TRACER-DILUTION EXPERIMENTS AND SOLUTE-TRANSPORT SIMULATIONS FOR A MOUNTAIN STREAM, SAINT KEVIN GULCH, COLORADO

by Robert E. Broshears, Kenneth E. Bencala,
Briant A. Kimball, and Diane M. McKnight

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FIGURES

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
centimeter per second	3.281×10^{-2}	foot per second
cubic meter per second	3.531×10^{1}	cubic foot per second
liter per second	3.531×10^{-2}	cubic foot per second
meter	3.281	foot
micrometer	3.937×10^{-5}	inch
millimeter	3.937×10^{-2}	inch
milliliter per minute	2.642×10^{-4}	gallon per minute
square meter	1.076×10^{1}	square foot
square meter per second	1.076×10^{1}	square foot per second

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ABSTRACT

Tracer-dilution experiments and associated solute-transport simulations provided estimates of discharge and time of travel along several reaches of Saint Kevin Gulch, a stream receiving acidic effluent from mine tailings in Lake County, Colorado. Profiles of time-varying tracer (lithium chloride) concentration were simulated with a transport model depicting advection, dispersion, lateral inflow, and the transient storage of solutes in immobile zones along the stream channel. Simulated profiles were sensitive to variations in the model's transient-storage parameters, including the cross-sectional area of the storage zone and the stream-storage exchange coefficient. Although similar to values calibrated in simulations of tracer profiles in other mountain streams, these transient-storage parameters were specific to individual reaches and could not be predicted from linear combinations of simple hydraulic variables. Parameters that were calibrated for the simulation of lithium concentrations could be used without adjustment to simulate measured concentrations of chloride. This result increased confidence in the ability of the model to simulate the nonreactive behavior of any solute. The steady-state profile of lithium concentrations during the plateau stage of the experiment also was simulated successfully. Assumptions underlying tracer-dilution methods are violated in losing reaches of streams. Injection of a second tracer (sodium bromide) and a direct measurement of discharge provided an improved estimate of the flow rate downstream from a losing reach of Saint Kevin Gulch.

INTRODUCTION

Understanding flow and solute transport in mountain streams is important for the effective protection of these environmentally sensitive areas. Because direct human impact may not extend into mountain watersheds, some of these streams provide sites for sampling pristine water quality. Even streams in undeveloped areas, however, may be affected by acid precipitation (Smith and Alexander, 1983; Turk and Spahr, 1991). Where mountain watersheds have been disturbed by mining, acidification and attendant mobilization of hazardous constituents may be pronounced. Transport of these hazardous constituents may affect downstream water quality.

Conventional methods for measuring the physical movement of water in surface channels often are not effective in mountain streams (Zellweger and others, 1989), because these methods depend on accurate measurements of water velocity and cross-sectional area. Velocity profiles in high-gradient streams are often complex, and large and irregular bottom relief confounds estimates of cross-sectional area (Marchand and others, 1984). Also, underflow through coarse bottom material is not measurable with conventional instrumentation. Due to these constraints, tracer-dilution methods may be more applicable for the measurement of discharge in mountain streams. Even the use of conventional tracers

may be inappropriate, however, as common organic dyes (for example, rhodamine WT) may not be stable in the acidic conditions common to mountain watersheds that have been disturbed by mining (Bencala and others, 1983; Bencala and others, 1986).

In 1986, the U.S. Geological Survey began an investigation to characterize within-stream hydrologic, chemical, and biological processes that influence the distribution and transport of hazardous constituents in the headwaters of the Arkansas River (Kimball and others, 1989; Kimball, 1991). Most of this work has focused on heavy metals, including copper, lead, iron, and zinc. The investigation has addressed characterization of sediment and colloidal chemistry, equilibrium and kinetic restraints on chemical reactions, and biotic effects. Developing criteria for the selection of appropriate scales of time and distance for sampling has been a major emphasis.

Evaluation of chemical or biological processes in a stream requires a thorough understanding of physical transport mechanisms. Accordingly, an initial focus of the investigation was a quantification of these mechanisms using observations from tracer-dilution experiments and simulations with solute-transport models.

Purpose and Scope

This report describes the results of tracer-dilution experiments and associated solute-transport simulations for a mountain stream. Experiments were conducted in August 1986, along a 1804-meter stretch of Saint Kevin Gulch, a stream affected by acid mine drainage in Lake County, Colorado. The report describes transient changes in tracer (lithium chloride) concentration at six instream sites. These changes are interpreted in terms of hydrologic processes within the stream and adjacent water-bearing zones. The primary interpretive tool was a solute-transport model that simulates advection, dispersion, mixing with lateral inflows, and transient storage

(Bencala and Walters, 1983). A second tracer-dilution experiment helped define the flow rate downstream from a losing reach in Saint Kevin Gulch.

Description of the Study Area

The study area includes reaches of Saint Kevin Gulch, a small tributary of Tennessee Creek in northwestern Lake County, Colorado (fig. 1). Most of the drainage basin is forested with spruce and pine. Average annual precipitation is 420 millimeters (Benci and McKee, 1977), most of which occurs as snow. Currently (1992) there is little active mining in the basin, but abandoned mines and associated tailings remain from excavations made earlier in this century. Saint Kevin Gulch receives acidic, metal-enriched drainage from these areas, and hydrous iron oxides are ubiquitous on the stream bed. Shingle Mill Gulch, which joins Saint Kevin Gulch near a major mine tailings site (fig. 1), drains a relatively pristine basin.

METHODS

Tracer-Dilution Experiments

In August 1986, tracer solutions containing either lithium chloride (LiCl) or sodium bromide (NaBr) were injected at two sites in the study area (fig. 1). At the LiCl injection site (fig. 1), a solution of 4.7 molar LiCl was injected at an average rate of 27 milliliters per minute for 52 hours. At a site 1,560 meters downstream from the site of the LiCl injection, a solution of 0.9 molar NaBr was injected for 30 hours at an average rate of 25 milliliters per minute.

Water samples were collected at frequent time intervals at six sites located from 26 to 1,804 meters downstream from the site of the LiCl injection (fig. 1). Additional water samples were collected one time only at 19 intermediate sites. Timing of the single collec-

EXPLANATION

——··—·· DRAINAGE BASIN BOUNDARY

▼ 526 SAMPLE SITE AND NUMBER--
Number represents distance
downstream from lithium chloride
injection site, in meters

INJECTION SITE AND NUMBER--
Number represents distance
downstream from lithium chloride
injection site, in meters

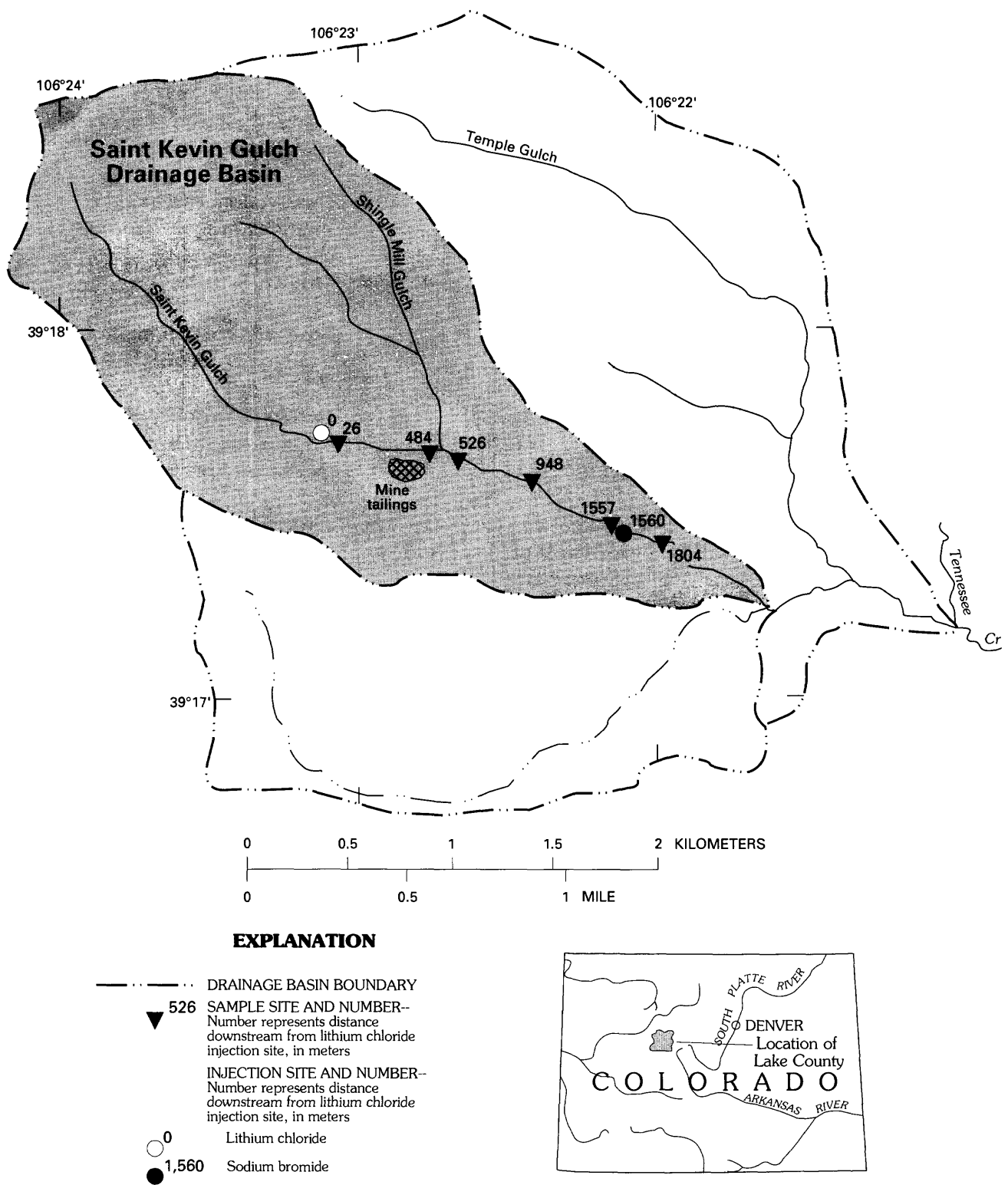○ 0 Lithium chloride

● 1,560 Sodium bromide

Figure 1.--Location of Saint Kevin Gulch drainage basin and injection and sampling sites.

tion at these additional sites was intended to permit the prior development of a locally constant tracer concentration. During the NaBr injection, water samples were collected at frequent time intervals only at the site located 1,804 meters downstream from the LiCl injection. Filtered (less than 0.1 micrometer pore size) samples were analyzed for lithium and sodium by atomic-absorption spectroscopy and for chloride and bromide by ion chromatography (Fishman and Friedman, 1985). Lithium and bromide concentrations were measured to the nearest 0.01 milligram per liter. Sodium and chloride concentrations were measured to the nearest 0.1 milligram per liter.

Solute-Transport Simulations

Physical transport of conservative solutes in a stream is dominated by the processes of advection, dispersion, lateral inflow, and transient storage. Advection is downstream movement at the mean longitudinal velocity of the current. Dispersion is the longitudinal spreading of a solute pulse due primarily to turbulent motion. Lateral inflow results in mixing with water of possibly different chemical composition. Transient storage is the reversible transfer of solutes between the stream and relatively immobile zones of water along the active stream channel. These processes are expressed for a one-dimensional system by the following equations:

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial\left(AD\frac{\partial C}{\partial x}\right)}{\partial x}$$

$$+ \frac{q_L}{A}(C_L - C) + \alpha(C_S - C) \quad (1)$$

$$\frac{dC_S}{dt} = -\alpha\frac{A}{A_S}(C_S - C) \quad (2)$$

where C = solute concentration in the stream, in milligrams per liter;

t = time, in seconds;

Q = stream discharge rate, in cubic meters per second;

A = cross-sectional area of the channel, in square meters;

x = distance, in meters;

D = dispersion coefficient, in square meters per second;

q_L = lateral inflow rate per unit stream length, in cubic meters per second per meter;

C_L = solute concentration in the lateral inflow, in milligrams per liter;

α = stream-storage exchange coefficient, in reciprocal seconds;

C_S = solute concentration in the storage zone, in milligrams per liter; and,

A_S = cross-sectional area of the storage zone, in square meters.

The preceding equations depict transient storage as the consequence of reversible, gradient-driven mass transfer between the stream and an adjacent, well-mixed, but immobile storage zone. This depiction may not be physically complete because transient storage also may include exchange of solute with solid phases or with mobile or poorly mixed substream zones. However, this conceptual approach has been used successfully to simulate measured solute concentrations in several tracer-dilution experiments (Bencala and Walters, 1983; Bencala, 1984; Bencala and others, 1990).

Equations 1 and 2 were solved by a Crank-Nicolson finite-difference technique. Within each simulated reach, parameters were adjusted to provide a good visual fit between measured concentrations and simulated values. The parameter estimation procedure was patterned after the approach outlined by the Stream Solute Workshop (1990). Discharge at each sampling site was calculated by the dilution required to simulate the measured plateau concentration of the tracer. The calculation is based on a mass-flow balance that assumes the injection rate is negligible relative to stream discharge:

$$Q_i C_i + Q C_b = Q C_p \qquad (3a)$$

Solving for Q:

$$Q = \frac{(Q_i C_i)}{(C_p - C_b)} \qquad (3b)$$

where Q_i = injection rate, in cubic meters per second;

C_i = injectate concentration, in milligrams per liter;

Q = stream-discharge rate, in cubic meters per second;

C_b = background concentration of tracer, in milligrams per liter;

C_p = plateau concentration of tracer, in milligrams per liter.

Cross-sectional area was adjusted to reproduce a solute arrival consistent with the observed arrival of the tracer. The cross-sectional area of the storage zone and the stream-storage exchange coefficient were adjusted to accommodate deviations from traditional advective-dispersive behavior in the observed concentration profile.

Because the duration of the LiCl injection exceeded time of travel through the study area, steady-state conditions developed at each sampling site. For steady-state conditions, equations 1 and 2 can be rewritten as:

$$-\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial (AD\frac{\partial C}{\partial x})}{\partial x}$$

$$+\frac{q_L}{A}(C_L - C) = 0 \qquad (4)$$

$$C_S = C \qquad (5)$$

where all variables are described earlier. Equation 4 was solved by a finite-difference technique. Values of physical parameters from the transient LiCl simulation, including flow rates, cross-sectional areas, dispersion coefficients, and lateral-inflow rates, were used as input for the steady-state simulation.

RESULTS OF THE TRACER-DILUTION EXPERIMENTS

During the interval of lithium chloride injection, concentrations of lithium and chloride increased to plateau values at the six frequently sampled sites (fig. 2, table 1). After the injection stopped, concentrations of these constituents decreased toward background values. In the following discussion, all sites are identified by their downstream distance in meters from the LiCl injection site. Plateau concentrations for lithium ranged from 2.36 mg/L at site 26 to 0.72 mg/L at site 1804 (table 1). Plateau concentrations of chloride were 13.4 mg/L and 4.2 mg/L, respectively, at these two sites (table 1). Using the lithium plateau and background concentrations and equation 3b, calculated stream discharge increased from 6.19×10^{-3} cubic meter per second in the reach ending at site 26 to 1.97×10^{-2} cubic meter per second in the reach ending
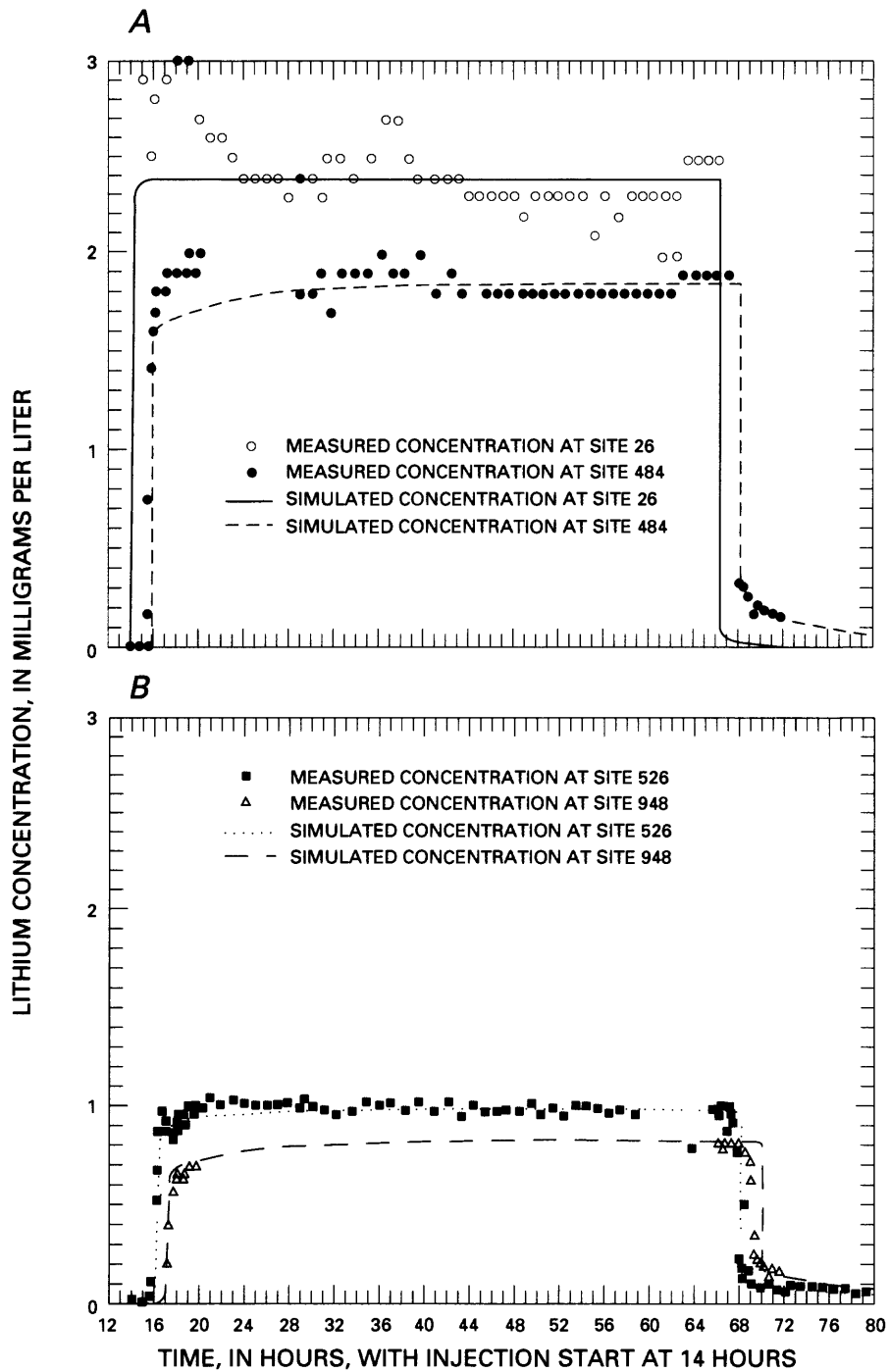
Figure 2.--Measured and simulated transient concentrations of lithium during the tracer-dilution experiment.
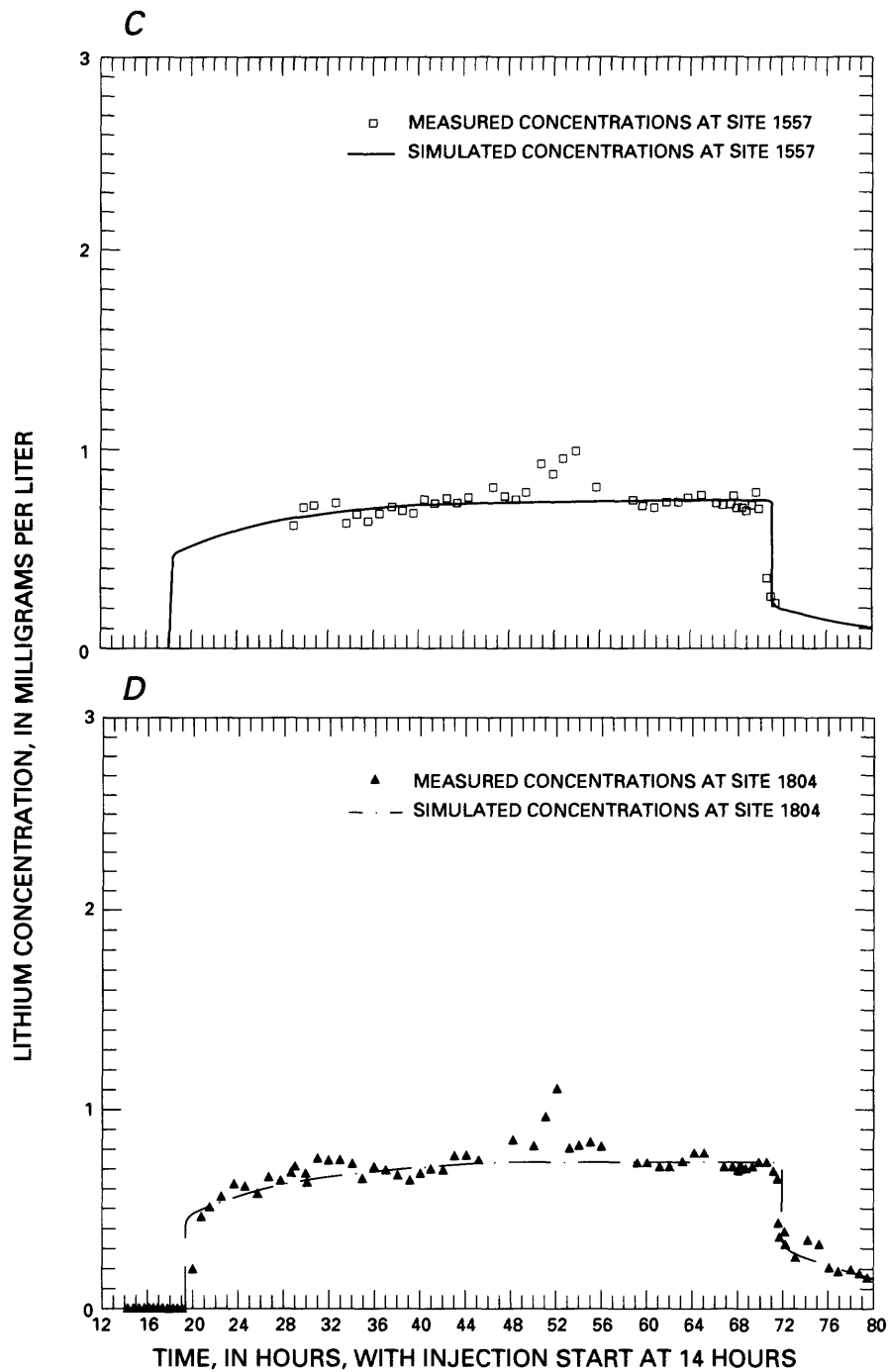
Figure 2.--Measured and simulated transient concentrations of lithium during the tracer-dilution experiment.--Continued

Table 1.—*Results of the lithium chloride tracer-dilution experiment and calculated instream discharge and time of travel at Saint Kevin Gulch in 1986*

[mg/L, milligrams per liter; m³/s, cubic meters per second; s, seconds; <, less than; nc, not calculated]

Sampling site number (fig. 1)[a]	Lithium concentration		Chloride concentration		Maximum upstream discharge based on lithium dilution (m³/s)
	Background (mg/L)	Plateau (mg/L)	Background (mg/L)	Plateau (mg/L)	
26	<0.01	2.36	0.2	13.4	6.19×10^{-3}
484	<.01	1.84	.2	9.9	7.92×10^{-3}
526	<.01	.97	.2	5.3	1.51×10^{-2}
948	<.01	.87	.2	4.8	1.68×10^{-2}
1557	<.01	.74	.2	4.2	1.97×10^{-2}
1804	<.01	.72	.2	4.2	nc

Reach boundaries[b]	Time of travel within reach (s)
0-26	500
26-484	6,300
484-526	520
526-948	5,200
948-1557	5,100
1557-1804	2,600

a. Sampling site number represents distance downstream from lithium choride injection site, in meters.
b. Reach is interval between consecutive sampling sites.

at site 1557. Lithium values were chosen for the discharge calculation because, compared with chloride, lithium background concentrations were lower and analytical precision was higher. Time of travel within each reach varied from several minutes to more than an hour (table 1). Total travel time through the 1,804-meter study area was approximately 5.6 hours.

Determination of discharge by tracer-dilution methods is based on the assumption that a stream gains flow along all reaches. If inflow concentrations are significantly less than instream concentrations, changes in flow within the stream can be calculated from the instream dilution of the tracer. A stream can lose flow, however, with no concomitant change in the concentration of the tracer. In losing reaches, instream tracer concentration would remain constant while discharge decreases.

Because measured plateau concentrations of lithium and chloride did not decrease significantly between the two most downstream sites (table 1), discharge at the lower end of the study reach could not be determined reliably using the results of the LiCl experiment. Therefore, a NaBr tracer injection and a direct measurement of discharge were used to provide an improved estimate of flow. Data from the NaBr injection experiment indicated that Saint Kevin Gulch was losing water in the suspect area. The NaBr tracer solution was injected near the upstream boundary of the final reach (fig. 1). At the most downstream site (site 1804), measured plateau concentrations of sodium and bromide were 3.3 mg/L and 1.92 mg/L, respectively (table 2). These concentrations are consistent with a discharge of 1.47×10^{-2} cubic meter per second. This discharge represents the maximum rate of flow between the NaBr-injection at site 1560 and site 1804. The discharge at site 1804 could have been less than this value. A discharge of 1.5×10^{-2} cubic meter per second was measured with a pygmy meter near the NaBr-injection site. This measurement is consistent with the results of the NaBr tracer-dilution experiment;

together the two methods indicate that discharge at site 1557 does not exceed 1.5×10^{-2} cubic meter per second. The point of maximum discharge between sites 948 and 1557 is uncertain. The presence of willows upstream and adjacent to site 1499 indicates a high water table and most likely a gaining reach. Tracer experiments conducted in 1989 and 1990 (B. A. Kimball, U.S. Geological Survey, written commun., 1991) indicated no gain in flow between sites 1499 and 1557 in those years. Based on these observations, the maximum discharge of 1.97×10^{-2} cubic meter per second was assumed to occur at site 1499. Discharge was assumed to decrease to 1.47×10^{-2} cubic meter per second at site 1557 and to remain constant between sites 1557 and 1804.

RESULTS OF THE SOLUTE-TRANSPORT SIMULATIONS

Simulated concentrations of lithium through time at the frequently sampled sites compared favorably with observed values (fig. 2). Simulated discharge increased between all frequently sampled sites except the most downstream pair. Best-fit storage parameters varied among reaches within a factor of five or less (table 3). This level of variability was consistent with that obtained in simulations of tracer behavior in other mountain streams (table 4). Values for the stream-storage exchange coefficient were similar to those determined in previous investigations.

The observed profile of tracer concentration through time at each sampling site (fig. 2) illustrated the relative importance of the processes simulated by each of the terms in equations 1 and 2. Simple advection accounted for the orderly arrival of the concentration pulse at sequential downstream sampling sites. Simulations were not sensitive to the value of the dispersion coefficient within a range of two orders of magnitude (0.002–0.2 square meter per second). Lateral inflow along the channel resulted in increased discharge and an associated decrease in the plateau

Table 2.--*Results of the sodium bromide tracer-dilution experiment and calculated instream discharge at Saint Kevin Gulch in 1986*

[mg/L, milligram per liter; m³/s, cubic meter per second]

Sampling site number[a] (fig. 1)	Sodium concentration		Bromide concentration		Calculated discharge based on average dilution (m³/s)
	Background (mg/L)	Plateau (mg/L)	Background (mg/L)	Plateau (mg/L)	
1804	2.7	3.3	0.01	1.92	1.47×10^{-2}

a. Sampling site number represents distance downstream from lithium chloride injection site, in meters.

Table 3.--*Variables for the simulation of solute transport during the tracer-dilution experiment at Saint Kevin Gulch in 1986*

[m³/s, cubic meters per second; m², square meters; s⁻¹, reciprocal seconds; m²/s, square meters per second]

Reach[a] boundaries (fig. 1)	Maximum discharge within reach (m³/s)	Stream cross-sectional area (m²)	Storage cross-sectional area (m²)	Stream-storage exchange coefficient (s⁻¹)	Dispersion coefficient (m²/s)
0-26	6.19×10^{-3}	0.120	0.05	3.0×10^{-5}	0.02
26-484	7.92×10^{-3}	.097	.05	2.0×10^{-5}	.02
484-526	1.51×10^{-2}	.138	.25	2.0×10^{-5}	.02
526-948	1.68×10^{-2}	.199	.10	1.5×10^{-5}	.02
948-1557	1.97×10^{-2}	.152	.20	5.0×10^{-5}	.02
1557-1804	1.47×10^{-2}	.153	.10	1.5×10^{-5}	.02

a. Reach is interval between consecutive sampling sites. Sampling sites are defined by their distance in meters downstream from the lithium chloride injection site.

Table 4.–*Hydraulic characteristics and calibrated storage parameters for tracer simulations in four mountain streams*

[Data sorted by ascending stream velocity; cm/s, centimeters per second; m, meters; L/s, liters per second; s^{-1}, per second; m^2, square meters; LLM, Little Lost Man Creek, Humbolt County, California; UVS, Uvas Creek, Santa Clara County, California; SKG, Saint Kevin Gulch, Lake County, Colorado; SNK, Snake River, Summit County, Colorado]

Stream	Water velocity (cm/s)	Reach length (m)	Average discharge (L/s)	Stream-storage exchange coefficient (s^{-1})	Storage cross-sectional area (m^2)	Ratio of storage area to stream area	Reference
LLM	1.3	57	7.7	20.0×10^{-5}	1.50	2.50	Bencala, 1984
LLM	1.3	142	7.8	2.0×10^{-5}	.60	1.00	"
LLM	1.5	63	7.5	8.0×10^{-5}	2.00	4.00	"
LLM	2.0	57	7.3	4.0×10^{-5}	.12	.33	"
UVS	2.7	186	13.8	4.5×10^{-5}	1.56	3.00	Bencala and Walters, 1983
UVS	3.3	152	13.5	1.0×10^{-5}	.41	1.00	"
UVS	3.6	176	12.9	3.0×10^{-5}	.36	1.00	"
SKG	5.2	26	6.2	3.0×10^{-5}	.05	.42	This paper
SKG	7.3	458	7.1	2.0×10^{-5}	.05	.52	"
SKG	8.0	422	15.9	1.5×10^{-5}	.10	.50	"
SKG	8.3	42	11.5	2.0×10^{-5}	.25	1.81	"
SKG	9.6	247	14.7	1.5×10^{-5}	.10	.65	"
SKG	12.0	609	18.3	5.0×10^{-5}	.20	1.32	"
SNK	17.5	122	332	50.0×10^{-5}	1.50	.79	Bencala and others, 1990
SNK	19.4	118	350	10.0×10^{-5}	.50	.28	"
SNK	39.8	628	243	2.5×10^{-5}	.10	.16	"
SNK	46.6	1,342	745	10.0×10^{-5}	.50	.31	"
SNK	53.4	737	294	5.0×10^{-5}	.02	.04	"
SNK	53.8	1,240	376	20.0×10^{-5}	.12	.17	"
SNK	55.4	697	670	5.0×10^{-5}	.05	.04	"
SNK	58.4	279	631	5.0×10^{-5}	.05	.05	"
SNK	62.5	68	500	20.0×10^{-5}	.05	.06	"

concentration of the tracer between all adjacent sites except the final pair.

A dimensionless plot is shown in figure 3. In this plot, concentration values at site 1804 are nondimensionalized by dividing each value by the plateau concentration; values of time are nondimensionalized by dividing each value by the mean travel time between the injection point and site 1804. A square pulse traveling with no transient storage by definition would increase instantaneously from a nondimensional concentration of zero to a nondimensional concentration of one at a nondimensional time of one. As shown in figure 3, three to four travel times are required before the plateau concentration is achieved. This observation demonstrates the importance of transient storage in increasing the mean residence time of solutes in the stream.

Simulations were sensitive to variations by a factor of two in the stream-storage exchange coefficient (fig. 4). In the simulations, use of a larger stream-storage exchange coefficient has the effect of transferring solutes more rapidly between the stream and the storage zone. Transfer is significant even when the concentration gradient between these two compartments is low. On the rising limb of the concentration profile, when the concentration within the storage zone is low, the effects of transient storage are manifested at a relatively low stream concentration. At the onset of the falling limb of the profile, when the concentration within the storage zone is at its maximum, the effects of transient storage are manifested at a relatively higher stream concentration.

Simulations were also sensitive to variations by a factor of two in the storage cross-sectional area (fig. 5). In the simulations, use of a larger storage cross-sectional area has the effect of extending the time necessary to achieve a plateau concentration. A larger stream cross-sectional area also produces a longer tail on the concentration profile, because a longer period of time is required to transfer solutes from the larger storage zone back to the stream.

The stream-storage exchange coefficient and the storage cross-sectional area are operational parameters that cannot be predicted with confidence from readily available hydraulic variables. Calibrated transient-storage parameters for the simulations described in this report and those from simulations in three other streams (table 4) were compared with simple hydraulic characteristics, including water velocity, reach length, and discharge. No linear combination of the three hydraulic variables was predictive of the transient-storage parameters. (The fraction of the total sum of squares explained by the regression was always less than 0.30.) The absence of a statistically obvious relation among the variables is indicative of the complex, reach-specific character of the transient-storage parameters.

In addition to the six plateau values, measured concentrations of lithium at the 19 sites where single samples were collected compared favorably with the results of a steady-state simulation (fig. 6). Observed values at five of these sites (located 413, 421, 439, 455, and 464 meters downstream from the LiCl injection) were used to refine estimates of discharge in reaches near the mine tailings (fig. 1); as a result, simulated values in these reaches corresponded directly with measured concentrations. Agreement was less satisfactory in the downstream reaches of the study area, where measured concentrations were consistently lower than the simulated values (fig. 6). This result was attributable in part to the timing of sample collection, which occurred before a plateau concentration was attained in these reaches.

Because input parameters for the steady-state simulation were developed using the results of the transient solute-transport simulations, the fit portrayed in figure 6 represents little more than a check on the consistency of the steady-state code. This check is important, however, as a prelude to future simulations of the steady-state profiles of nonconservative constituents in Saint Kevin Gulch.
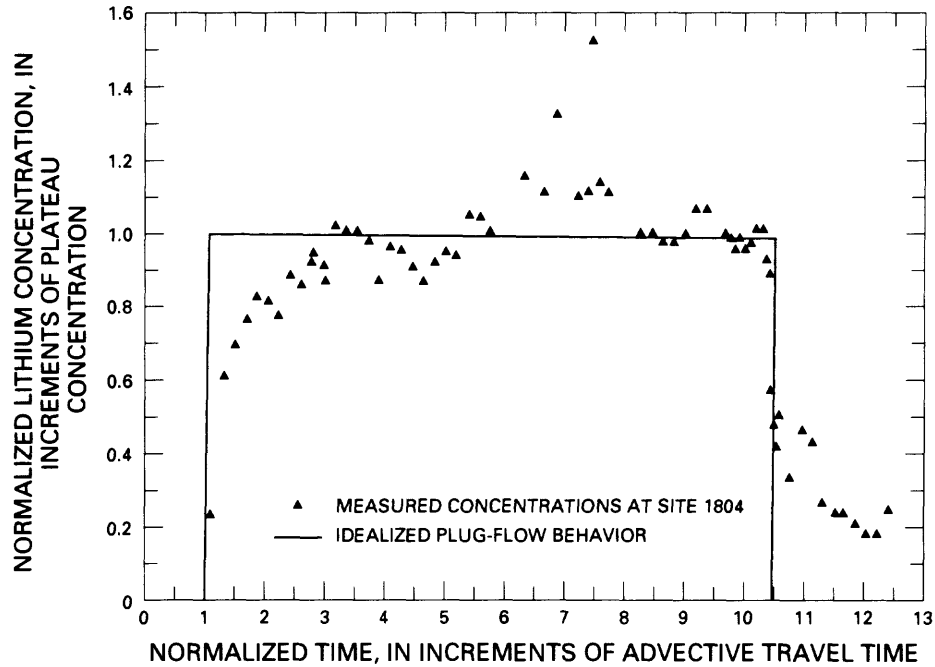
Figure 3.--Relation of measured lithium concentrations normalized to the plateau concentration to a time scale normalized to the advective travel time at site 1804.
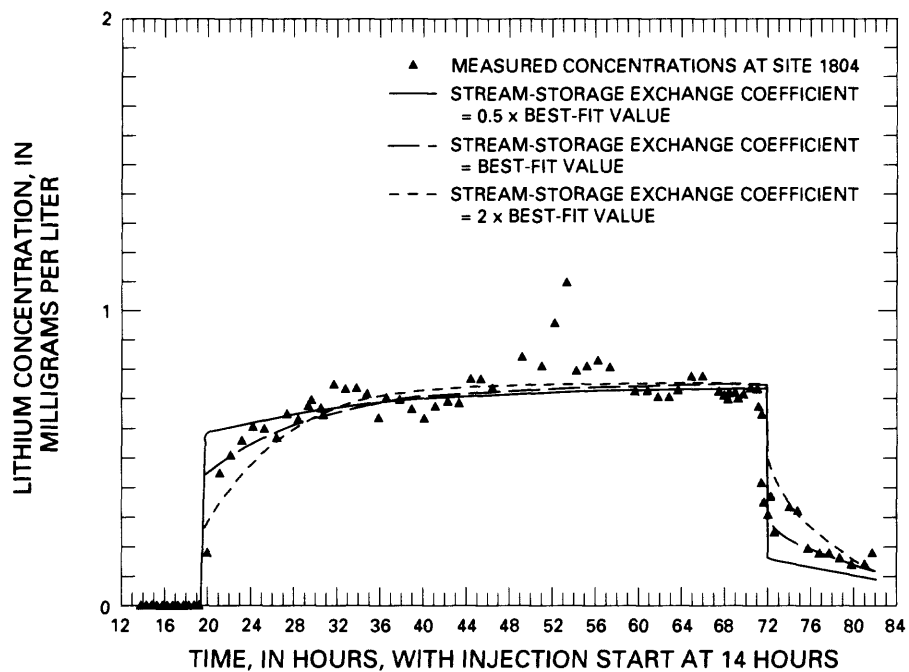

Figure 4.--Sensitivity of lithium transient simulation to variations in the stream-storage exchange coefficient.
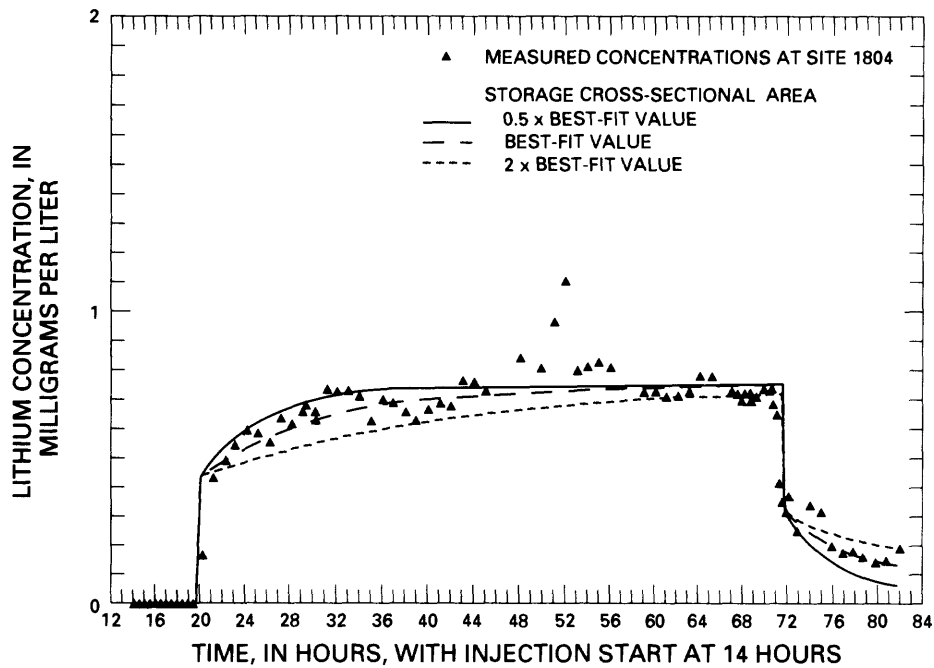
Figure 5.--Sensitivity of lithium transient simulation to variations in the storage cross-sectional area.
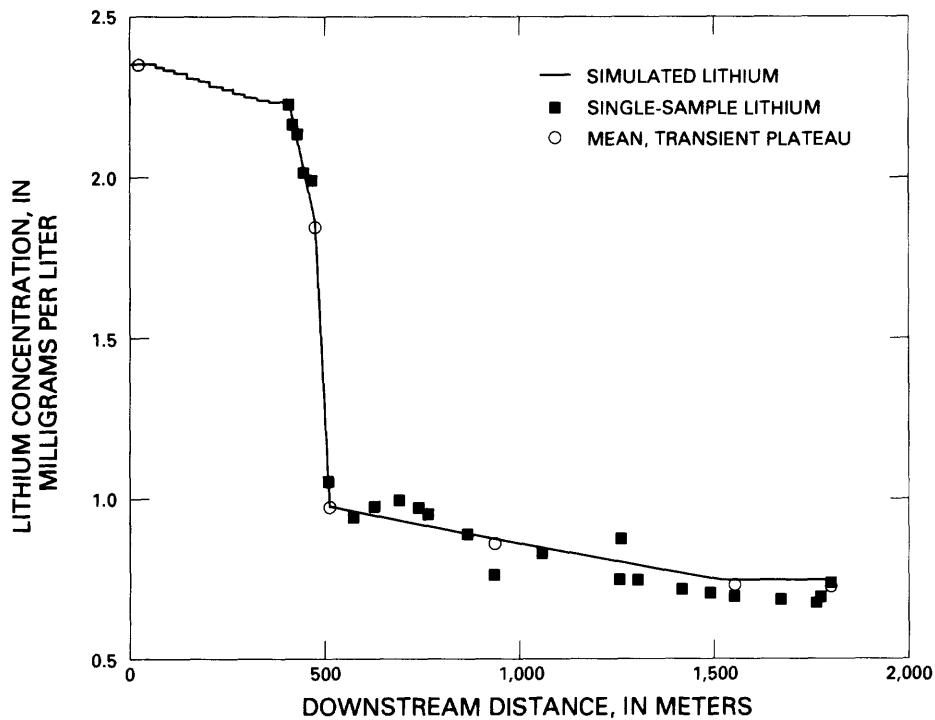

Figure 6.--Measured and simulated steady-state concentrations of lithium during the tracer-dilution experiment.

Chloride concentrations at the frequently sampled sites were simulated using the best-fit physical parameters from the lithium transient simulation (fig. 7). Agreement between measured and simulated chloride concentrations promoted confidence in the ability of the model to describe the physical, non-reactive behavior of multiple solutes in the stream.

Injection of conservative solutes in streams and subsequent observation of their behavior provide data by which baseline physical transport can be understood. This understanding then may serve as a foundation for addressing questions concerning the behavior and fate of chemically and biologically reactive solutes. Transient storage itself may influence nonconservative solute behavior. Where transient storage is significant, solutes experience longer residence times in streams. Longer residence times, particularly when they are associated with storage in zones providing intimate water-sediment contact, may provide greatly increased opportunity for reactions that are otherwise limited by kinetic restraints or by the availability of reactive surfaces.

SUMMARY

Tracer-dilution experiments provided estimates of discharge and time of travel along several reaches of Saint Kevin Gulch, a stream affected by acid mine drainage in Lake County, Colorado. In addition, experiments and associated simulations characterized physical processes that affected the transport of conservative solutes in the stream. Downstream advective transport was accompanied by dilution from lateral inflow. Longitudinal dispersion had a limited effect on solute concentration. Measured profiles of tracer concentration versus time showed delayed development of plateau values and the persistence of concentrations above background levels for considerable periods after the bulk of the tracer had passed. These profiles were simulated by solutions to mass-balance equations depicting reversible transfer between the flowing stream water and immobile water in an adjacent storage zone. Agreement between measured and simulated values was sensitive to variations in transient-storage parameters. Transient-storage parameters varied among reaches and could not be predicted from simple hydraulic variables. Similar results for two conservative tracers (lithium and chloride) promoted confidence in the ability of the model to simulate the physical, non-reactive behavior of solutes in the stream.

Lithium chloride is an effective tracer in acidic mountain streams. However, where losing reaches are suspected, multiple injections of tracers or current meter measurements are required to define profiles of stream flow. At Saint Kevin Gulch, injection of a second tracer (sodium bromide) and a direct measurement of discharge indicated that flow decreased in or near the downstream reaches of the study area. These results illustrate the efficacy of multiple approaches to the determination of discharge in mountain streams.
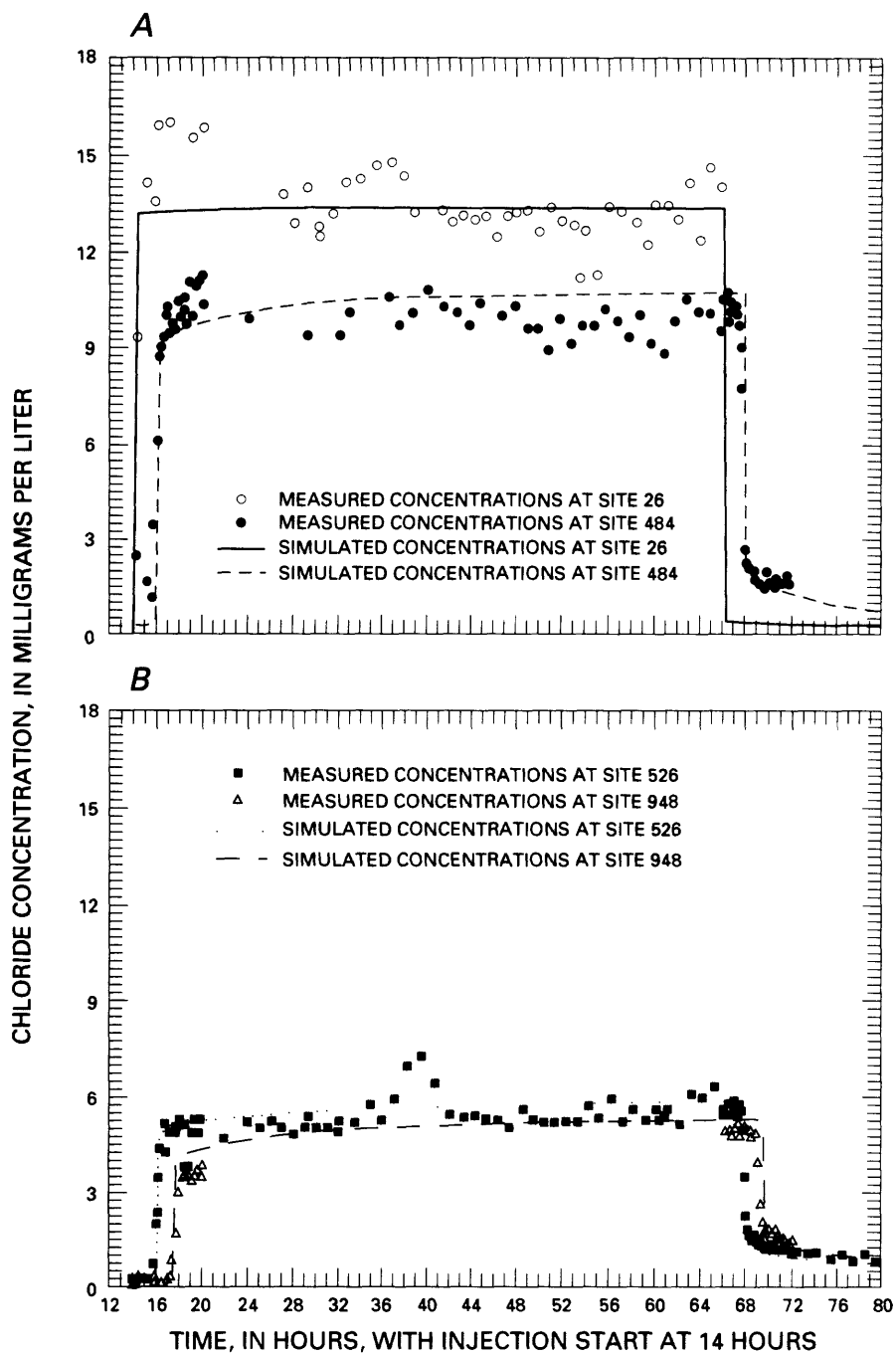
Figure 7.--Measured and simulated transient concentrations of chloride during the tracer-dilution experiment based on physical parameters from simulations of lithium concentrations.
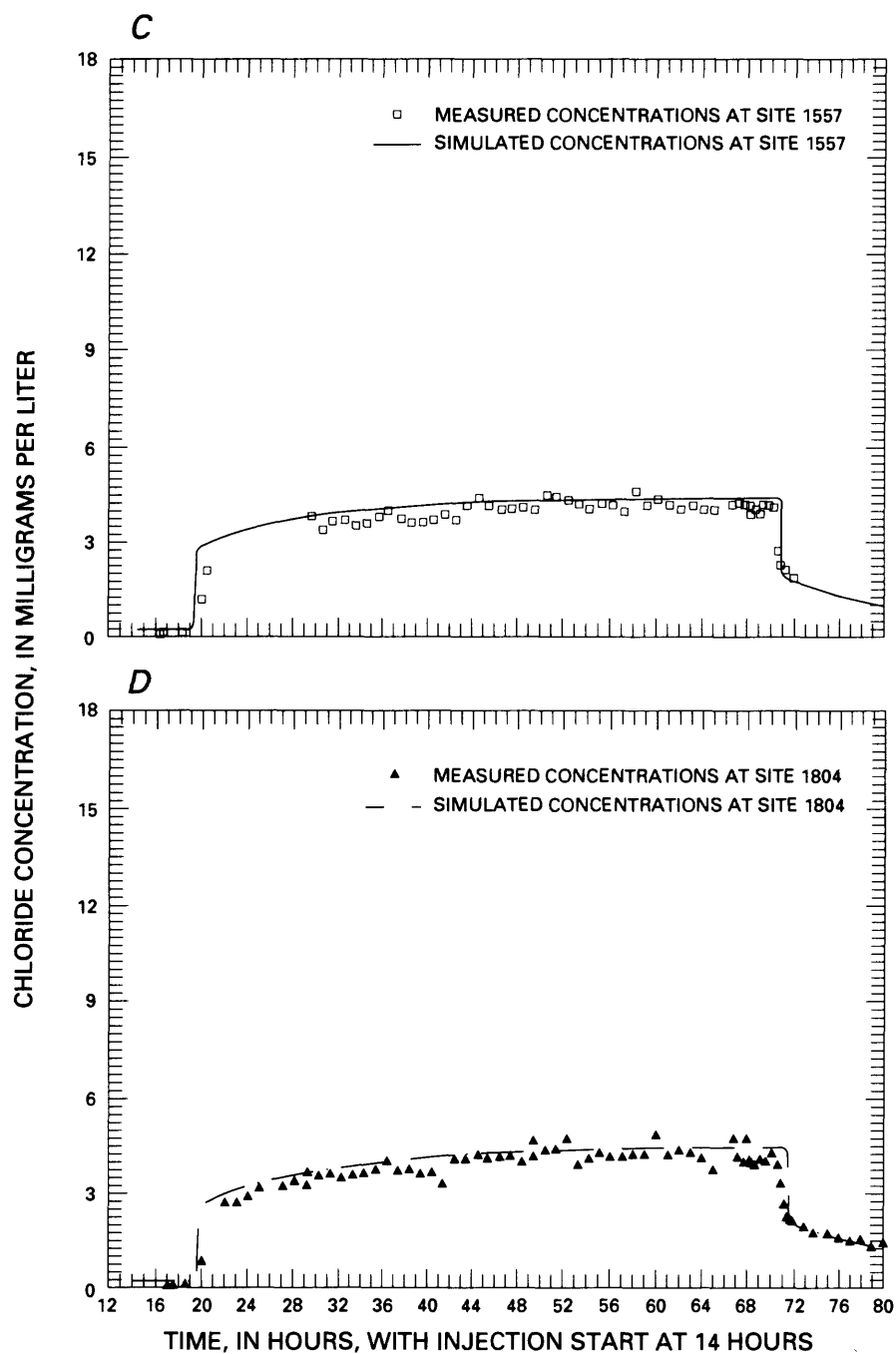
Figure 7.--Measured and simulated transient concentrations of chloride during the tracer-dilution experiment based on physical parameters from simulations of lithium concentrations.--Continued

REFERENCES

Bencala, K.E., 1984, Interactions of solutes and streambed sediment -- 2. A dynamic analysis of coupled hydrologic and chemical processes that determine solute transport: Water Resources Research, v. 20, no. 12, p. 1804-1814.

Bencala, K.E., McKnight, D.M., and Zellweger, G.W., 1990, Characterization of transport in an acidic and metal-rich mountain stream based on a lithium tracer injection and simulations of transient storage: Water Resources Research, v. 26, no. 5, p. 989-1000.

Bencala, K.E., McKnight, D.M., Zellweger, G.W., and Goad, Julie, 1986, The stability of rhodamine WT dye in trial studies of solute transport in an acidic and metal-rich stream: in Subitzky, Seymour, ed., Selected papers in the hydrologic sciences: U.S. Geological Survey Water-Supply Paper 2310, p. 87-95.

Bencala, K.E., Rathbun, R.E., Jackman, A.P., Kennedy, V.C., Zellweger, G.W., and Avanzino, R.J., 1983, Rhodamine WT dye losses in a mountain stream environment: Water Resources Bulletin, v. 19, no. 6, p. 943-950.

Bencala, K.E. and Walters, R.A., 1983, Simulation of solute transport in a mountain pool-and-riffle stream: A transient storage model: Water Resources Research, v. 19, no. 3, p. 718-724.

Benci, J.F. and McKee, T.B., 1977, Colorado monthly temperature and precipitation summary for period 1951-1970: Fort Collins, Colorado State University, 300 p.

Fishman, M.J. and Friedman, L.C., eds., 1985, Methods for the determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Open-File Report 85-495, 709 p.

Kimball, B.A., 1991, Physical, chemical, and biological processes in waters affected by acid mine drainage: From headwater streams to downstream reservoirs, in Mallard, G.E. and Aronson, D.A., eds., U.S. Geological Survey Toxic Substances Hydrology Program -- Proceedings of the technical meeting, Monterey, California, March 11-15, 1991: U.S. Geological Survey Water-Resources Investigations Report 91-4034, p. 365-370.

Kimball, B.A., Bencala, K.E., and McKnight, D.M., 1989, Research on metals in acid mine drainage in the Leadville, Colorado, area: in Mallard, G.E., ed., U.S. Geological Survey Toxic Substances Hydrology Program -- Proceedings of the technical meeting, Phoenix, Arizona, September 26-30, 1988: U.S. Geological Survey Water-Resources Investigations Report 88-4220, p. 65-70.

Marchand, J.P., Jarrett, R.D., and Jones, L.L., 1984, Velocity profile, water-surface slope, and bed-material size for selected streams in Colorado: U.S. Geological Survey Open-File Report 84-733, 82 p.

Smith, R.A. and Alexander, R.B., 1983, Evidence for acid-precipitation-induced trends in stream chemistry at hydrologic bench-mark stations: U.S. Geological Survey Circular 910, 12 p.

Stream Solute Workshop, 1990, Concepts and methods for assessing solute dynamics in stream ecosystems: Journal of the North American Benthological Society, v. 9, no. 2, p. 95-119.

Turk, J.T., and Spahr, N.E., 1991, Rocky Mountains, in Charles, D., ed., Acidic deposition in aquatic ecosystems -- Regional case studies: New York, Springer-Verlag, p. 471-502.

Zellweger, G.W., Avanzino, R.J., and Bencala, K.E., 1989, Comparison of tracer-dilution and current-meter discharge measurements in a small gravel-bed stream, Little Lost Man Creek, California: U.S. Geological Survey Water-Resources Investigations Report 89-4150, 20 p.