocity												
Subreach 3a—western injection site	LPI1	1.3	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Highway 6 crossing below injection site	LPI1a	1.1	--	--	--	--	--	--	--	--	--	--
Confluence with main stem of stream	LPS1a	0.9	--	--	--	--	--	--	--	--	--	--
Above west confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS1	0.0	0.97	00:58	1.34	2.05	1.23	01:13	1.06	1.85	01:51	0.70
Subreach 3b—main-stem (western) injection site	LPI2	1.3	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Above west confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS1	0.0	0.72	00:43	1.81	2.05	0.82	00:49	1.59	0.95	00:57	1.37
Subreach 3c—eastern injection site	LPI3	0.8	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Above east confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS2	0.0	0.63	00:37	1.27	1.74	0.78	00:46	1.03	1.24	01:14	0.65
Transitional-flow elapsed time and velocity												
Subreach 3a—western injection site[2]	LPI1	1.3	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Highway 6 crossing below injection site	LPI1a	1.1	--	--	--	--	--	--	--	--	--	--
Confluence with main stem of stream	LPS1a	0.9	--	--	--	--	--	--	--	--	--	--
Above west confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS1	0.0	3.00	03:00	0.43	1.58	4.00	04:00	0.33	6.25	06:15	0.21
Subreach 3b—main-stem (western) injection site	LPI2	1.3	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Above west confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS1	0.0	2.36	02:21	0.55	1.58	2.77	02:46	0.47	5.10	05:06	0.25
Subreach 3c—eastern injection site	LPI3	0.8	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Above east confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS2	0.0	1.62	01:37	0.49	1.50	2.06	02:03	0.39	4.24	04:14	0.19
Low-flow elapsed time and velocity												
Subreach 3a—western injection site[3]	LPI1	1.3	([3])	--	--	--	([3])	--	--	([3])	--	--
Highway 6 crossing below injection site	LPI1a	1.1	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Confluence with main stem of stream	LPS1a	0.9	0.89	00:53	0.22	--	1.17	01:10	0.17	1.82	01:49	0.11
Above west confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS1	0.0	3.09	03:05	0.36	0.47	3.62	03:37	0.30	6.45	06:27	0.17
Subreach 3b—main-stem (western) injection site	LPI2	1.3	0.00	00:00	--	--	0.00	00:00	--	--	00:00	--
Above west confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS1	0.0	2.91	02:54	0.45	0.47	3.43	03:25	0.38	5.62	05:37	0.23
Subreach 3c—eastern injection site	LPI3	0.8	0.00	00:00	--	--	0.00	00:00	--	--	00:00	--
Above east confluence with Clear Creek main channel at Loveland Valley Ski Area	LPS2	0.0	2.60	02:36	0.31	0.28	3.36	03:21	0.24	12.31	12:18	0.06

[1]Subreach 3a and 3b final sampling site (LPS1) was located upstream from the western tributary confluence with the Clear Creek main channel. Subreach 3c final sampling site (LPS2) was located upstream from the eastern tributary confluence with the Clear Creek main channel. Both confluences were located along the western edge of the Loveland Valley Ski Area parking lot.

[2]Subreach 3a traveltime measurements estimated for transitional flow. Traveltimes affected by low flows in drainage.

[3]Subreach 3a traveltimes determined from injection site LPI1a. Snow in drainage upstream from injection site LPI1a absorbed 1,250 gallons of dye water from fire tanker truck.

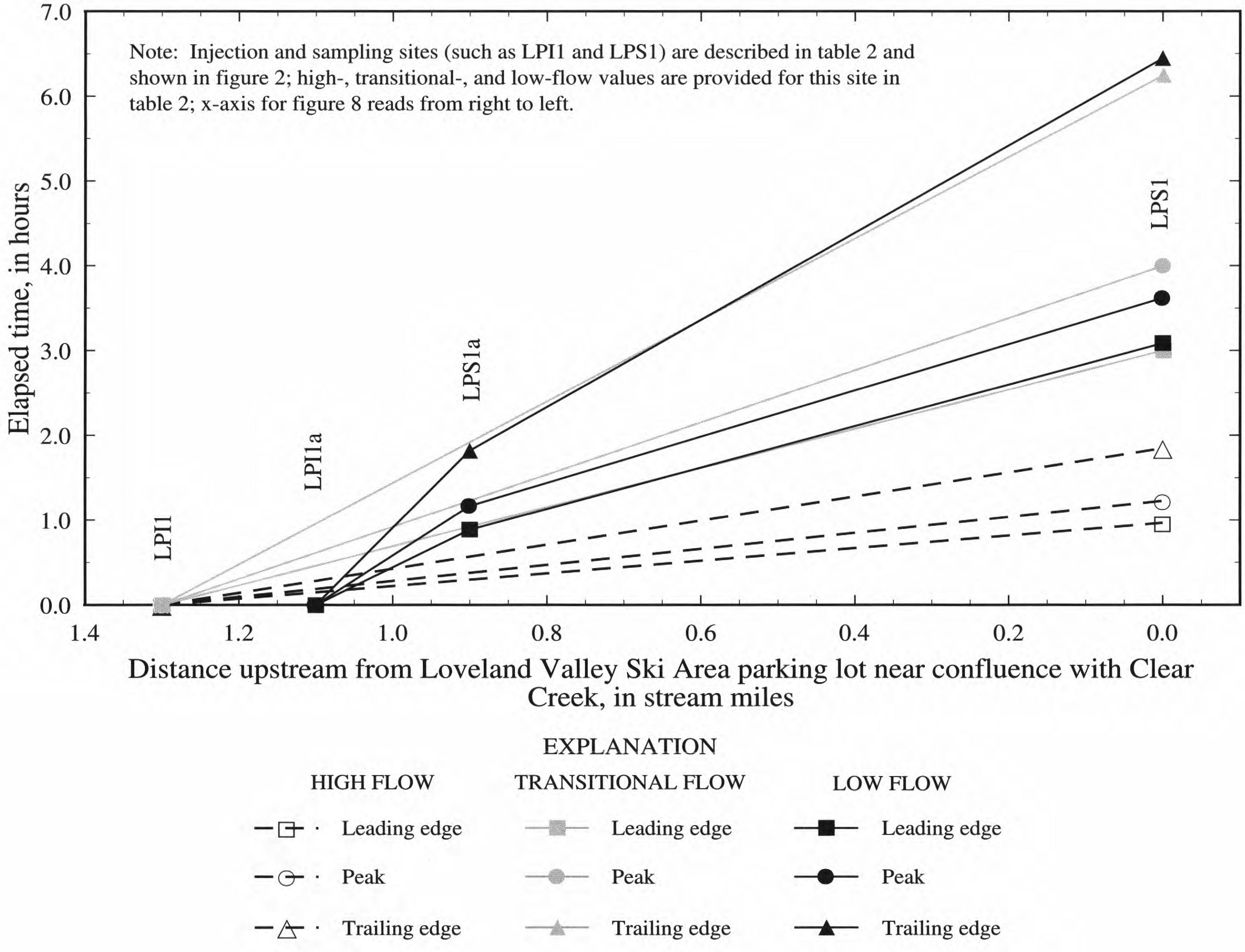

Figure 8. Study Reach 3—Loveland Pass western tributary (subreach 3a) traveltimes for three flow conditions.

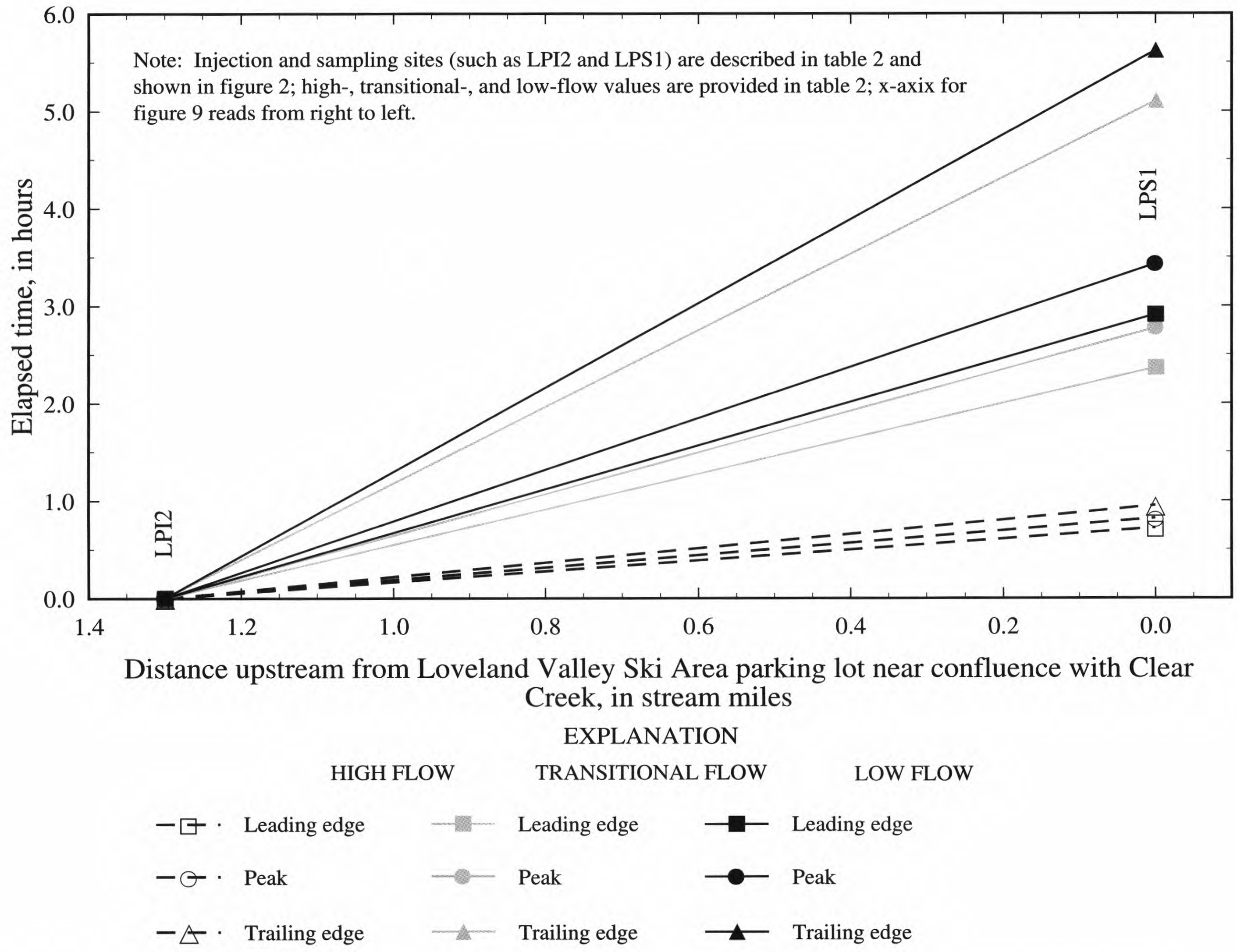

Figure 9. Study Reach 3—Loveland Pass western tributary main-stem (subreach 3b) traveltimes for three flow conditions.

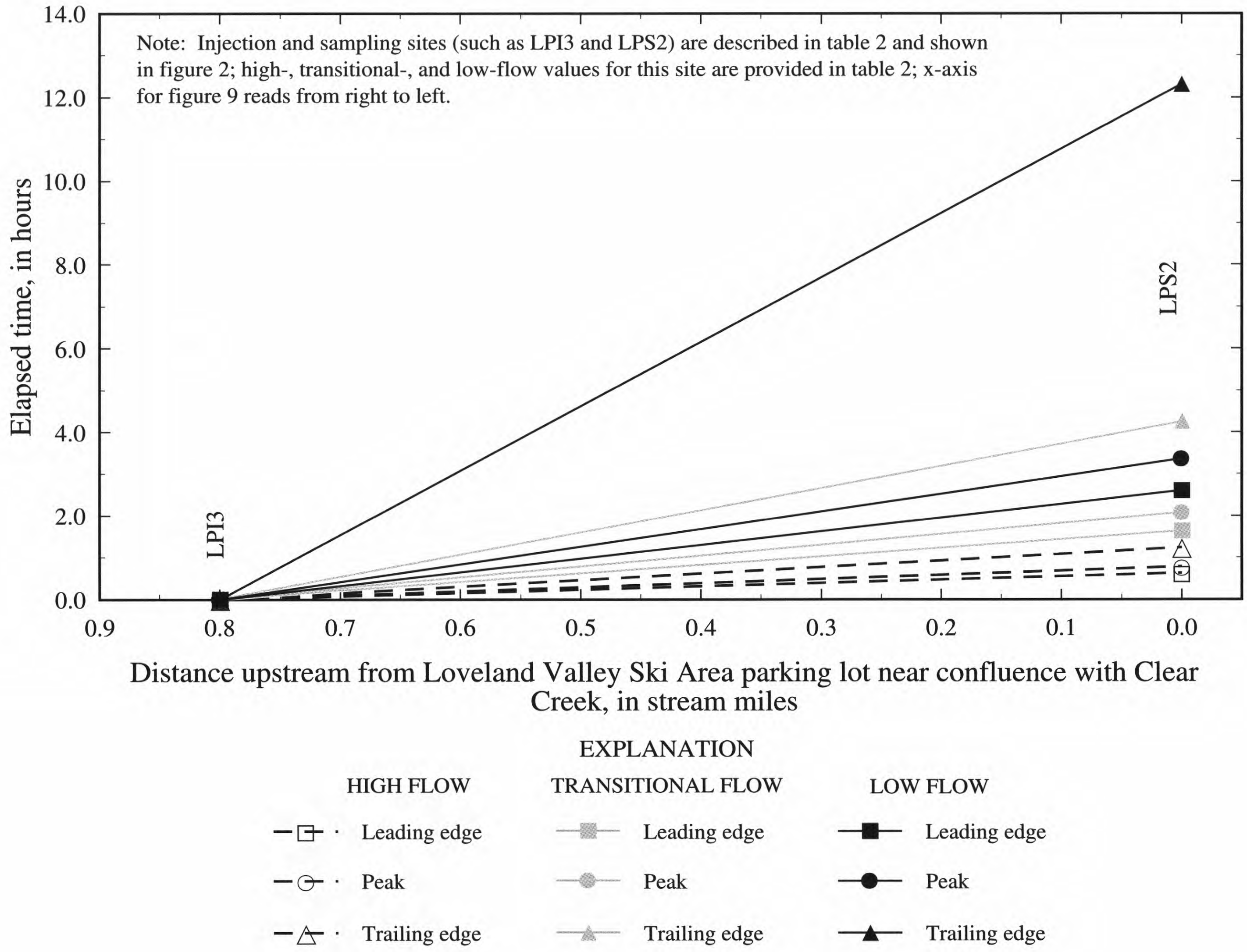

Figure 10. Study Reach 3—Loveland Pass eastern tributary (subreach 3c) traveltimes for three flow conditions.

The characteristics of each of the three subreaches affected the traveltime results. Traveltimes in subreach 3a had the greatest variability between flow regimes because of the intermittent nature of the drainage and complicating factors such as step pools, wetlands, amount of snow cover, and meanders. Subreaches 3b and 3c followed established stream channels (the first 400 to 500 ft of the subreach 3c drainage was intermittent), decreasing variability in the traveltimes at different flow regimes.

The hydrology of subreach 3a made it the most difficult among the subreaches to effectively measure traveltimes (fig. 8). During high flow, sufficient water moved along the subbasin to carry the dye cloud through the step pools and wetlands. The leading edge of the dye cloud was easily detected at site LPS1 about 1.0 hour after it was injected at the top of the pass (table 5, fig. 8). By mid-summer (transitional flow), most of the base flow was underground near the injection site and a barely detectable amount of dye managed to escape the step pools and wetlands. About 3.0 hours elapsed before the dye cloud was detected at site LPS1, and the concentrations never exceeded 0.20 μg/L. Because of the low concentrations, the actual arrival of the dye leading edge was hard to determine, but after the initial detection, dye was measured for at least 3.3 hours. Snow had fallen on the pass by the time of the low-flow measurement. After waiting more than an hour for the dye to travel 0.2 mi, it was determined that the entire 1,250 gal injected by the tanker truck had been absorbed by the new snow in the drainage. To complete the measurement, a slug of dye was injected at the highway crossing (LPI1a). About 3.1 hours had elapsed as the dye-cloud leading edge passed through the shortened route (table 5). Dispersion for subreach 3a can be determined from the traveltimes provided in table 5, but previously mentioned characteristics (intermittent flow and snow cover in the drainage) in this subreach limit the accuracy of dispersion calculations.

Subreach 3b follows a perennial stream to the confluence with the main stem of Clear Creek. The leading edge of the dye cloud arrived at the subreach 3b sampling site (LPS1) in about 0.7 hour during high flow and about 2.9 hours during low flow (table 5, fig. 9). The effect of discharge on dispersion in subreach 3b is evident in the time required for the dye cloud to pass the sampling site. In subreach 3b, the time required for the dye cloud to pass site LPS1 varied from about 0.2 hour during high flow to about 2.7 hours during low flow.

The arrival of the leading edge of the dye cloud in subreach 3c was not affected significantly by the intermittent nature of the start of the subreach. The leading edge of the dye cloud arrived at the subreach 3c sampling site (LPS2) in about 0.6 hour during high flow and about 2.6 hours during low flow (table 5, fig. 10). The effect of discharge on dispersion was more significant in subreach 3c than in subreach 3b. In subreach 3c, the time required for the dye cloud to pass site LPS2 varied from about 0.6 hour during high flow to about 9.7 hours during low flow. Factors that affected dispersion in subreach 3c included the use of the fire tanker truck (it required about 3 minutes to empty the 1,250 gal of dyed water) and the number of step pools.

The high-flow leading-edge average velocities for the subreaches are as follows: subreach 3a, about 1.3 mi/hr; subreach 3b, about 1.8 mi/hr; and subreach 3c, about 1.3 mi/hr. The gradients of the lines plotted in figures 8 through 10 (and the data in table 5) indicate slower velocities than the velocities determined in Study Reaches 1 and 2. Slopes (S) in Study Reach 3 are almost an order of magnitude greater than slopes in Study Reaches 1 and 2 (table 2). The major characteristics affecting stream velocities in Study Reach 3 seem to be small discharge volumes, meanders, wetlands, snow cover, and step pools, but not the slope.

Study Reach 4—Berthoud Pass

The results of the three traveltime measurements for the two subreaches in Study Reach 4 are presented in table 6 and figures 11 and 12. Sampling-site locations and numbers are provided in table 2 and shown in figure 3. The precision of the traveltime measurements varied from about 1 minute for the samples collected at HS3 during high flow to between ±10 minutes (subreach 4b) and ±20 minutes (subreach 4a) during low flow. Because Study Reach 4 was added to the overall study after the initial high-flow measurements, an additional traveltime measurement was conducted in late spring 1997 to quantify the high-flow conditions.

Table 6. Elapsed time between injection and arrival of dye at sampling sites and average velocity between sites for Study Reach 4—Berthoud Pass

[Average velocity is determined by dividing reach length by traveltime between sites; measured velocity is the velocity determined by a discharge measurement at the site during traveltime sampling; --, no data]

Sampling site	Site number	Distance upstream from final sampling site[1] (miles)	Arrival of leading edge (hours)	Arrival of leading edge (hours: minutes)	Average velocity between sites (miles per hour)	Measured stream velocity (miles per hour)	Arrival of peak (hours)	Arrival of peak (hours: minutes)	Average velocity between sites (miles per hour)	Arrival of trailing edge (hours)	Arrival of trailing edge (hours: minutes)	Average velocity between sites (miles per hour)
High-flow elapsed time and velocity												
Subreach 4a—eastern injection site	HI1	1.6	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Floral Park campground	HS1	1.1	0.22	00:13	2.27	--	0.32	00:19	1.56	0.41	00:24	1.22
Eastern switchback below Floral Park	HS2	0.6	0.46	00:27	2.08	--	0.57	00:34	2.00	0.66	00:39	2.00
Highway 40 crossing above confluence with West Fork of Clear Creek	HS3	0.0	0.76	00:45	2.00	--	0.90	00:54	1.82	1.02	01:01	1.67
Subreach 4b—western injection site	HI2	1.2	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Western switchback below Floral Park	HS4	0.7	0.29	00:17	1.72	--	0.42	00:25	1.19	0.53	00:31	0.94
Highway 40 crossing above confluence with West Fork of Clear Creek	HS3	0.0	0.67	00:40	1.84	--	0.80	00:48	1.84	0.93	00:55	1.75
Transitional-flow elapsed time and velocity												
Subreach 4a—eastern injection site	HI1	1.6	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Floral Park campground	HS1	1.1	1.02	01:01	0.49	--	1.36	01:21	0.37	2.02	02:01	0.25
Eastern switchback below Floral Park	HS2	0.6	2.03	02:01	0.50	--	2.18	02:10	0.61	3.15	03:09	0.44
Highway 40 crossing above confluence with West Fork of Clear Creek	HS3	0.0	2.90	02:54	0.69	1.60	3.27	03:16	0.55	5.47	05:28	0.26
Subreach 4b—western injection site	HI2	1.2	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Western switchback below Floral Park	HS4	0.7	0.76	00:45	0.66	--	0.98	00:58	0.51	1.17	01:10	0.43
Highway 40 crossing above confluence with West Fork of Clear Creek	HS3	0.0	1.84	01:50	0.65	1.60	2.14	02:08	0.60	2.61	02:36	0.49
Low-flow elapsed time and velocity												
Subreach 4a—eastern injection site	HI1	1.6	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Floral Park campground	HS1	1.1	1.40	01:24	0.36	--	1.88	01:52	0.27	2.84	02:50	0.18
Eastern switchback below Floral Park	HS2	0.6	3.09	03:05	0.30	--	3.67	03:40	0.28	5.95	05:57	0.16
Highway 40 crossing above confluence with West Fork of Clear Creek	HS3	0.0	4.96	04:57	0.32	0.96	5.74	05:44	0.29	12.51	12:30	0.09
Subreach 4b—western injection site	HI2	1.2	0.00	00:00	--	--	0.00	00:00	--	0.00	00:00	--
Western switchback below Floral Park	HS4	0.7	1.14	01:08	0.44	--	1.44	01:26	0.35	1.83	01:49	0.27
Highway 40 crossing above confluence with West Fork of Clear Creek	HS3	0.0	2.81	02:48	0.42	0.96	3.41	03:24	0.36	4.63	04:37	0.25

[1]Sampling site (HS3) was located at the Hoop Creek Highway 40 crossing upstream from the confluence with the West Fork of Clear Creek.

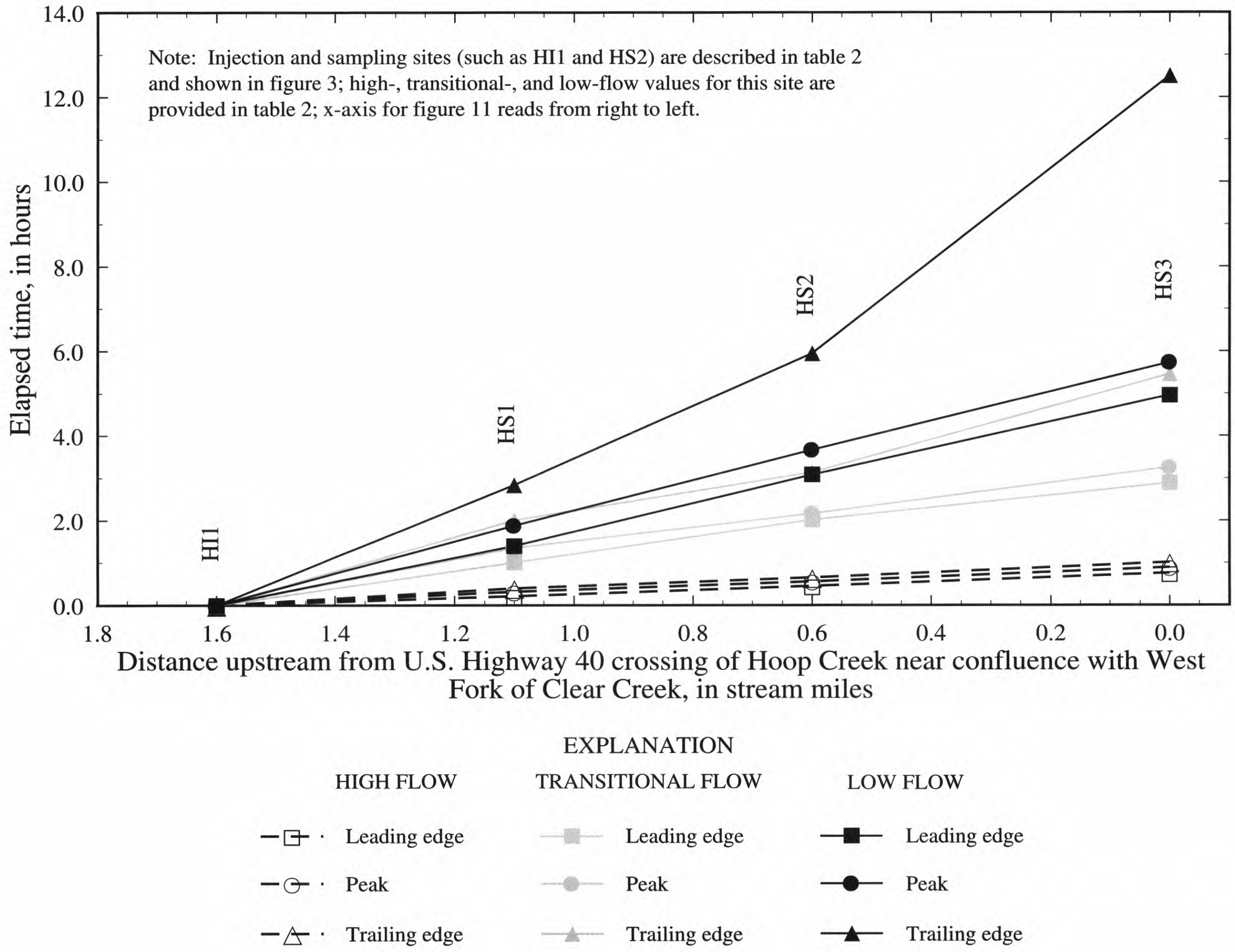

Figure 11. Study Reach 4—Eastern Hoop Creek tributary (subreach 4a) traveltimes for three flow conditions.

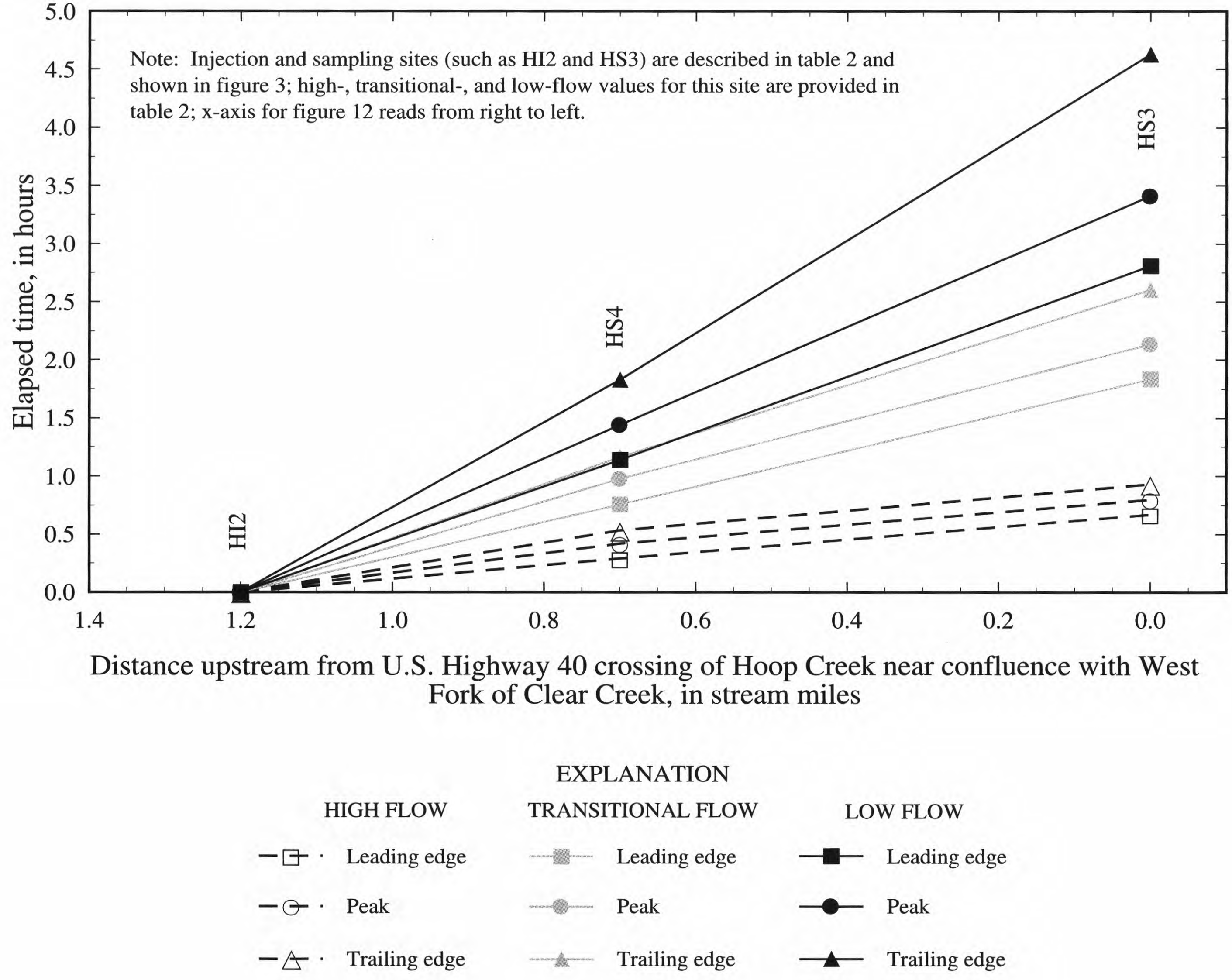

Figure 12. Study Reach 4—Western Hoop Creek tributary (subreach 4b) traveltimes for three flow conditions.

Leading-edge traveltimes for subreach 4a at site HS3 ranged from about 0.8 hour for high flow to about 5.0 hours during low flow (table 6, fig. 11). When the upstream diversion gate is closed, the upper reach of subreach 4a loses about one-half its discharge, and traveltimes are increased. The diversion was flowing during the high- and transitional-flow measurements, but not during the low-flow measurement. The dye cloud passed sampling site HS3 in about 0.3 hour during high flow, but required about 7.6 hours to pass during low flow. Step pools were the primary dispersion mechanism as the dye cloud moved down the drainage. Average velocities for the leading edge of the dye cloud for subreach 4a varied from about 2.1 mi/hr during high flow to about 0.3 mi/hr during low flow.

In subreach 4b, leading-edge traveltimes at site HS3 ranged from about 0.7 hours during high flow to about 2.8 hours during low flow (table 6, fig. 12). The dye cloud passed sampling site HS3 in about 0.3 hour during high flow and in about 1.8 hours during low flow. Average velocities for the leading edge of the dye cloud were about 1.8 mi/hr during high flow and about 0.4 mi/hr during low flow.

Although subreach 4a is longer (1.6 mi for subreach 4a and 1.2 mi for subreach 4b), the effect of the upstream diversion on subreach 4a is evident in the variability between low- and high-flow measurements for the two subreaches. Additional factors that affected the subreach 4a traveltime include meanders, step pools, and vegetation along the streambank.

As with Study Reach 3, the gradients of the lines plotted in figures 11 and 12 (and the data in table 6) indicate slower velocities than velocities in Study Reaches 1 and 2. Mountain slopes in Study Reach 4 are about an order of magnitude steeper than slopes in Study Reaches 1 and 2 (table 2), but the primary factors affecting stream velocity through these subreaches include the step pools and the variable discharge.

ESTIMATION OF UPPER CLEAR CREEK TRAVELTIMES

The transferability of traveltime measurement data from this study are limited because the elapsed times are best used for the discharges occurring in Clear Creek during the time of the study measurements. A method was needed to estimate traveltimes for other discharges.

It is desirable to be able to relate elapsed traveltime to discharge. Because most emergency responders do not arrive at the scene with a method of determining stream discharge, access to current discharge data is needed. Real-time information from two stream gages in the Clear Creek Basin is available on the Internet (http://nwis-colo.cr.usgs.gov/rt-cgi/gen_tbl_pg), and this information can be accessed by most emergency dispatchers. One gage is located at the city limits of Golden, and another is located near Lawson. The Golden gage is affected by diversions for the Golden water-treatment plant, the Welch ditch, and the Church ditch. The Lawson gage is located near the center of the basin and has no major diversions upstream from it. Forty-four years of discharge data are available for the Lawson gage, which are shown in figure 13. The mean discharges (and variation) that occurred during the three traveltime measurements also are shown in figure 13. The mean discharges recorded at the Lawson gage during the traveltime measurements at the four study reaches and the amount of discharge variation during each sampling period are provided in table 7.

To provide estimates of traveltime for discharges other than the discharges existing at the time of the study, leading-edge elapsed time compared to the Lawson discharge was plotted. A curve-fitting program was used to achieve the best fit of the data. A power curve fit of the following form was selected:

$$y = ax^b \qquad (5)$$

where

a and b are constants determined by the curve-fitting program,

x is the discharge, and

y is the elapsed time.

Leading-edge data from high, transitional, and low flows were used to develop a set of curves for each sampling site in Study Reaches 1 through 4, and these curves were used to generate estimated traveltimes for discharges other than discharges that occurred during the study (tables 8–11).

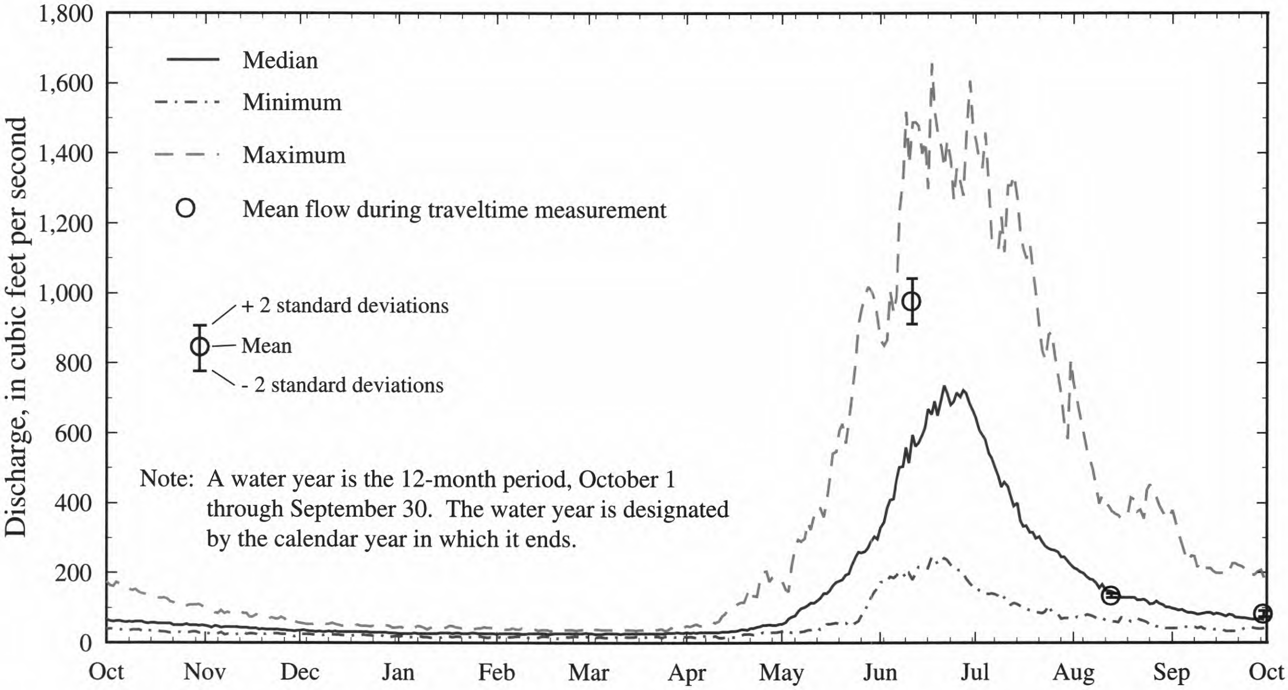

Figure 13. Maximum, median, and minimum discharge at the Lawson gage for water years 1946 through 1986 and 1995 through 1997 and mean discharge during the three traveltime measurements.

Table 7. Mean discharges recorded at Lawson gage during traveltime measurements

[Discharge measured in cubic feet per second]

Traveltime measurement	Flow conditions	Date of dye injection	Mean discharge at Lawson gage during traveltime measurement (±2 standard deviations)[1]
Berthoud Falls to Golden gage (fig. 1)	High—1996	06/11/96	977±65
	Transitional—1996	08/13/96	134±6
	Low—1996	09/30/96	82±8
Loveland Basin Ski Area to Georgetown (fig. 1)	High—1996	06/10/96	987±24
	Transitional—1996	08/14/96	131±6
	Low—1996	10/01/96	78±1
Loveland Pass vicinity to Loveland Valley Ski Area (fig. 2)	High—1996	06/14/96	923±33
	Transitional—1996	08/15/96	128±7
	Low—1996	10/01/96	78±1
Hoop Creek tributaries to confluence with West Clear Creek (fig. 3)	High—1996	08/15/96	126±4
	Transitional—1996	10/01/96	80±5
	Low—1997	06/18/96	875±3

[1]Mean and standard deviation values were determined from the discharge values recorded (discharge recorded every 15 minutes) at the Lawson gage over the sampling period (time from injection until passage of trailing edge at final sampling site).

Table 8. Estimates of leading-edge traveltime to Golden from various upstream sites over a range of Lawson gage discharges

[Data in this table are subject to the limitations discussed in the “Estimation of Upper Clear Creek Traveltimes” section of the report; sampling sites shown in fig. 1 and described in table 2; ft^3/s, cubic feet per second; hr, hours; min, minutes]

Discharge at Lawson gage (ft^3/s)	Sampling site															
	Berthoud Falls (BGI1)		Berthoud Falls gage (BGS1)		Hoop Creek confluence (BGS2)		West Fork of Clear Creek gage (BGS3)		Lawson gage (BGS4)		Idaho Springs 23d Street bridge (BGS5)		Clear Creek above Johnson Gulch gage (BGS6)		Junction Highways 6 and 119 (BGS7)	
	hr	min	hr	min	hr	min	hr	min	hr	min	hr	min	hr	min	hr	min
20	57	02	55	53	54	35	38	30	35	02	25	13	19	58	16	02
40	40	54	40	07	39	05	28	01	25	30	18	27	14	34	11	41
60	33	40	33	02	32	09	23	15	21	11	15	22	12	07	9	43
80	29	20	28	47	27	59	20	22	18	33	13	30	10	38	8	31
100	26	21	25	52	25	08	18	23	16	45	12	12	9	36	7	42
120	24	09	23	42	23	01	16	54	15	24	11	14	8	50	7	05
140	22	25	22	01	21	22	15	45	14	21	10	29	8	14	6	36
160	21	02	20	39	20	02	14	48	13	29	9	52	7	45	6	12
180	19	52	19	31	18	55	14	01	12	47	9	21	7	21	5	53
200	18	54	18	34	17	59	13	21	12	10	8	55	7	00	5	36
250	16	59	16	41	16	09	12	03	10	59	8	03	6	19	5	04
300	15	33	15	17	14	47	11	05	10	06	7	25	5	49	4	39
350	14	27	14	12	13	44	10	19	9	24	6	55	5	25	4	20
400	13	33	13	19	12	52	9	42	8	51	6	31	5	06	4	05
450	12	48	12	35	12	10	9	11	8	23	6	10	4	50	3	52
500	12	10	11	58	11	34	8	45	7	59	5	53	4	36	3	41
550	11	38	11	26	11	02	8	22	7	38	5	38	4	24	3	31
600	11	09	10	58	10	35	8	02	7	20	5	25	4	14	3	23
650	10	44	10	33	10	11	7	45	7	04	5	13	4	05	3	16
700	10	21	10	11	9	50	7	29	6	50	5	03	3	57	3	09
750	10	01	9	51	9	30	7	15	6	37	4	53	3	49	3	03
800	9	43	9	33	9	13	7	02	6	25	4	45	3	43	2	58
850	9	26	9	17	8	57	6	51	6	15	4	37	3	37	2	53
900	9	11	9	02	8	42	6	40	6	05	4	30	3	31	2	49
950	8	57	8	48	8	29	6	30	5	56	4	23	3	26	2	45
1,000	8	44	8	35	8	16	6	21	5	48	4	17	3	21	2	41
1,050	8	31	8	23	8	05	6	12	5	40	4	12	3	17	2	37
1,100	8	20	8	12	7	54	6	04	5	33	4	06	3	12	2	34
1,150	8	10	8	02	7	44	5	57	5	26	4	01	3	09	2	31
1,200	8	00	7	52	7	35	5	50	5	19	3	57	3	05	2	28
1,250	7	50	7	43	7	26	5	43	5	14	3	52	3	02	2	25
1,300	7	42	7	34	7	17	5	37	5	08	3	48	2	58	2	22
1,350	7	33	7	26	7	09	5	31	5	03	3	44	2	55	2	20
1,400	7	25	7	18	7	02	5	26	4	57	3	41	2	52	2	18
1,450	7	18	7	11	6	55	5	20	4	53	3	37	2	50	2	15

Table 9. Estimates of leading-edge traveltime to Silver Plume alluvial wells and Georgetown from various upstream sites over a range of Lawson gage discharges

[Data in this table are subject to the limitations discussed in the "Estimation of Upper Clear Creek Traveltimes" section of the report; site locations shown in fig. 1 and described in table 2; ft^3/s, cubic feet per second; hr, hours; min, minutes]

Discharge at Lawson gage (ft^3/s)	Traveltime to Silver Plume infiltration wells from: Sampling sites						Traveltime to Georgetown from: Sampling sites							
	Loveland Basin Ski Area (LGI1)		Loveland Valley Ski Area gage (LGS1)		Bakerville staff gage (LGS2)		Loveland Basin Ski Area (LGI1)		Loveland Valley Ski Area gage (LGS1)		Bakerville staff gage (LGS2)		Silver Plume infiltration wells (LGS3)	
	hr	min	hr	min	hr	min	hr	min	hr	min	hr	min	hr	min
20	27	02	23	55	7	46	34	22	31	15	15	05	7	19
40	17	52	15	51	5	14	22	53	20	52	10	16	5	01
60	14	01	12	27	4	10	18	03	16	28	8	11	4	01
80	11	48	10	29	3	32	15	14	13	56	6	58	3	26
100	10	20	9	11	3	07	13	22	12	14	6	09	3	02
120	9	15	8	15	2	48	12	01	11	00	5	34	2	45
140	8	27	7	31	2	34	10	59	10	03	5	06	2	32
160	7	48	6	57	2	23	10	09	9	18	4	44	2	21
180	7	16	6	29	2	13	9	28	8	41	4	26	2	12
200	6	49	6	05	2	06	8	54	8	10	4	11	2	05
250	5	58	5	20	1	51	7	49	7	10	3	41	1	50
300	5	21	4	47	1	40	7	01	6	27	3	20	1	40
350	4	53	4	22	1	31	6	25	5	54	3	03	1	32
400	4	30	4	02	1	24	5	56	5	27	2	50	1	25
450	4	12	3	45	1	19	5	32	5	05	2	39	1	20
500	3	56	3	31	1	14	5	12	4	47	2	30	1	15
550	3	43	3	20	1	10	4	55	4	32	2	22	1	11
600	3	32	3	10	1	07	4	40	4	18	2	15	1	08
650	3	22	3	01	1	04	4	27	4	06	2	09	1	05
700	3	13	2	53	1	01	4	16	3	56	2	04	1	02
750	3	05	2	46	0	59	4	06	3	47	1	59	1	00
800	2	58	2	40	0	57	3	57	3	38	1	55	0	58
850	2	52	2	34	0	55	3	48	3	31	1	51	0	56
900	2	46	2	29	0	53	3	41	3	24	1	48	0	54
950	2	41	2	24	0	51	3	34	3	17	1	44	0	53
1,000	2	36	2	20	0	50	3	28	3	12	1	41	0	51
1,050	2	32	2	16	0	48	3	22	3	06	1	39	0	50
1,100	2	27	2	12	0	47	3	16	3	01	1	36	0	49
1,150	2	23	2	09	0	46	3	11	2	56	1	34	0	47
1,200	2	20	2	05	0	45	3	07	2	52	1	32	0	46
1,250	2	16	2	02	0	44	3	02	2	48	1	29	0	45
1,300	2	13	2	00	0	43	2	58	2	44	1	28	0	44
1,350	2	10	1	57	0	42	2	54	2	41	1	26	0	43
1,400	2	08	1	54	0	41	2	50	2	37	1	24	0	42
1,450	2	05	1	52	0	40	2	47	2	34	1	22	0	42

Table 10. Estimates of leading-edge traveltime to confluence with Clear Creek main channel from sites along U.S. Highway 6 on Loveland Pass over a range of Lawson gage discharges

[Data in this table are subject to the limitations discussed in the "Estimation of Upper Clear Creek Traveltimes" section of the report; site locations shown in fig. 2 and described in table 2; ft^3/s, cubic feet per second]

Discharge at Lawson gage (ft^3/s)	Sampling sites					
	West injection site (LPI1)		Main-stem injection site (LPI2)		East injection site (LPI3)	
	hour	minute	hour	minute	hour	minute
20	8	40	6	35	4	59
40	5	49	4	25	3	25
60	4	37	3	29	2	44
80	3	55	2	57	2	20
100	3	27	2	36	2	04
120	3	06	2	20	1	52
140	2	51	2	08	1	43
160	2	38	1	59	1	36
180	2	28	1	51	1	30
200	2	19	1	45	1	25
250	2	02	1	32	1	15
300	1	50	1	23	1	08
350	1	41	1	16	1	02
400	1	33	1	10	0	58
450	1	27	1	05	0	54
500	1	22	1	02	0	51
550	1	18	0	58	0	49
600	1	14	0	55	0	46
650	1	11	0	53	0	44
700	1	08	0	51	0	42
750	1	05	0	49	0	41
800	1	03	0	47	0	39
850	1	01	0	45	0	38
900	0	59	0	44	0	37
950	0	57	0	42	0	36
1,000	0	55	0	41	0	35
1,050	0	54	0	40	0	34
1,100	0	52	0	39	0	33
1,150	0	51	0	38	0	32
1,200	0	50	0	37	0	32
1,250	0	48	0	36	0	31
1,300	0	47	0	35	0	30
1,350	0	46	0	35	0	30
1,400	0	45	0	34	0	29
1,450	0	44	0	33	0	28

Table 11. Estimates of leading-edge traveltime to Hoop Creek confluence with West Fork of Clear Creek from sites along U.S. Highway 40 over a range of Lawson gage discharges

[Data in this table are subject to the limitations discussed in the "Estimation of Upper Clear Creek Traveltimes" section of the report; sampling sites shown in fig. 3 and described in table 2; ft^3/s, cubic feet per second]

Discharge at Lawson gage (ft^3/s)	Sampling sites									
	East injection site (HI1)		Floral Park campground (HS1)		East switchback (HS2)		West injection site (HI2)		West switchback (HS4)	
	hour	minute	hour	minute	hour	minute	hour	minute	hour	minute
20	12	59	8	47	4	02	5	48	3	31
40	7	41	5	14	2	30	3	53	2	20
60	5	39	3	52	1	53	3	05	1	50
80	4	32	3	07	1	32	2	36	1	33
100	3	50	2	38	1	19	2	17	1	21
120	3	20	2	18	1	09	2	04	1	13
140	2	58	2	03	1	02	1	53	1	06
160	2	41	1	51	0	57	1	45	1	01
180	2	27	1	42	0	52	1	38	0	57
200	2	16	1	34	0	48	1	32	0	53
250	1	55	1	20	0	41	1	21	0	47
300	1	40	1	09	0	36	1	13	0	42
350	1	29	1	02	0	32	1	07	0	38
400	1	20	0	56	0	30	1	02	0	35
450	1	13	0	51	0	27	0	57	0	33
500	1	08	0	47	0	25	0	54	0	31
550	1	03	0	44	0	23	0	51	0	29
600	0	59	0	41	0	22	0	49	0	28
650	0	55	0	39	0	21	0	46	0	26
700	0	52	0	37	0	20	0	44	0	25
750	0	50	0	35	0	19	0	43	0	24
800	0	47	0	33	0	18	0	41	0	23
850	0	45	0	32	0	17	0	40	0	22
900	0	43	0	30	0	16	0	38	0	22
950	0	41	0	29	0	16	0	37	0	21
1,000	0	40	0	28	0	15	0	36	0	20
1,050	0	38	0	27	0	15	0	35	0	20
1,100	0	37	0	26	0	14	0	34	0	19
1,150	0	36	0	25	0	14	0	33	0	19
1,200	0	35	0	24	0	13	0	32	0	18
1,250	0	34	0	24	0	13	0	32	0	18
1,300	0	33	0	23	0	13	0	31	0	17
1,350	0	32	0	22	0	12	0	30	0	17
1,400	0	31	0	22	0	12	0	30	0	16
1,450	0	30	0	21	0	12	0	29	0	16

Because the data set for each sampling site consisted of only three data points, these fitted curve estimates need to be used with care. Although the traveltime estimation within the range of the Lawson discharges (about 80 to 990 ft^3/s) may be relatively accurate, large deviations could occur for discharges greater than and less than this range. The correlation coefficients (r^2) ranged from 0.95 to 0.99, but this range would be expected for a three data-point curve fit. The actual variation of the data between the three points may be large, introducing error into the elapsed time calculated for a specific discharge. Users need to allow a safety factor when using these tables and need to assume the leading edge can arrive sooner than the tables estimate.

In addition to the uncertainty of the curve fit, errors were introduced into the estimations because of conditions occurring during the actual traveltime-data measurements. A heavy rainstorm occurred late in the afternoon during the low-flow sampling at Study Reach 3. Stream discharge probably increased during this time, but the procedure used to generate the estimation tables assumed a constant discharge. Traveltimes estimated for the low-flow periods in Study Reach 3 probably are conservative because the estimation curve was based on lower flows (table 10). The diversion was closed during the low-flow traveltime measurements in Study Reach 4, which again may have introduced error into the estimates (table 11). For the low-flow periods when the diversion remains open, the estimated traveltimes are underestimated (that is, the contamination would move faster).

Localized precipitation in one or more subbasins can have major effects on discharge in other parts of the Clear Creek Basin. For example, a heavy summer rainstorm in the Chicago Creek Basin (fig. 1) could decrease the amount of traveltime between Idaho Springs and Golden, and the gage at Lawson would record nothing unusual. The relation between median discharge recorded at the Golden and Lawson surface-water gages is shown in figure 14. Large variations from this relation could indicate flooding in the lower basin, but the graph shows variations of more than ±100 ft^3/s, making it difficult to determine

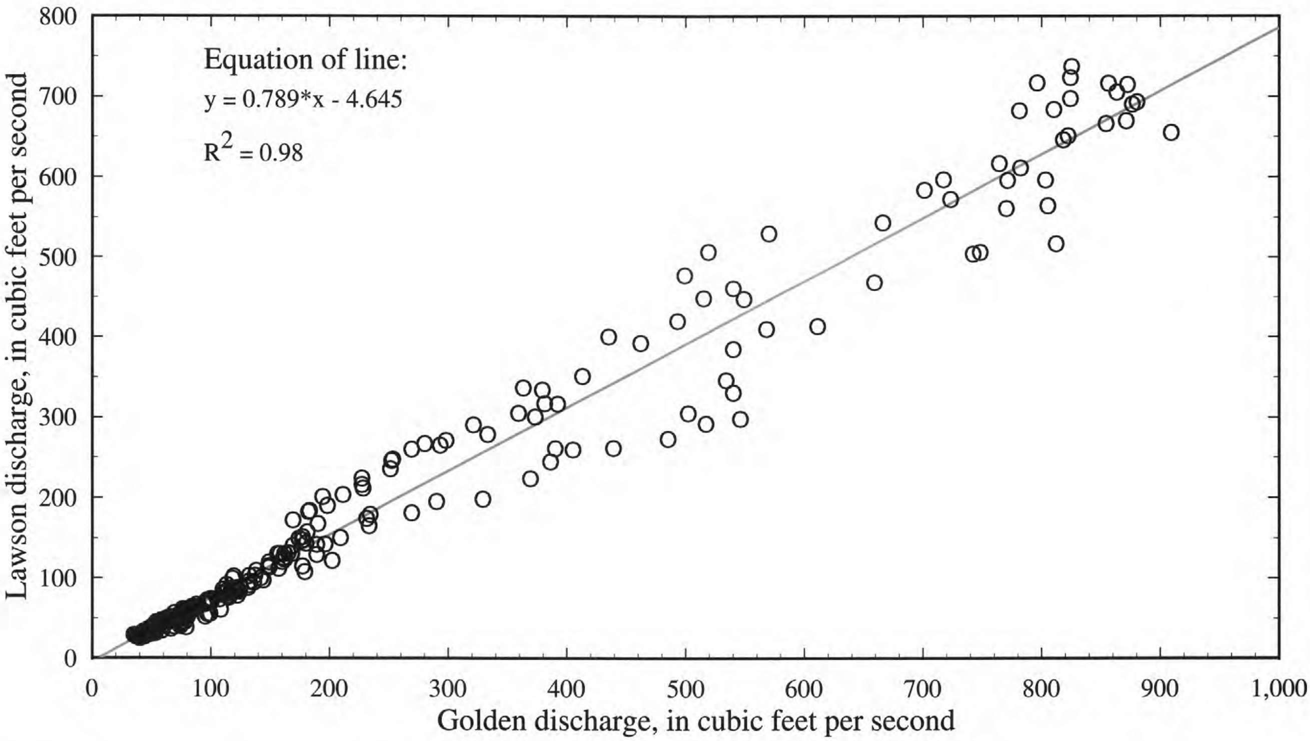

Figure 14. Relation between historical median discharges recorded at the Golden and the Lawson surface-water gages.

if diversions, flooding, or surface-water-gage error is involved. An alternative would be to check weather conditions along with the Lawson discharge. The estimation tables were not designed to be used during times of flooding. If flooding does occur in the lower basin, a conservative safety factor needs to be applied to the estimated traveltimes (about 1 to 2 hours during high flow and 2 or more hours during low flow) to ensure the leading edge of a plume will be contained.

Several additional factors can affect traveltime to downstream locations. Diversions upstream from Golden can affect traveltimes, as can reservoirs, such as Georgetown Lake. Also, the type of hazardous material spilled needs to be noted. Rhodamine-WT dye is very water soluble, whereas gasoline is not. A soluble chemical behaves similarly to the rhodamine-WT, but organic chemicals that have low solubility cling to surfaces, potentially leaching into the stream for an extended period of time. The leading edge may arrive at about the same time as the rhodamine-WT, but the trailing edge can be extended. Another factor is that the rhodamine-WT dye was injected as a slug. An actual spill may leak contamination into the stream for a number of hours, again lengthening the trailing edge.

SUMMARY

Population growth in the mountainous areas along the Colorado Front Range has resulted in increased traffic and a corresponding potential increase for accidents, possibly involving hazardous-material carriers. Because of the proximity of mountain streams to highways, hazardous-material spills can affect downstream water supplies. This study determined traveltimes along four reaches of the upper Clear Creek Basin to provide downstream water managers and hazardous-material-response teams with a method of estimating the arrival times of hazardous-material spills.

Traveltime studies are a useful tool that help to minimize the effect of hazardous-material spills into streams that are used for water supply. The complex nature of mountain streams affects many estimation techniques and requires actual measurements to determine the actual traveltimes. Channel characteristics in the upper Clear Creek Basin vary from intermittent rills flowing from snow fields to artificially straightened channels contained by steep canyon walls. Dye-tracer (rhodamine-WT) measurements provide useful information from such areas.

Traveltime measurements were made at three times of the year to obtain data during three different flow conditions. Leading-edge traveltimes along the study reaches varied between high and low flow as follows: about 8.8 to about 28.6 hours between Berthoud Falls and Golden (average velocity varied from about 4.4 to about 1.3 mi/hr); about 3.5 to about 15.7 hours between the Loveland Basin Ski Area and Georgetown (average velocity varied from about 3.5 to about 0.8 mi/hr); about 0.7 to about 2.9 hours between the Loveland Pass subreach 3b injection site (LPI2) and sampling site (LPS1) (average velocity varied from about 1.8 to about 0.4 mi/hr); and about 0.8 to about 5.0 hours between Berthoud Pass subreach 4a injection site (HI1) and sampling site (HS3) (average velocity varied from about 2.1 to about 0.3 mi/hr).

The study indicated the great variability of a mountainous system where leading-edge traveltimes could be three to six times longer at low flow than at high flow. Factors such as beaver ponds, waterfalls, and manmade structures for fish habitat improvement can substantially affect the time required for a dye cloud to pass through a stream reach. The step-pool characteristic of high mountain streams proved to be a major factor in average reach velocity in the headwater streams. Snow fields near the Continental Divide seemed to be effective, temporary spill-containment systems.

The variable nature of Clear Creek and its tributaries can cause problems when making estimations from the data. Measurements during three discharge conditions provided sufficient data to develop a relation between discharge and the time required for the leading edge of a contaminant plume to arrive at a downstream site. The validity of the estimated traveltimes for discharges greater than or less than the discharges measured during the study was not determined. Estimated traveltimes always need to be used with care until additional data can verify the estimation. Factors that did not occur during the study, such as intense rainfalls in one or two subbasins, need to be considered when using the estimated traveltime tables. The estimated traveltimes need to be used as guidelines, not as absolute values.

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