Application of Multiple Tracers to Characterize Complex Sediment and Pathogen Transport in Karst

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ABSTRACT

Injections of multiple tracers were conduced to characterize ground-water flow, sediment transport, and *E. coli* transport in a mantled-karst aquifer under variable flow conditions at the Savoy Experimental Watershed. Rhodamine WT and fluorescein, used as conservative tracers in this study, were injected two hours after the injection of lanthanum-labeled clay and europium-labeled *E.coli* into a losing-stream reach under a natural hydraulic gradient. The injection occurred on the recessional limb of a major storm pulse, and fate and transport of the tracers were observed for multiple tests under varying hydrologic conditions using multiple tracers for two springs of an underflow/overflow spring complex. The underflow spring, Langle, is located approximately 490 meters in a straight-line direction from the injection point, in a different surface-water catchment than the losing stream. The major overflow spring, Copperhead, is 453 meters in a straight-line from the injection point, and it lies in the same surface-water catchment as the losing stream. The altitude of the resurgence of Langle Spring is about 3 centimeters less than the resurgence of Copperhead Spring, based on multiple surveys using a total station.

Results from the tracer breakthrough for near steady-state conditions showed the arrival of suspended sediment and *E. coli* at 10.7- and 5.9 hours respectively before the conservative dye tracers at Langle Spring. The early arrival of sediment and *E. coli* is hypothesized to result from gravitational settling velocity coupled with the effect of pore-size exclusion. The conservative dye tracers arrived first at Copperhead Spring, followed by *E. coli* and sediment, essentially a reversal of the sequence at Langle Spring. During later storm-induced tracer tests, all tracers were observed to arrive simultaneously at each spring, with Copperhead Spring, along the shorter flow path, receiving the tracer pulses about an hour before Langle Spring. This and other tracer tests in this overflow/underflow system suggest that sediment and *E. coli* are stored in pools in the subsurface. These pools provide continuous full-conduit flow to Langle, the underflow spring, and only partially-full conduit flow to Copperhead, the overflow spring. However, during high flows associated with transient storm events, the tracers are flushed from ephemeral storage in the pools and move as a pulse associated with the rising limb of the hydrograph. The application of multiple tracers proved to be an invaluable tool in providing mechanisms to fully characterize the subsurface flow.

Estimating Ground-Water Age Distribution from CFC and Tritium Data in the Madison Aquifer, Black Hills, South Dakota

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Abstract

Ground-water age distribution was estimated for water collected from a well in the karstic Madison aquifer in the Black Hills of South Dakota using a ground-water mixing model for chlorofluorocarbon (CFC) and tritium data. Input functions for the model included precipitation concentrations for four tracers—CFC12, CFC11, CFC113 (6-month data), and tritium (yearly data). Madison aquifer water often is a complex mixture of waters of various ages; however, existing ground-water age-dating methods generally are not well suited for estimating the unique age distributions of ground water that can occur in karst aquifers. CFC data alone often can provide estimates of piston-flow ages or binary mixtures of young and old water, but generally are inadequate for estimating age distributions at a finer time discretization. However, if a time series of tritium data is incorporated into an age-dating model along with CFC data, an age distribution discretized to a 6-month time step can be estimated with statistical significance by assuming that ground-water age fits a probability density function (PDF). This method estimates one age distribution that satisfies all of the combined tracer data and thus has two advantages. The first of which is that the number of measured values applied to a single problem is maximized, which helps to constrain the solution, and second is that confidence in the solution is increased if a single solution satisfies more than one type of data. The PDF indicates the estimated fraction of water at a site for each 6-month age category. Because results from multiple age-dating tracers should agree, and because together they may provide complimentary information, combining all of the data into one model can be a powerful method for describing the history of recharge to a well or spring.

The best fit of CFC and tritium data for samples from a municipal water supply well open to the Madison aquifer was a bimodal age distribution, which was a composite of a uniform and a lognormal PDF. Data used in the model included the concentrations for each of the 3 CFCs (1 sample) and a time series of tritium concentrations (4 samples over 10 years). These samples provided a total of 7 tracer concentrations, which were compared to the corresponding modeled values. Parameter optimization methods, which minimize the residuals of measured and modeled values, were used to estimate the 4 parameters that describe the bimodal age distribution. Because there were 7 measured tracer concentrations and only 4 parameters to be estimated, the solution was adequately constrained, and the parameters could be estimated with reasonable confidence. Results indicated that about 33 percent of the mixture was less than 2 years old (uniform PDF component), 5 percent was 10 to 30 years old (lognormal PDF component), and the remaining 62 percent was more than 50 years old. Because CFC and tritium concentrations in precipitation were very low before 1950, the age distribution of water more than about 50 years old could not be estimated. The bimodal age distribution was the only distribution tested that could explain the combined CFC and the tritium data with acceptable 95-percent confidence limits on the estimated parameter values.

A Multi-Tracer Approach for Evaluating the Transport of Whirling Disease to Mammoth Creek Fish Hatchery Springs, Southwestern Utah

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ABSTRACT

The Utah Division of Wildlife Resources has been concerned about the vulnerability of selected spring-fed fish hatcheries to whirling disease caused by the microscopic parasite *Myxobolus cerebralis*. Whirling disease is typically transmitted from one water body to another by birds or fishermen but can potentially migrate along underground flow paths in areas where aquifer permeability is high and ground-water movement is rapid enough to allow passage and survival of the parasite. Mammoth Creek Fish Hatchery in southwestern Utah tested positive for whirling disease in 2002. Because adjacent Mammoth Creek also tested positive, a study was begun to evaluate potential hydrologic connections between the creek, an irrigation canal off the creek, and the hatchery springs.

Dye-tracer studies indicate that water lost through the channel of Mammoth Creek discharges from the west and east hatchery springs. Ground-water time of travel to the springs was about 7.5 hours, well within the 2-week timeframe of viability of the parasite. Results of studies using soil bacteria and club moss spores as surrogate particle tracers indicate that the potential for transport of the parasite through the fractured basalt may be low. Bacteria concentrations in spring water generally were below reporting limits, and club moss spores were recovered from only a few samples. However, peak concentrations for the bacteria and club moss spores in water from the east hatchery spring coincided with peak dye recovery. No particle tracers were recovered from the west hatchery spring.

INTRODUCTION

The Utah Division of Wildlife Resources operates 10 fish hatcheries in Utah that use water from large springs and has been concerned about the vulnerability of these hatcheries to whirling disease caused by the microscopic parasite *Myxobolus cerebralis.* Whirling disease is typically transmitted from one water body to another by birds or fishermen. However, the triactinomyxon spores (TAMs) produced by the parasite can potentially migrate along underground flow paths in areas where aquifer permeability is high, such as in karst and volcanic terrains, and the movement of ground water is sufficiently rapid to allow viable passage of the spores.

In 2000, whirling disease was detected in the Midway Fish Hatchery, about 30 miles (mi) southeast of Salt Lake City. Results of investigations by Carreon-Diazconti and others (2003) showed that the likely source of the parasite in the spring water supplying the hatchery was the Provo River. Water diverted from the river, which also tested positive for the disease, was used to irrigate farmland upgradient from the hatchery and subsequently moved downward into the karst (travertine) aquifer supplying the springs. Use of cultured soil bacteria as a surrogate tracer for the parasite showed that transport of the spore to the springs through open conduits and fractures in the limestone was possible (Stephen Nelson and Alan Mayo, Brigham Young University, written commun., 2000).

In 2002, Mammoth Creek Fish Hatchery in southwestern Utah became the second State- operated facility to become infected by whirling disease. Because adjacent Mammoth Creek also tested positive, the U.S. Geological Survey, in cooperation with the Utah Division of Wildlife Resources, began a study to evaluate potential hydrologic connections and determine ground-water travel times between the creek, an irrigation canal off the creek, and the hatchery springs, and to assess the potential for transport of the parasite along underground flow paths to the springs. This paper summarizes the results of tracer studies.

DESCRIPTION OF STUDY AREA

Mammoth Creek State Fish Hatchery is located about 2 mi southwest of Hatch, Utah, at the mouth of Mammoth Creek Valley, at an altitude of 7,000 feet (ft) (fig. 1). The hatchery is situated at the base of a 40-ft-high basalt cliff, from which two major (west and east) springs discharge. Total discharge of the springs averages about 3 cubic feet per second (ft^3/sec), with a variability of less than 1 ft^3/sec. Flow from the springs is diverted through the hatchery for fish-rearing operations and is then discharged into Mammoth Creek, which flows past the hatchery. McCormick spring also discharges from near the base of the basalt cliff about 750 ft northeast of the hatchery springs, on private land (fig. 1). Discharge of this spring was about 50 gallons per minute (gpm) during the study and appeared to be fairly constant. Bonanza spring emerges from talus alongside the channel of Mammoth Creek about 1,200 ft upstream from the hatchery (fig. 1) and discharged about 40 gpm. Discharge of this spring was observed to vary with changes in streamflow in Mammoth Creek.

During the summer, water is diverted from Mammoth Creek into a canal about 2 mi west of the hatchery (fig. 1) for irrigation in the lower part of the valley. During the study, all water from the creek was diverted into the canal and only a small amount of inflow from springs was observed downstream in the channel, which subsequently was lost through the streambed (fig. 2).

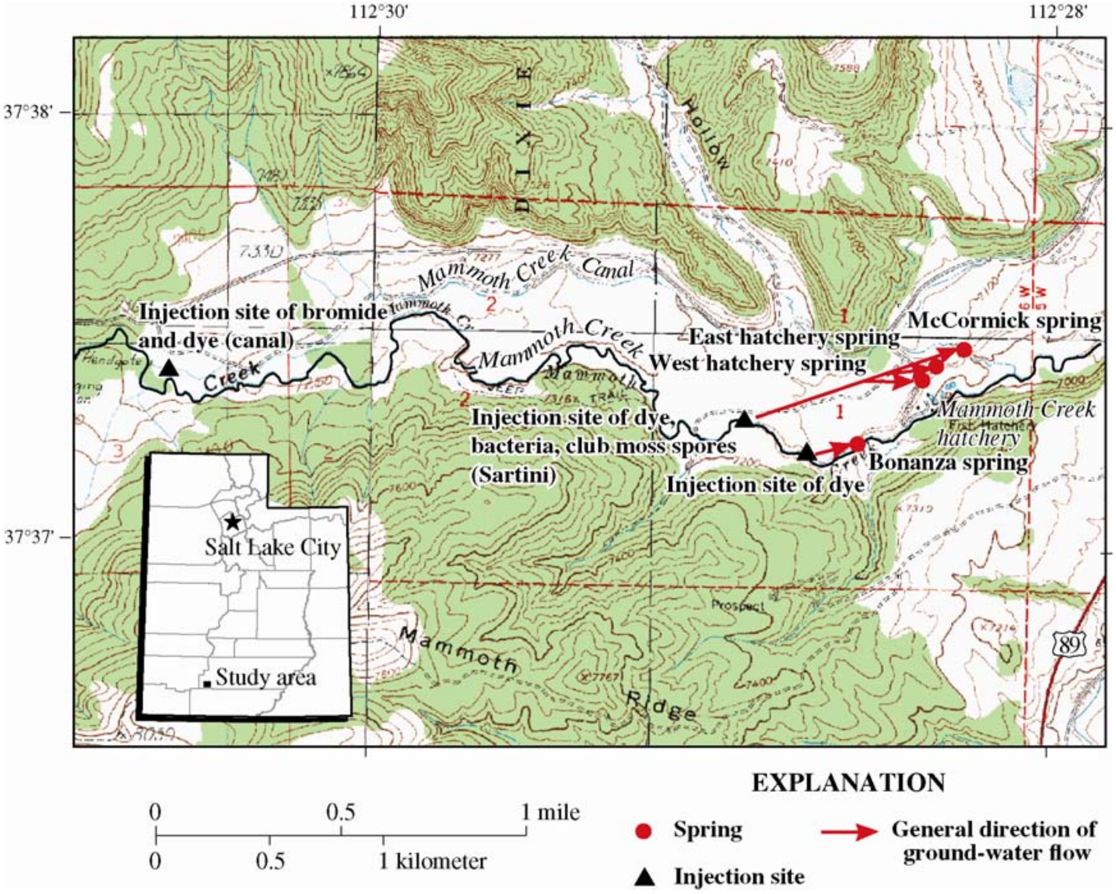

Figure 1. Location of injection sites and springs and general directions of ground-water movement in the Mammoth Creek study area, southwestern Utah.

Quaternary-age basaltic lava partly fills Mammoth Creek Valley and caps adjacent ridges. In the vicinity of the hatchery, the basalt has been entrenched by Mammoth Creek to a depth of as much as 40 ft (fig. 2). Vertical and horizontal fracturing is pervasive throughout the basalt. Limestones, marls, and calcareous shales of the Tertiary-age Claron Formation underlie the basalt and adjacent hillsides and are locally cavernous.

METHODOLOGY

Major-ion chemistry, tritium age-dating, streamflow measurements, spring discharge variability, and tracer studies were used to determine hydrologic relations in the Mammoth Creek hatchery area. Fluorescent dyes (sodium fluorescein and rhodamine WT) and sodium bromide were used to establish ground-water connections between Mammoth Creek, an irrigation canal off the creek, and the springs at, and in the vicinity of, the fish hatchery. Automatic samplers collected water directly from the springs for analysis. Dye samples were analyzed by filter fluorometry (Wilson and others, 1986). Sodium bromide samples were analyzed by ion chromatography (Fishman and Friedman, 1989). Non-pathogenic cultured soil bacteria *(Acidovorax)* and club moss *(Lycopodium)* spores were used as surrogate particle tracers to simulate the size (10 to 100 microns) and transport characteristics of the whirling disease parasite through the fractured basalt aquifer. Bacteria samples were collected manually in centrifuge vials, magnetically tagged, and analyzed by ferrographic techniques (Johnson and McIntosh, 2003). Club moss spores were collected in plankton nets (fig. 3), isolated by filtration, and analyzed by standard microscopic techniques (Gardner and Gray, 1976).

RESULTS AND DISCUSSION

On the basis of dye-tracer tests completed in October 2002 and October 2003 (table 1), water lost through the channel of Mammoth Creek about 3,000 ft southwest of the hatchery (at Sartini) discharges from the west and east hatchery springs and from McCormick spring (fig. 1). However, water lost through the channel farther downstream appears

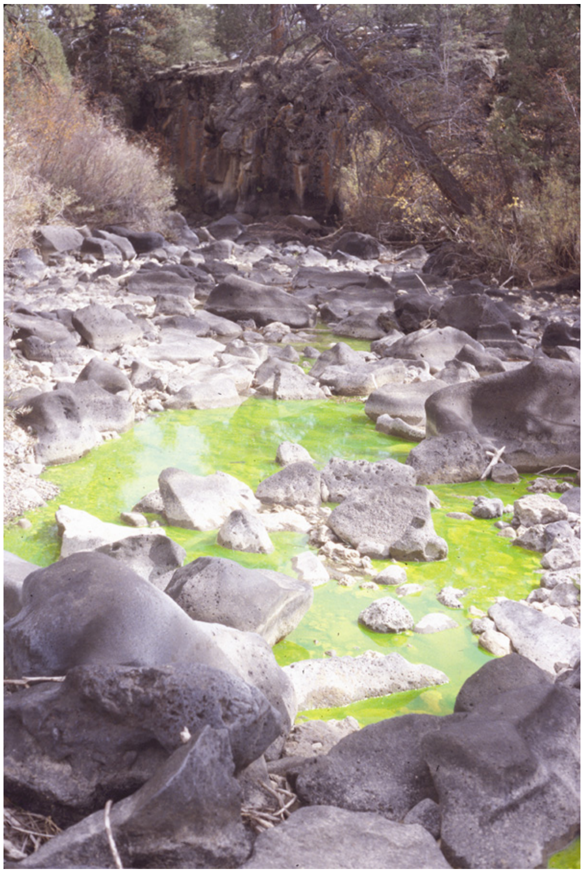

Figure 2. Mammoth Creek channel at the Sartini tracer-injection site, looking downstream. Surface water seeps into the streambed and appears to move along fractures within the basalt to the springs.

Figure 3. Plankton nets were used to collect club moss spores from the west and east hatchery springs. Spores were used as surrogate tracers (33 microns) for the whirling disease parasite.

Table 1. Summary of tracer injections in the Mammoth Creek study area, southwestern Utah.

[g, grams; kg, kilograms; —, no data]

Tracer-injection site	Date-time of tracer injection	Type of tracer	Amount of tracer	Tracer-recovery site	Date-time of tracer recovery (first arrival)	Travel time to first arrival (hours)	Linear distance (feet)
Mammoth Creek	10/02/02 1300	Rhodamine WT dye	1 liter	Bonanza spring	10/02/02 2015	[1]7.25	750
Mammoth Creek at Sartini	10/12/02 1300	Fluorescein dye	454 g	Hatchery springs (combined)	10/12/02 2300	10	2,800
				McCormick spring	10/13/02 1100	[2]22	3,300
Mammoth Creek at Sartini	10/09/03 1630	Rhodamine WT dye	1 liter	West hatchery spring	10/10/03 0000	7.5	2,800
				East hatchery spring	10/10/03 0100	8.5	3,000
				McCormick spring	10/10/03 1045	[3]18.25	3,300
	10/09/03 1615	Bacteria (OY-107 strain)	10^{14} cells	East hatchery spring	10/10/03 0700	[4]14.75	3,000
	10/09/03 1645	Club moss spores	1 kg	East hatchery spring	10/10/03 1205	[5]19.25	3,000
Mammoth Creek canal	10/10/02 1340	Sodium bromide	25 kg	No recovery	— —	—	—
	10/11/02 1720	Sodium bromide	25 kg	No recovery	— —	—	—
Mammoth Creek canal	07/31/03 2200	Fluorescein dye	1.36 kg	McCormick spring	08/19/03 1700	[6]451	(7)—

[1] Samples collected downstream of spring; maximum travel time.

[2] Samples collected daily; maximum travel time.

[3] Samples collected twice daily; maximum travel time.

[4] Recovered near peak dye concentration; maximum travel time.

[5] Represents composite sample over previous 13.5 hours.

[6] Dye recovered on activated charcoal; maximum travel time.

[7] Exact location of loss zone along canal unknown.

to discharge only from Bonanza spring. Ground-water travel time (first arrival) from Mammoth Creek (at Sartini) to the west hatchery spring was about 7.5 hours with a lag of about 1 hour between the west and east springs (fig. 4). Time to peak dye concentration (about 7 parts per billion) occurred about 8 hours after first arrival. Total dye-mass recovery for both springs was about 22 percent of that injected.

Ground-water movement from Mammoth Creek to the hatchery springs appears to be along flow path(s) that are separate from those to Bonanza spring and are probably related to fracturing within the basalt. However, because water from the hatchery springs and McCormick spring discharges from multiple outlets along the same horizon, flow appears to be, at least in part, along lateral zones of high permeability within the basalt. These zones could include horizontal fractures, interflow horizons between successive lava flows, or possibly the contact between the base of the basalt and the original valley floor.

Although pathways of rapid ground-water flow exist between the losing reach along Mammoth Creek and the hatchery springs, low variability in spring flow indicates that this is probably a small component of total discharge and that average ground-water travel time within the aquifer is likely to be considerably longer. The concentration of tritium (15.4 picocuries per liter) in water from the west hatchery spring indicates, however, a substantial component of modern (post-1960s) water.

Results of dye-tracer studies indicate that ground-water time of travel between Mammoth Creek and the west and east hatchery springs is well within the 2-week timeframe of viability of the whirling disease parasite. However, results of studies using bacteria and club moss spores as surrogate tracers to simulate the size and movement of the parasite underground indicate that the potential for transport of the parasite through the fractured basalt aquifer from the creek may be low. Bacteria concentrations in water samples from the springs generally were below reporting limits (less than 10 cells per milliliter), and club moss spores were recovered from only a few samples. Substantial losses of the particle tracers probably occurred during infiltration through the streambed sediments and during transport within the aquifer.

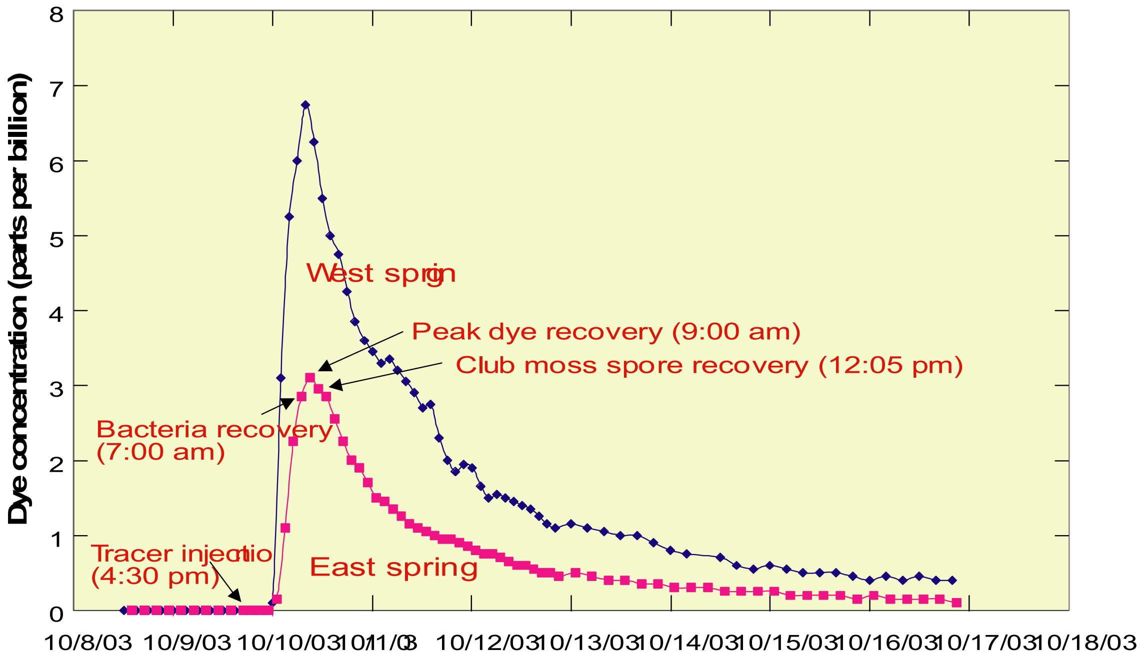

Figure 4. Rhodamine WT dye-recovery curves, and bacteria and club moss spore peak recoveries for the east hatchery spring. No particle tracers were recovered from the west hatchery spring.

Although the vast majority of particle tracers were not recovered, peak concentrations for the bacteria (about 10 cells per milliliter) and club moss spores (about 60 spores per milliliter) in water from the east hatchery spring coincided with peak dye recovery (fig. 4). No particle tracers were recovered from the west hatchery spring.

Streamflow measurements along the irrigation canal off Mammoth Creek showed substantial losses along selected reaches, particularly in the upper part of the canal (fig. 1). Measured streamflow losses along a 2-mi reach below the diversion were as much as 2 ft^3/sec, or about 22 percent of the flow. Bromide and dye tracers injected in the canal just below the diversion in October 2002 and July 2003, respectively, were not detected at the hatchery springs, but dye was detected at McCormick spring (table 1). Non-detection of the tracers at the hatchery springs probably resulted from dispersion and dilution within the matrix of the basalt aquifer, resulting in ground-water travel times greater than the 6-week monitoring period and (or) tracer concentrations below the detection limits. Although water lost along the upper reaches of the canal probably discharges at the hatchery springs, ground-water travel times likely exceed the timeframe of viability for transport of the parasite through the basalt.

SUMMARY

Dye-tracer studies at the Mammoth Creek Fish Hatchery indicate that water lost through the channel of Mammoth Creek discharges from the west and east hatchery springs. Ground-water time of travel to the springs was about 7.5 hours, well within the 2-week timeframe of viability of the whirling disease parasite. However, results of studies using soil bacteria (*Acidovorax*) and club moss (*Lycopodium*) spores as surrogate particle tracers for the parasite indicate that the potential for transport through the fractured basalt from the creek may be low. Substantial losses of the particle tracers occurred during streambed infiltration and aquifer transport. Bacteria concentrations generally were below reporting limits and club moss spores were recovered from only a few samples. However, peak concentrations for the bacteria and club moss spores in water from the east hatchery spring coincided with peak dye recovery. No particle tracers were recovered from the west hatchery spring. In addition, bromide and dye tracers injected in an irrigation canal were not detected at the hatchery springs.

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