Virus Fate and Transport During Recharge Using Recycled Water at a Research Field Site in the Montebello Forebay, Los Angeles County, California, 1997–2000

By Robert Anders, William A. Yanko, Roy A. Schroeder, and James L. Jackson

In cooperation with the
Water Replenishment District of Southern California and the
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	Area	
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot
square centimeter (cm^2)	0.1550	square inch
	Volume	
cubic centimeter (cm^3)	0.06102	cubic inch
cubic meter (m^3)	0.0008107	acre-foot
	Flow rate	
cubic meter per year (m^3/yr)	0.000811	acre-foot per year
meter per day (m/d)	3.281	foot per day
liter per second (L/s)	15.85	gallon per minute
	Mass	
kilogram (kg)	2.205	pound avoirdupois
	Pressure	
kilopascal (kPa)	0.1450	pound per square inch

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

$$°F=1.8\ °C+32.$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

VERTICAL DATUM

Sea level: In this report, "sea level" refers to the 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.

ABBREVIATIONS

Constituents or properties

α	collision efficiency, defined in equation 2
α_L	longitudinal dispersivity
A_s	Happel sphere-in-cell model correction factor, defined in equation 4
Br_0	initial bromide concentration
Br(t)	time-dependent bromide concentration
C_0	initial bacteriophage concentration
C(t)	time-dependent bacteriophage concentration

$CaCl_2$	calcium chloride
d_p	average grain diameter of the porous particle
d_v	diameter of virus
D	hydrodynamic dispersion coefficient
D_e	effective diffusion coefficient
ε	equal to $(1-\theta)^{1/3}$
η	single collector efficiency, defined in equation 3
GP	stainless steel implants
k_B	Boltzman's constant
λ	inactivation rate coefficient of bacteriophage
l_z	distance between injection and sampling locations
μ	viscosity of the liquid
MgCl	magnesium chloride
PR	PVC monitoring wells
PVC	polyvinyl chloride
q	specific discharge
θ	porosity of the porous medium
r^2	coefficient of determination
t	time
t_0	beginning times
t_f	ending times
TSA	trypticase soy agar
TSB	trypticase soy broth
T	solute temperature
U	average interstitial velocity
WP	steel well points

Other abbreviations

^oC	degrees Celsius
cfu	colony-forming units
cfu/gm	colony-forming units per gram
cfu/mL	colony-forming units per millilter
gm	gram
>	greater than
<	less than
L	liter
m	meter

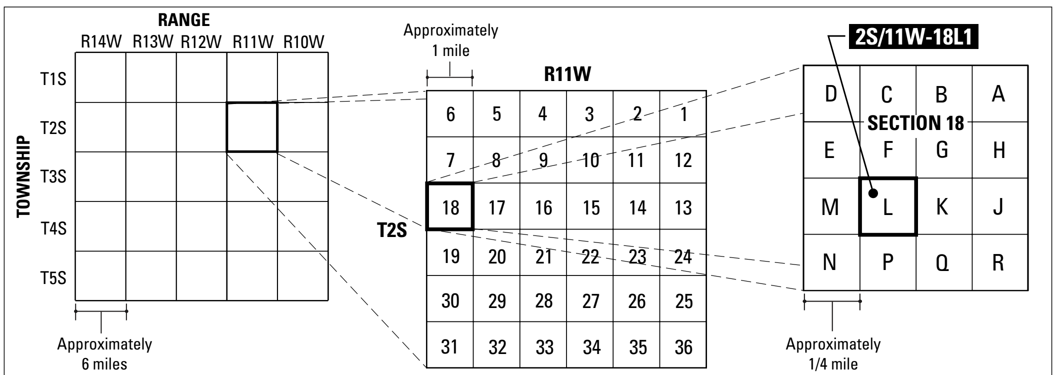
µL	microliter
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25 ^{o}C
mg/L	milligrams per liter
mL	milliliter
mM	millimole
MPN	most probable number
MPN/mL	most probable number per milliliter
PFU	plaque-forming units
PFU/mL	plaque-forming units per milliliter
pH	log hydrogen concentration
RB	relative breakthrough, defined in equation 1

Organizations

ATCC	American Type Culture Collection
CSDLAC	County Sanitation Districts of Los Angeles County
NWQL	U.S. Geological Survey National Water Quality Laboratory
USGS	U. S. Geological Survey

WELL-NUMBERING SYSTEM

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referenced to the San Bernardino base line and meridian (S) Well numbers consist of 15 characters and follow the format 002S011W018L001S. In this report, well numbers are abbreviated and written 2S/11W-18L1. Wells in the same township and range are referred to only by their section designation, -18L1. The following diagram shows how the number for well 2S/11W-18L1 is derived.



Well-numbering diagram

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Abstract

Total and fecal coliform bacteria distributions in subsurface water samples collected at a research field site in Los Angeles County were found to increase from nondetectable levels immediately before artificial recharge using tertiary-treated municipal wastewater (recycled water). The rapid increase indicates that bacteria can move through the soil with the percolating recycled water over intervals of a few days and vertical and horizontal distances of about 3 meters. This conclusion formed the basis for three field-scale experiments using bacterial viruses (bacteriophage) MS2 and PRD1 as surrogates for human enteric viruses and bromide as a conservative tracer to determine the fate and transport of viruses in recycled water during subsurface transport under actual recharge conditions. The research field site consists of a test basin constructed adjacent to a large recharge facility (spreading grounds) located in the Montebello Forebay of Los Angeles County, California. The soil beneath the test basin is predominantly medium to coarse, moderately sorted, grayish-brown sand.

The three tracer experiments were conducted during August 1997, August–September 1998, and August 2000. For each experiment, prepared solutions of bacteriophage and bromide were sprayed on the surface of the water in the test basin and injected, using peristaltic pumps, directly into the feed pipe delivering the recycled water to the test basin. Extensive data were obtained for water samples collected from the test basin itself and from depths of 0.3, 0.6, 1.0, 1.5, 3.0, and 7.6 meters below the bottom of the test basin.

The rate of bacteriophage inactivation in the recycled water, independent of any processes occurring in the subsurface, was determined from measurements on water samples from the test basin. Regression analysis of the ratios of bacteriophage to bromide was used to determine the attenuation rates for MS2 and PRD1, defined as the logarithmic reduction in the ratio during each experiment. Although the inactivation rates increased during the third tracer experiment, they were nearly two orders of magnitude less than the attenuation rates. Therefore, adsorption, not inactivation, is the predominant removal mechanism for viruses during artificial recharge.

Using the colloid-filtration model, the collision efficiency was determined for both bacteriophage during the second and third field-scale tracer experiments. The collision efficiency confirms that more favorable attachment conditions existed for PRD1, especially during the third tracer experiment. The different collision efficiencies between the second and third tracer experiments possibly were due to changing hydraulic conditions at the research field site during each experiment. The field data suggest that an optimal management scenario might exist to maximize the amount of recycled water that can be applied to the spreading grounds while still maintaining favorable attachment conditions for virus removal and thereby ensuring protection of the ground-water supply.

Introduction

Artificial Recharge Using Wastewater

The use of treated municipal wastewater effluent (recycled water) for artificial recharge of ground water is increasing, especially in the southwestern United States. In Los Angles County, for example, approximately 60 km^3 of recycled water is delivered annually to the Montebello Forebay in the northern part of the Central Ground-Water Basin. The recycled water, along with imported water and local runoff, is applied to two large spreading grounds and a portion of an unlined downstream river channel that have a total area of recharge of almost 3.5 km^2. The recharged water moves down and laterally from the area of the spreading grounds southwest in the direction of regional ground-water flow (Reichard and others, 2003). Aquifer material beneath the spreading grounds consists of alluvial deposits of nearly all sands and gravels, with some relatively fine-grained materials of possibly limited extent (Bookman-Edmonston Engineering Inc., 1994).

During the practice of artificial recharge using recycled water, the soil is considered the final step in a multi-barrier treatment system to protect public health (National Research Council, 1994). In California, the Department of Health Services governs the recharge of ground water with recycled water. Currently, draft regulations state that the applied recycled water used for a surface-spreading project shall be retained underground for a minimum of 6 months prior to extraction for use as a drinking water supply, and shall not be extracted within 500 feet (152 m) of the point of recharge (Hultquist and others, 1991; Asano and Cotruvo, 2004). These provisions are intended to protect ground-water resources by ensuring that adequate soil retention time requirements are met for pathogen removal.

Background

The major processes controlling the ability of viruses to travel long distances through the subsurface are their adsorption characteristics and their degree of inactivation (Gerba and Keswick, 1981). Inactivation of liquid-phase as well as sorbed or attached viruses is due to degradation of the viral capsid, and the most important factor controlling the degree of virus inactivation in the subsurface is temperature (Yates, 1987). The degree of virus attachment during subsurface transport is affected by several factors including viral surface properties, ground-water chemistry, and sediment-surface electrical charge (Gerba, 1984). Several investigators have described the physical and chemical factors that influence the adsorption process of viruses to a surface by the colloid-filtration model (Kinoshita and others, 1993; Penrod and others, 1996; Redman and others, 1997). The colloid-filtration model is commonly used to describe the removal of colloidal particles (such as viruses) during pack-bed filtration in water-treatment applications. The colloid-filtration model assumes that particle attachment is governed by their collision efficiency, which represents the ratio of the rate of collisions resulting in attachments to the total number of attachments (Yao and others, 1971; Rajagopalan and Tien, 1976). Several laboratory- or field-scale experiments have been conducted to investigate the magnitude of adsorption and inactivation of viruses under saturated conditions (Bales and others, 1997; Jin and others, 1997; Pieper and others, 1997; Deborde and others, 1999; Ryan and others, 1999; Schijven and others, 1999). The magnitude of adsorption of viruses also was investigated by fitting experimental breakthrough curves to different one-dimensional advection-dispersion models (Jin and others, 1997; Bales and others, 1997). Finally, analytical solutions also were developed for virus transport in one- and three-dimensional, saturated, homogeneous porous media, accounting for virus sorption and inactivation (Sim and Chrysikopoulos, 1996, 1998).

Although these approaches can provide partial understanding of virus transport in the subsurface, they have some important limitations (Yates, 1995). These limitations are due, in large part, to the high degree of uncertainty associated with site-specific information on the virus inactivation rate and adsorption to soil. This is because many of the factors controlling virus transport and inactivation are interrelated. Furthermore, during artificial recharge the subsurface beneath the spreading grounds can exhibit significant changes in water flux and hydraulic conductivities over time due to the presence of entrapped air, sealing of the soil surface, and the effect of biofilms sealing the pores within the wetted zones (Faybishenko, 1999)—conditions difficult to replicate in controlled laboratory experiments or to simulate in mathematical models. Therefore, field-scale experiments using surrogates for human viruses also are needed to more accurately determine the influence of distance and time on virus attenuation during subsurface transport under actual recharge conditions. Conducting such experiments may provide regulatory agencies with the information necessary to determine allowable limits on amounts of recycled water that can be used for replenishment purposes (artificial recharge) while ensuring that necessary retention times for pathogen removal are being met.

Prior Recharge Experiments

Three previous recharge experiments were conducted at the research field site to better understand the microbiological and chemical processes that contribute to the changes in the quality of the recycled water during artificial recharge occurring over intervals of several days and vertical and horizontal distances of about 10 m. The first experiment was conducted in August 1993; the second from April–June 1994; and the third in July 1995. Although the primary focus of analyses during the recharge experiments was on a broad suite of inorganic, isotopic, and organic constituents, some analyses also were done for microorganisms. These recharge experiments showed: (1) reduction of nitrogen was slightly greater than one-third, although actual removal rates can vary under different environmental and operational conditions; (2) reduction of organic carbon was about one-third regardless of pre-existing conditions at the research field site; and (3) the total and fecal coliform bacteria distributions in subsurface water samples from beneath the research field site increased from nondetectable levels immediately before recharge with recycled water. Complete results of the inorganic, isotopic, organic, and microbiological analyses from the three recharge experiments are presented in other reports (Anders, 1997; Anders and Schroeder, 1997; Barber and others, 1997; Schroeder and others, 1997; Leenheer and others, 2001; Schroeder and others, 2003; Anders and Schroeder, 2003).

Purpose and Scope

Evidence that bacteria can move through the soil along with the percolating recycled water during artificial recharge occurring over intervals of a few days and vertical and horizontal distances of about 3 m formed the basis for three tracer experiments. The tracer experiments were conducted to determine the fate and transport of viruses released into the environment during artificial recharge using recycled water. The purpose of this report is to present the results of these experiments.

The three field-scale tracer experiments were conducted during August 1997, August–September 1998, and August 2000. The specific goal of the first experiment was to establish the feasibility of conducting field-scale tracer experiments under actual artificial recharge conditions using recycled water seeded (augmented) with high concentrations of bacteriophage and bromide as tracers. On the basis of the results of the first tracer experiment, a second tracer experiment was designed to measure more precisely the fate and transport of surrogates for human viruses under actual recharge conditions. The third tracer experiment was done during the summer of 2000 to confirm the results obtained from the second tracer experiment.

Acknowledgments

Funds for this investigation were provided by the County Sanitation Districts of Los Angeles County (CSDLAC) and the Water Replenishment District of Southern California as part of the Soil Aquifer Treatment for Sustainable Water Reuse research program. The authors are grateful to the CSDLAC and U.S. Geological Survey (USGS) personnel for their assistance in conducting the experiments.

Description of Study Area

Research Field Site

The three tracer experiments were conducted at a research field site located at the north end of the San Gabriel River Coastal Basin Spreading Grounds in the Montebello Forebay, Los Angeles County (fig. 1). Tertiary-treated effluent from the San Jose Creek Water Reclamation Plant, which has undergone chlorination-dechlorination and either mono- (anthracite only) or dual-media (anthracite and sand) filtration, is delivered through a 2.4-m-diameter culvert to the spreading grounds. A portion of the flow can be diverted on demand to the research site through a 15.2-cm pipeline using a 1,100-m^3/d pump installed in the culvert. During construction of the research field site, overlying fine-grained soil was excavated from the desilting basin to expose a well-sorted sand and gravel unit about 3 m below the local land surface. The excavated silty soil was used to construct a berm around the test basin to isolate it from the desilting basin in the adjacent large spreading grounds. Construction exposed an effective percolation area of about 500 m^2 at a maximum operating water depth of about 2.4 m.

Instrumentation at the research field site includes two 5-cm-diameter PVC monitoring wells in the center of the test basin, two 5-cm-diameter PVC monitoring wells in the surrounding berm, and two 5-cm-diameter PVC monitoring wells outside the perimeter of the test basin (fig. 2). The monitoring wells within the test basin were installed at 15.2 m (PR8) and 7.6 m (PR9) below the floor of the test basin. The monitoring wells at the top of the 3-m berm separating the test basin from the desilting basin were installed at 18.3 m (PR10) and 10.7 m (PR11) below land surface. Two monitoring wells were installed 45.7 m to the north, upgradient from the test basin on the basis of the direction of regional ground-water flow, at 18.3 m (PR14) and 10.6 m (PR15) below land surface. All the monitoring wells at the research field site are screened upwards from the bottom for an interval of 1.5 m.

In addition to the six monitoring wells, numerous steel well points were installed as needed (fig. 2). The well points consist of a conical drive shoe at the bottom (0.15 m), 0.6-m screens, and galvanized-steel pipe extending from the depth of installation to a height sufficient to provide access during recharge experiments. Two well points located within the center of the test basin were installed at depths of about 2.1 and 3.6 m (WP1 and WP2, respectively); three well points located 15.2 m south of the test basin, in the downgradient direction of regional ground-water flow, were installed at depths of about 2.1, 3.6, and 5.7 m below land surface (WP8, WP7, and WP6, respectively); and three more well points located 45.7 m south of the test basin, in the downgradient direction of regional ground-water flow, were installed at depths of about 2.1, 3.5, and 6.3 m below land surface (WP3, WP4, and WP5, respectively). The six PVC monitoring wells and eight steel well points were hydraulically developed by air-surging.

Other instruments installed at the research field site to collect water samples during the tracer experiments consist of 15.2-cm stainless steel implants (GP1–GP5)(Geoprobe Systems, Salina, Kansas). These instruments were installed at about 0.3-m intervals to a depth of 1.5 m below the floor of the test basin (GP1 through GP5, respectively; fig. 2).

Schroeder and others (2003) provide additional details of the instrumentation at the research field site.

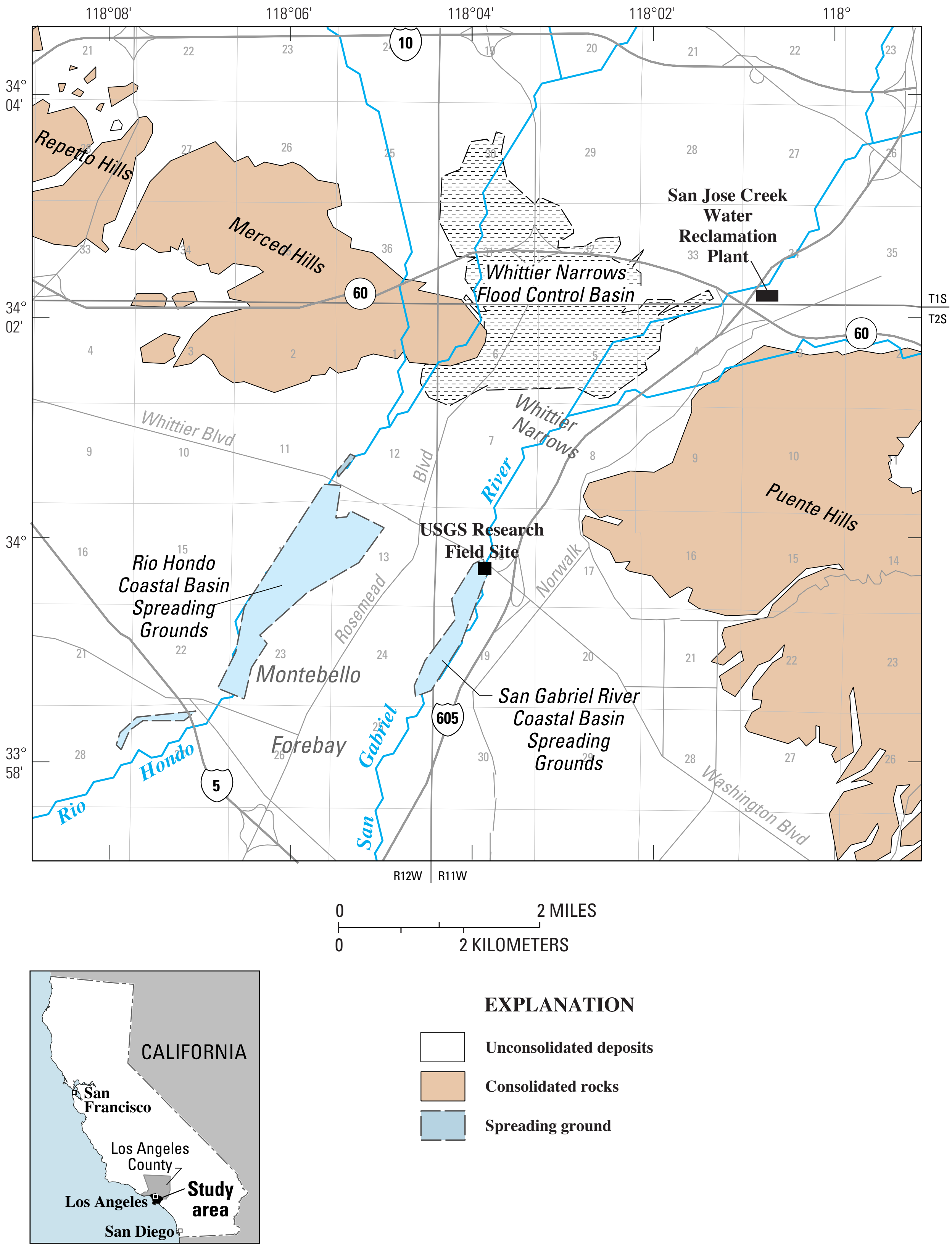

Figure 1. Location of the research field site in the Montebello Forebay, Los Angeles County, California.

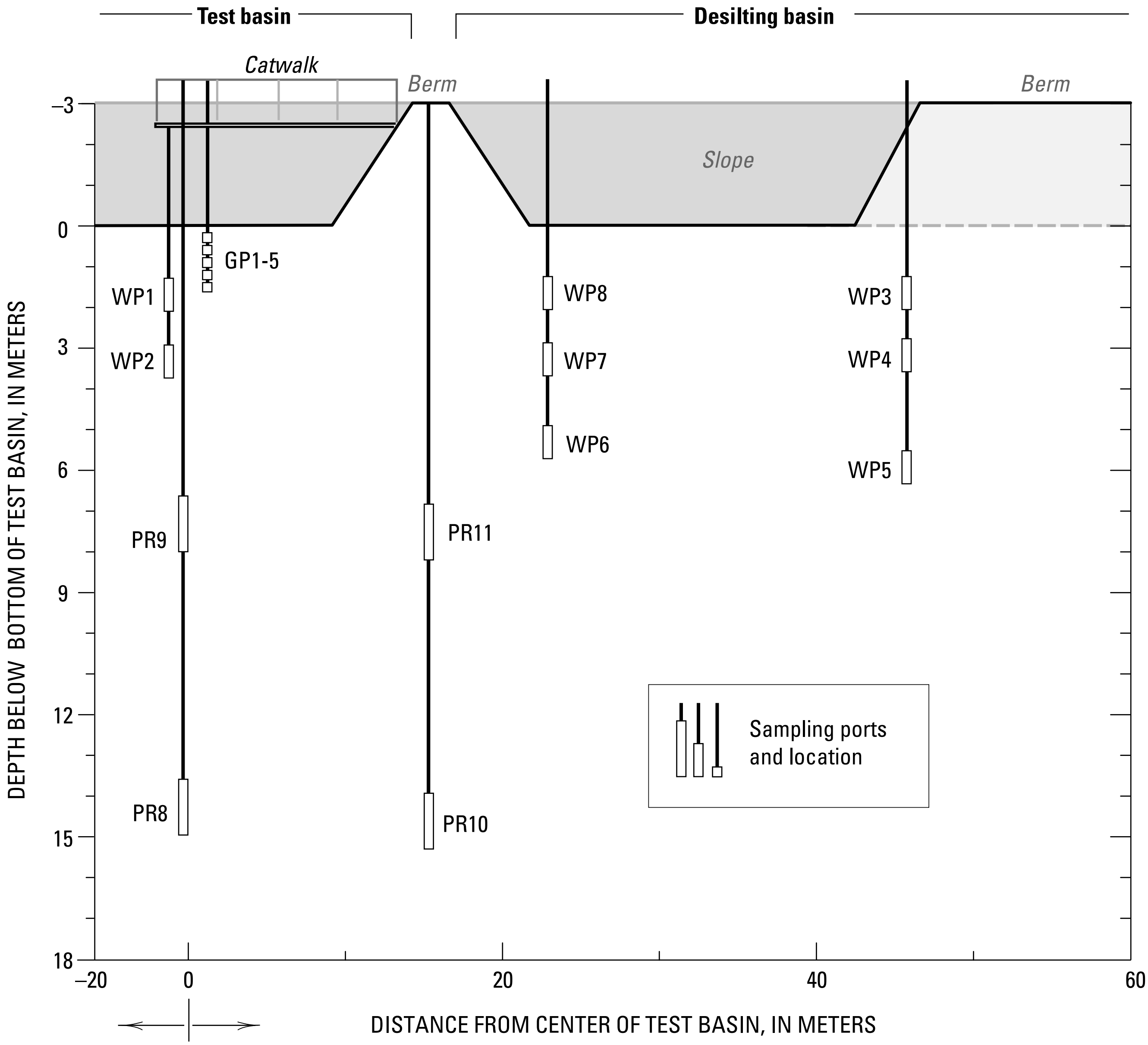

Figure 2. Research field site with the PVC monitoring wells (PR8–PR11; PR14 and PR15, located 45.7 m north of the test basin, in the upgradient direction of ground-water flow, not shown), steel well points (WP1–WP8), and stainless-steel implants (GP1–GP5). Catwalk provides access to instrumentation during experiments; depth given in meters below the floor of the test basin. Direction of regional ground-water flow beneath the test basin is from left to right (Reichard and others, 2003).

Site Characterization

Core material was collected during the construction of the test basin at the research field site by driving a flame-sterilized, split-spoon core barrel through the bottom of the hole produced by hollow-stem augering. The core material was recovered at approximately 0.3-m intervals to a depth of about 10.6 m below the floor of the test basin. A lithology log compiled from visual inspection indicates that soil beneath the test basin is fine to coarse, moderately sorted, grayish-brown sand. Measured grain-size distributions beneath the test basin confirmed predominantly medium (0.25 mm–0.50 mm) to coarse (0.50 m –1.00 mm) sand (fig. 3). Both the descriptive lithology and the measured grain-size distribution show the existence of a thin clay lens beginning about 9.4 m beneath the test basin. The lens may thin southward, or be of variable thickness, even over short distances at the research field site. Below the clay lens is a lower sand unit, which extends below the total depth of drilling (15.2 m) at the research site.

Vertical hydraulic conductivities of core sections collected after the second recharge experiment ranged from 0.25 to 26.7 m/d (Anders, 1997). The low value, found nearest the floor of the test basin, reflects accumulation of a thin layer of fine-grained, organic-rich sediment on the site floor. Although thin, and probably of variable thickness, this material exerts a strong influence on the rate at which percolation occurs during artificial recharge experiments. Higher values of hydraulic conductivity in the percolation zone beneath the test basin are likely to more closely approximate conditions in shallow parts of the subsurface beneath the research field site. Horizontal hydraulic conductivity of the subsurface beneath the research field site, determined from slug tests and analyzed using the computer program AQTESOLV with the Bouwer-Rice straight-line solution for an unconfined aquifer (Geraghty and Miller, Inc., Reston, Virginia), yielded values between 25.9 m/d and 38.1 m/d.

Microbiological Changes During Recharge

Portions of the core material collected during the construction of the test basin at the research field site were placed in sterile polyethylene “Whirl-Pak” bags and stored at 4^{o}C until analyzed in the laboratory. The core samples were analyzed for fecal coliform bacteria by the membrane filter procedure and for nitrifying (ammonia- and nitrite-oxidizing), nitrate-reducing and denitrifying bacteria by the most probable number (MPN) method as described by Britton and Gresson (1987).

Table 1 shows the distribution of selected bacteria in the core samples collected from beneath the test basin during construction. No fecal coliform bacteria were detected in the soil column. The ammonia-oxidizing bacteria were more abundant at shallower than at greater depths, and nitrite-oxidizing bacteria were detected in about one-half the core samples. The nitrate-reducing and denitrifying bacteria were abundant throughout the soil column and their densities varied by as much as five orders of magnitude.

Water samples collected during the second recharge experiment, which was conducted from April–June 1994, were analyzed for total and fecal coliform bacteria and for nitrifying, nitrate-reducing and denitrifying bacteria. The water samples were placed in sterile 250-mL bottles and sodium thiosulfate ($Na_2S_2O_3$) was added to remove subsequent influence from chlorine during storage. The membrane filter procedure, as described by the American Public Health Association (1985), was used for the enumeration of total and fecal coliform bacteria. The nitrate-reducing and denitrifying bacteria were enumerated using a modified MPN method with six five-tube decimal (10X) dilutions (Britton and Gresson, 1987). The procedure to enumerate the nitrifying bacteria was further modified to include three five-tube 10X dilutions.

Table 2 shows the distribution of selected bacteria in water samples collected as part of the second recharge experiment (April to June 1994): immediately before recharge, 2 days after the second recharge experiment began, and more than 1 month after recharge was discontinued. The densities of total coliform bacteria increased by two orders of magnitude during the first 48 hours after the recharge experiment began, from none detected to greater than 300 colony-forming units per 100 mL (cfu/100 mL). After recharge was discontinued, the densities of total coliform bacteria returned to nondetectable levels. The data in table 2 also shows the buildup of fecal coliform soon after recharge began, and then a return to nondetectable levels after recharge was discontinued. This rapid increase in both total and fecal coliform bacteria from nondetectable levels in the soil column and water samples prior to artificial recharge using recycled water indicates direct physical transport with the percolating recycled water, rather than simple regrowth of preexisting bacteria.

Nitrifying (ammonia- and nitrite-oxidizing) bacteria were detected in most water samples before, during, and after recharge. Densities increased at depths greater than 3 m, but increased only slightly at shallower depths, soon after recharge. Nitrate-reducing and denitrifying bacteria were found to be abundant in the recycled water itself, increased about an order of magnitude as the recycled water accumulated in the test basin itself, and then decreased by one-to-two orders of magnitude in the percolating water collected from beneath the test basin. The decrease could be the result of removal by soil or of die-off. Because nitrate-reducing and denitrifying bacteria appear to be abundant naturally in the soil as well as in the recycled water, evidence for their transport during recharge is inconclusive.

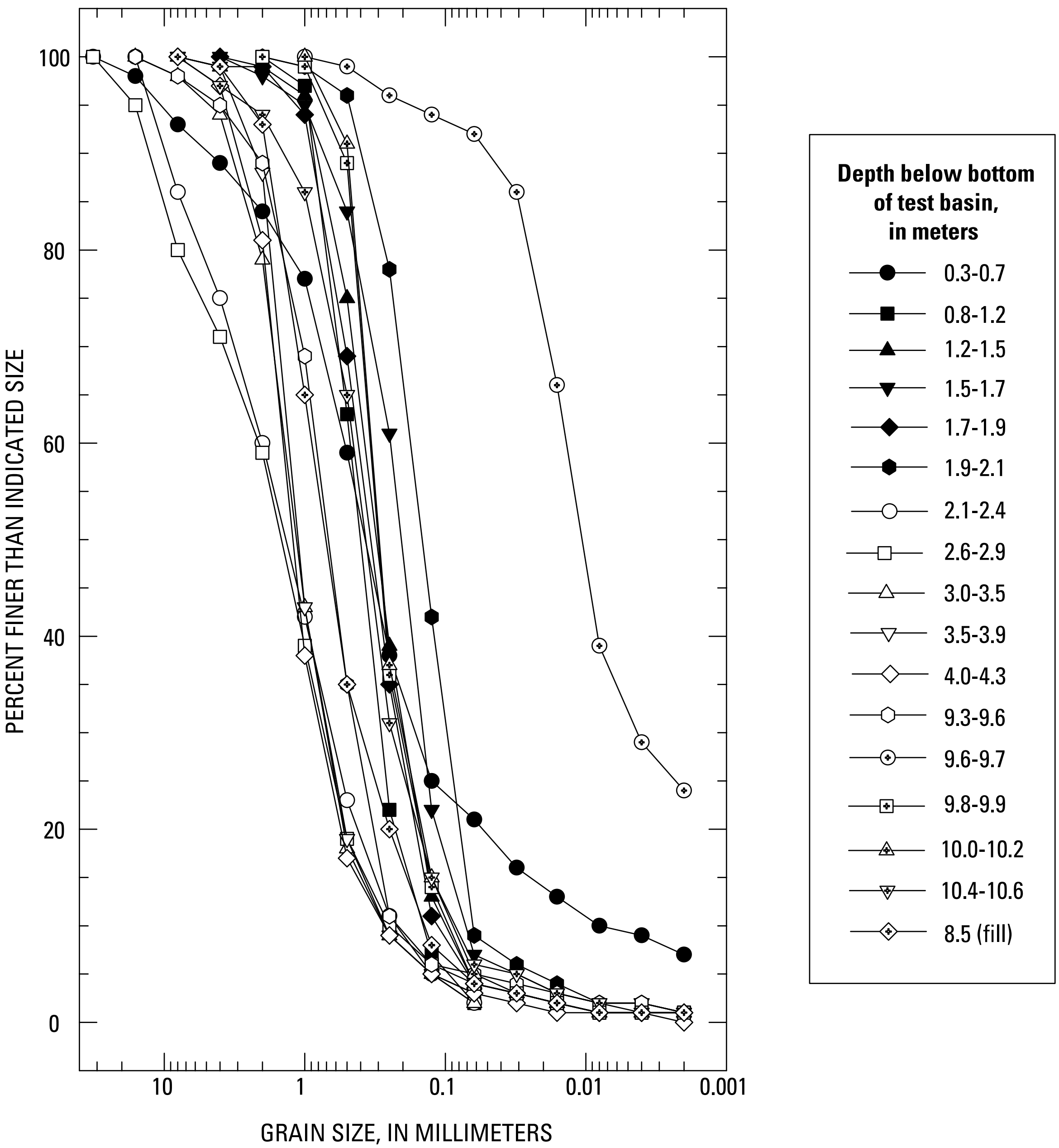

Figure 3. Grain-size distribution for core material from selected depths beneath the research field site, Los Angeles County, California.

Table 1. Distribution of selected bacteria in core samples collected during construction of the research field site, Los Angeles County, California

[Depth, in meters beneath the bottom of the test basin; m, meter; cfu/gm, colony-forming units per gram; MPN/gm, most probable number per gram; <, less than indicated value]

Depth (m)		Fecal coliform (cfu/gm wet soil)	Ammonia-oxidizing (MPN/gm wet soil)	Nitrite-oxidizing (MPN/gm wet soil)	Nitrate-reducing/denitrifying (MPN/gm wet soil)
From	To				
0.84	1.19	0	930	230	93,000
1.22	1.47	0	2,300	2,300	210,000
1.47	1.78	0	230	<30	4,300
1.78	1.88	0	390	230	93,000
1.88	2.13	0	230	<30	9,300
2.13	2.44	0	230	<30	240,000
2.59	2.95	0	430	150	23,000
3.05	3.51	0	230	430	240,000
3.51	3.94	0	230	230	1,100,000
3.96	4.32	0	230	40	240,000
9.30	9.58	0	230	90	460,000
9.58	9.75	0	<30	<30	90
9.75	9.80	0	<30	<30	9,300
9.80	9.83	0	<30	<30	15,000
9.83	9.98	0	<30	<30	43,000
10.06	10.21	0	<30	<30	460,000
10.46	10.59	0	<30	<30	460,000

Table 2. Distribution of selected bacteria in water samples collected during the second recharge experiment: immediately before recharge, 2 days after recharge began, and more than 1 month after recharge was discontinued

[Depth, in meters beneath the bottom of test basin; m, meter; cfu, colony-forming units; MPN, most probable number; mL, milliliter; total coliform data given left of slash, fecal coliform data given right of slash; >, greater than indicated value; —, no data]

Depth (m)	Total coliform/Fecal coliform (cfu/100mL)			Ammonia-oxidizing (MPN/mL)			Nitrite-oxidizing (MPN/mL)			Nitrate-reducing/denitrifying (MPN/mL)		
	Apr. 4	Apr. 6	Jun. 1	Apr. 4	Apr. 6	Jun. 1	Apr. 4	Apr.6	Jun. 1	Apr. 4	Apr. 6	Jun. 1
1.2	0/0	10/2	0/0	330	490	0	700	80	790	1,700	1,400	790
1.5	0/0	18/2	0/0	490	790	40	80	330	170	790	2,700	790
1.8	0/0	11/2	0/0	790	330	20	230	230	230	1,400	49,000	230
2.1	0/0	8/2	0/0	1,300	2,400	80	1,700	230	230	1,100	1,100	330
2.4	0/0	28/1	0/0	1,300	1,300	50	490	230	230	460	1,700	70
2.7	0/0	>300/18	0/0	0	490	0	20	140	50	130	33,000	700
3.0	0/0	19/6	0/0	0	490	0	20	80	80	4,900	2,400	340
7.6	0/0	9/0	0/0	0	0	230	0	20	230	4,900	700	1,700
Pond	—/—	>300/16	—/—	—	24,000	—	—	490	—	—	24,000	—
Effluent	—/—	>300/—	—/—	—	2,400	—	—	1,300	—	—	23,000	—

Methods and Materials

Field Preparation

Before each tracer experiment was initiated, the soil surface of the test basin was disked to break up any hardpan that might have remained from previous spreading operations at the research field site. Throughout each experiment, measurements of temperature, pH, specific conductance, dissolved oxygen, dissolved organic carbon, and redox sensitive species such as nitrogen, iron, and manganese were obtained in order to determine the water quality in the test basin itself and in the subsurface beneath the research field site.

All monitoring wells and steel well points were purged prior to the collection of water samples by removing three casing volumes using a submersible SP-300R sampling pump system (Fultz Pumps, Inc., Lewistown, Pennsylvania) until specific conductance, pH, and temperature measurements had stabilized. PFE-Teflon tubing (0.6-cm) was inserted into the casing and attached to peristaltic tubing to allow for continuous sampling throughout each experiment using peristaltic pumps. Water samples from GP1 through GP5 were collected through PFE-Teflon tubing (0.6-cm) attached to the ends of the stainless-steel implants using peristaltic pumps.

Field measurements of pH and specific conductance were made using an Orion 250A meter with an Orion model 9106 pH combination electrode calibrated daily using pH 4, 7, and 10 standards and a temperature-compensated conductivity meter (Orion model 124) calibrated daily against standard reference solutions. Water temperatures were measured using a hand-held alcohol-filled thermometer.

Water samples for analysis of common inorganic constituents and nutrients were pressure-filtered in the field through inline 0.45-mm polyether sulfone cartridge filters from Gelman Scientific. Aliquots for inorganic chemical analysis were dispensed into clear polyethylene bottles for storage after the bottle was rinsed three times. Bottles used for analysis of cations were acidified to approximately pH 2 by addition of nitric acid. Aliquots for nutrient analysis were distributed into 125-mL, pre-rinsed, opaque, polyethylene bottles and placed on ice to minimize microbial alteration. Inorganic chemical and nutrient analyses were done by the USGS National Water-Quality Laboratory in Arvada, Colorado, using methods described generally by Fishman (1993), Timme (1994), and Struzeski and others (1996).

Bromide Analysis

Bromide, in the form of potassium bromide (Ameribrom Inc., New York, NY, photo grade), was chosen as the conservative tracer to track the recharge front using bromide electrodes, and to estimate dilution of the recycled water by soil moisture and (or) ground water during recharge. Bromide concentrations were measured in the field at several locations throughout the tracer experiments using Orion 250A meters with Orion model 9635 IonPlus bromide electrodes calibrated daily using prepared 1.0 mM, 0.1 mM, and 0.01 mM bromide standards. All water samples for bromide analysis were collected into 125-mL polyethylene bottles and bromide concentrations were measured at the USGS National Water-Quality Laboratory in Arvada, Colorado (first tracer experiment), or the USGS Geochemistry Laboratory in San Diego, California (second and third tracer experiments), using ion chromatography.

Bacteriophage Assays

The *Salmonella typhimurium* phage, PRD1, was used during the first tracer experiment. The male-specific RNA coliphage, MS2, along with PRD1, was used during the second and third tracer experiments. These bacteriophage were chosen because similar bacteriophage are present in treated municipal wastewater and in recycled water used for recharge (Yanko and others, 1999). Furthermore, bacteriophage have been used extensively in virus transport studies and are considered to be good model viruses because they are less absorbed than most pathogenic viruses and are relatively persistent during transport through the subsurface (Bales and others, 1997; Jin and others, 1997; Ryan and others, 1999; Schijven and others, 1999). Water samples for bacteriophage analysis during the first and second tracer experiment were collected into sterile 100-mL bottles and stored at 4^{o}C until analysis was conducted at the CSDLAC microbiology laboratory. During the third tracer experiment, water samples for bacteriophage analysis were collected into different-sized (125 mL and 10 L) sterile bottles. The large volume samples collected from WP7, PR9, and PR11 were refrigerated and analyzed within a couple of days. Thirty percent sterile beef extract was added to each sample size of 200 mL or less and the samples were frozen until analyzed at the CSDLAC microbiology laboratory. The protein in the beef extract protects the virus during the freezing process. This was confirmed in a previous investigation (James L. Jackson, County Sanitation Districts of Los Angeles County, unpub. data, 2000).

Bacteriophage concentrations were measured using either the double-agar-layer assay procedure or a MPN procedure. Samples estimated to have bacteriophage concentrations less than 1 plaque-forming unit per milliliter (PFU/mL) were analyzed using a MPN procedure (Kott, 1966) or a modified MPN procedure (Yanko and others, 1999).

Trypticase soy broth (TSB) (Difco), TSB (Difco) soft agar (containing 0.05 percent 1N CaCl2) and trypticase soy agar (TSA) (Difco) bottom agar were used for analyzing PRD1 bacteriophage using *Salmonella typhimurium* LT2 (ATCC #15277) as the host bacteria for all three tracer experiments. MS2 bacteriophage were analyzed for the second and third tracer experiments using TSB (Difco), TSB (Difco) soft agar (containing 0.05 percent 1N CaCl2), TSA (Difco) bottom agar, *E. coli* F^- amp (ATCC #700981) as the host bacteria, and the same concentration of antibiotics as described by Debartolomeis and Cabelli (1991).

The double-agar-layer assay method was performed by preparing a mixture of 1 mL of host bacteria, 4 mL of molten soft agar (45°C), and 1 mL of sample. The mixture was gently vortexed and poured onto the appropriate plating medium. Plates were incubated at 37°C for 24 hours. The concentrations were determined by counting the number of plaques on each plate. Plates were made in duplicate and the concentration was averaged from the plaques counted on each plate. The double-agar-layer assay, used duplicate for this study had a detection limit of 0.5 PFU/mL.

The MPN method was set up in a 5-tube, 3-dilution assay. The method consisted of inoculating 10, 1, and 0.1 mL of sample into appropriate broth (containing 1.25 percent 4M $MgCl_2$) and adding 0.1 mL of appropriate host bacteria to each tube. The tubes were incubated at 37°C for 24 hours. Double strength (2X) media was used for the 10-mL inocula.

For the large-volume modified MPN procedure, 11X medium was substituted with 5.5X broth sterilized in the autoclave instead of the medium that was filter sterilized, as described in draft EPA Method 1601 (May 1999). The inocula included 1 L, 100 mL, and 10 mL set in a 5-bottle/tube, 3-dilution assay with 5.5X broth used for the 1 L and 100 mL inocula, and double-strength broth used for the 10-mL inocula with 1.25 percent 4M $MgCl_2$ added to each water sample. Host bacteria was added in the amount of 10 mL to each 1 L bottle, 1 mL to each 100-mL bottle, and 0.1 mL to each 10-mL tube. Tubes/bottles were incubated at 37°C for 48 hours. After incubation, a 100 µL aliquot from each tube/bottle was spotted onto a plate (or plates) of freshly prepared lawns of appropriate host to confirm the presence of phage, as described by Kott (1966). Up to 5 tubes were spotted on a single plate. Lawns were prepared by the addition of 0.5 mL of log-phage host to 3-mL soft agar and poured onto the respective plating media. Plates were incubated at 37°C overnight and observed for plaque formation. An MPN was computed from the resulting positive/negative bottles. The modified MPN method used for this study had a detection limit of 0.02 MPN PFU/mL.

Model Development

Assuming kinetically controlled irreversible attachment to the porous media grains, collision efficiencies were calculated based on the relative breakthrough of each bacteriophage during the second and third tracer experiments (Harvey and Garabedian, 1991). The relative breakthrough, *RB*, the ratio of the time-integrated mass of each bacteriophage (MS2 and PRD1) relative to that of a conservative tracer (bromide), is defined as:

$$RB = \frac{Br_0}{C_0}\int_{t_0}^{t_f}\frac{C(t)}{Br(t)}dt \qquad (1)$$

where

C_0 and Br_0 are the initial bacteriophage and bromide concentrations, respectively,

$C(t)$ and $Br(t)$ are the corresponding concentrations at a sampling point at some time t after the tracer experiment began, and

t_0 and t_f are the beginning times and ending times of each breakthrough curve, respectively.

The *RB* can be determined from experimental data by integrating the area under the corresponding normalized breakthrough curves using the trapezoid rule.

From the relative breakthroughs, the collision efficiency, α, can be calculated for MS2 and PRD1 during the tracer experiments from the colloid-filtration model and assuming that the bacteriophage and bromide enter the system as a pulse input (Harvey and Garabedian, 1991) by the following:

$$\alpha = \frac{d_p\{[1-2(\alpha_L/l_z)\ln RB\;]^2-1\}}{6(1-\theta)\eta\alpha_L} \qquad (2)$$

where

d_p is the average grain diameter of the porous medium,

θ is the porosity of the porous medium,

η is the overall single collector efficiency for favorable deposition,

l_z is the distance from the injection point to the sampling point, and

the longitudinal dispersivity is

$$\alpha_L = (D-D_e)/U$$

where

D is the hydrodynamic dispersion coefficient,
D_e is the effective molecular-diffusion coefficient, and
U is the average interstitial velocity.

Owing to the small size of each bacteriophage and in the absence of double layer interaction energy, the overall single collector efficiency, η, can be calculated with only the convective diffusion contribution as (Pieper and others, 1997):

$$\eta = 0.9 A_s^{\frac{1}{3}} \left[\frac{k_B T}{\mu d_p d_v q} \right]^{\frac{2}{3}} \quad (3)$$

where

k_B is the Boltzman constant,
T is the solute temperature in Kelvin
μ is the fluid viscosity,
d_v is the virus diameter,
$q=U\theta$ is the specific discharge or approach velocity, and
A_s is Happel's sphere-in-cell model correction factor defined as:

$$A_s = \frac{1 - \varepsilon^5}{1 - 1.5\varepsilon + 1.5\varepsilon^5 - \varepsilon^6} \quad (4)$$

where $\varepsilon = (1 - \theta)^{1/3}$.

The parameter values of U and D were determined by fitting the experimental bromide breakthrough curves using the computer program CXTFIT, which estimates solute-transport parameters using a nonlinear least-squares parameter optimization method (Toride and others, 1995).

Virus Fate and Transport During Recharge

Recharge experiments with recycled water conducted at a small research field site constructed adjacent to the large recharge facility in the Montebello Forebay of Los Angeles County, California, indicated that bacteria can move through the soil with the percolating recycled water (Anders, 1997; Anders and Schroeder, 2003). These conclusions formed the basis for three field-scale tracer experiments using bacterial viruses (bacteriophage) PRD1 and MS2 as surrogates for human viruses and bromide as a conservative tracer.

Water Quality

Water-quality data for selected wells at the research field site collected during the three tracer experiments is contained in Appendix A. The water temperature in the test basin during the three tracer experiments ranged from 27.4°C to 29.0°C. Specific conductance and pH measurements taken from the test basin during the three experiments ranged from 934 µS/cm to slightly less than 1,100 µS/cm and from about 6.9 to 7.2 pH units, respectively. Background water temperature, specific conductance, and pH, as measured from water samples collected from beneath the test basin prior to any delivery of bacteriophage and bromide, ranged from about 21.1°C to 21.6°C, from 632 µS/cm to 841 µS/cm, and from 7.3 to 7.6 pH units, respectively. These values indicate chemical conditions at the research field site changed very little throughout each experiment and are similar to those observed during previous recharge experiments at the research field site (Anders, 1997; Anders and Schroeder, 1997; Schroeder, 2003).

Results from Tracer Experiments

First Tracer Experiment, August 1997

The first tracer experiment was carried out over a 2-day period in August 1997. Prior to starting the experiment, the test basin was filled to a depth of about 0.6 m with recycled water. Delivery of recycled water to the test basin was halted briefly, and the surface of the water in the test basin was sprayed over a 30-min period with concentrated solutions of bacteriophage and bromide containing 4.8×10^{12} PFU of PRD1 and 18 kg of bromide. Delivery of recycled water (without addition of bacteriophage and bromide) to the test basin was resumed after about 3.5 hours. More than 100 water samples were collected from 1.5 m below the floor of the test basin (WP1) and 3.0 m below the floor of the test basin (WP2) [depths averaged over the screened interval] and from the test basin itself (PR12) for bacteriophage assays over the 2-day sampling period.

Bacteriophage PRD1 concentrations in water samples collected during the first tracer experiment are contained in Appendix B. Samples of ponded water collected from the perimeter and the center of the test basin indicated that bromide and bacteriophage were reasonably well mixed in the test basin. Initial concentrations for PRD1 and bromide averaged $4.8 \pm 0.35 \times 10^4$ PFU/mL and 77.8 ± 6.0 mg/L, respectively. The observed breakthrough curves for both PRD1 and bromide at WP1 indicate that PRD1 reached a maximum concentration of 140 PFU/mL shortly after the start of the experiment and that the bacteriophage peak coincided with the bromide peak (fig. 4). No bacteriophage were detected at WP2.

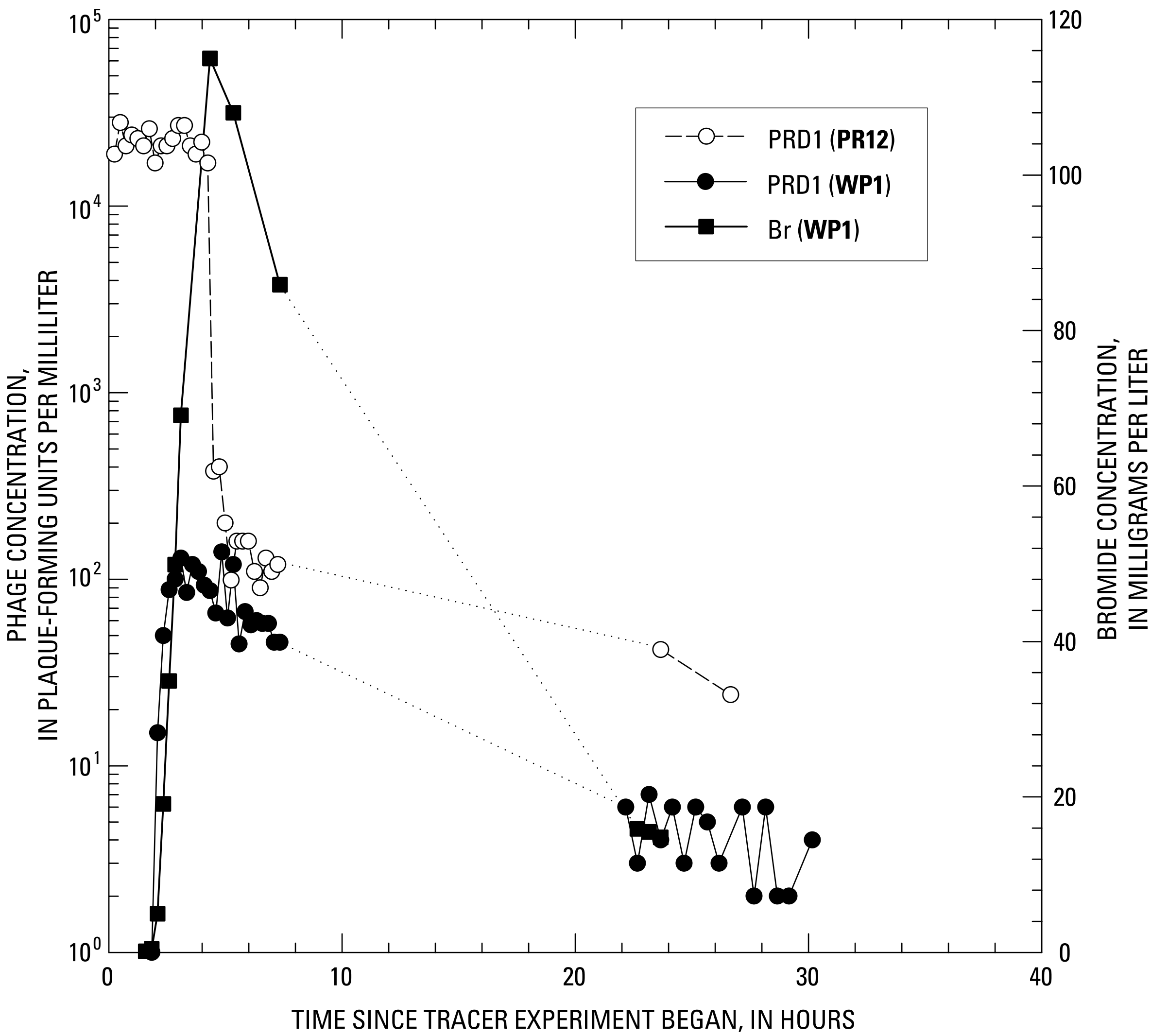

Figure 4. Bacteriophage PRD1 concentrations in water samples collected from the test basin (PR12; open circles) and WP1 (solid circles) and bromide concentrations in water samples collected from WP1 (solid squares) during the first tracer experiment, August 1997, from a research field site located in Los Angeles County, California.

Second Tracer Experiment, August–September 1998

During the second field-scale tracer experiment, bacteriophage MS2 was added along with bacteriophage PRD1 and bromide. With a depth of about 1.2 m, the volume of recycled water in the test basin was maintained at approximately 473 m^3 by addition of the recycled water at a delivery rate of about 1,063 m^3/d. The initial seeding of the test basin was accomplished in the same manner as the first tracer experiment. The surface of the water in the test basin was sprayed with solutions containing 8.5×10^{11} PFU of PRD1, 8.5×10^{13} PFU of MS2, and 49 kg of bromide. After the initial seeding of the test basin was completed, 4.7×10^{12} PFU of PRD1, 6.0×10^{13} PFU of MS2, and 11 kg of bromide were injected, using peristaltic pumps, directly into the feed pipe delivering the recycled water to the test basin. The injection process lasted several hours. After the metered injection was completed, delivery of recycled water to the test basin was halted. Delivery of recycled water was resumed without addition of bacteriophage and bromide after about 23 hours. During the 9-day experiment, water samples were collected from the same points as during the first experiment, and from WP7, GP1 through GP3, and PR8 through PR11.

Bromide concentrations in water samples collected during the second tracer experiment are contained in Appendix C. Bacteriophage MS2 and PRD1 concentrations during the second tracer experiment are contained in Appendix D. During the period when no recycled water was being delivered to the test basin, 24 grab samples were collected from 4 locations around the perimeter and near the center of the test basin to ascertain the degree of mixing (spatial heterogeneity) of the bacteriophage and bromide in the ponded water. The average concentrations in the 24 samples were determined to be $2.4 \pm 1.1 \times 10^4$ PFU/mL for PRD1, $2.4 \pm 1.4 \times 10^5$ PFU/mL for MS2, and 107.0 ± 28.0 mg /L for bromide. Bromide arrived at WP1 after about 4 hours and at WP2 after about 8 hours (fig. 5). The bromide breakthrough curves for WP7, PR9, and PR11 show that bromide arrived at the greater depths after about 2 days, with the bromide arriving at WP7 and PR11 beneath the berm of the test basin slightly before arriving at PR9 directly beneath the center of the test basin. The bromide breakthrough curves also indicated a 70 percent reduction [dilution by antecedent soil moisture and (or) regional ground water] in the maximum bromide concentration arriving at PR9.

The bacteriophage MS2 arrived at WP1 at about the same time as did bromide, and reached a maximum concentration slightly greater than 6×10^4 PFU/mL (fig.6). The arrival time for MS2 at WP2 was about 8 hours, and the maximum concentration was reduced to about 4×10^4 PFU/mL. The movement of bacteriophage PRD1 was coincident with that of MS2, arriving at WP1 slightly before 4 hours and at WP2 after about 8 hours (fig.7). However, the maximum concentration of PRD1 of almost 3×10^2 PFU/mL at WP2 was slightly greater than the maximum concentration achieved at WP1 and suggests no additional removal occurred after 1.5 m of subsurface transport. PRD1 was also detected at greater depths, although the results were presence/absence only. No bacteriophage or bromide were detected at PR8 or PR10, below the thin clay unit beginning about 9.4 m beneath the bottom of the test basin, during the second tracer experiment. It should be noted here that previous recharge experiments conducted at the research field site have shown that no displacement of preexisting water occurs below the clay lens until a few days after recharge from the test basin begins (Schroeder and others, 2003).

Third Tracer Experiment, August 2000

Because the third tracer experiment was conducted to confirm the results obtained from the second tracer experiment, the seeding procedure used for the second tracer experiment was repeated. During the third recharge experiment, the depth and volume of recycled water in the test basin were 2.0 m and about 1,000 m^3, respectively. Solutions containing 5×10^{13} PFU of PRD1, 5.3×10^{14} PFU of MS2, and 72 kg of bromide were applied to the test basin during the initial seeding and injection period. During the 7-day tracer experiment, water samples were collected from the same sampling points as during the second experiment, and from GP4 and GP5. No water samples were collected from PR8 and PR10 during the third tracer experiment.

Bromide concentrations in water samples collected during the third tracer experiment are contained in Appendix E, and bacteriophage MS2 and PRD1 concentrations are contained in Appendix F. The average concentrations of bacteriophage and bromide in the test basin were determined to be $8.9 \pm 4.8 \times 10^3$ PFU/mL for PRD1, $6.0 \pm 2.6 \times 10^4$ PFU/mL for MS2, and 85.0 ± 5.0 mg/L for bromide. Bromide arrived at WP1 after about 4 hours and at WP2 after about 8 hours (fig. 8). The bromide spikes at the shallower depths are due to overestimating the volume of recycled water present in the test basin and (or) incomplete mixing in the test basin during the first few hours of the experiment. The bromide breakthrough curves for WP7, PR9, and PR11 show that bromide arrived at these greater depths after about 1.2, 2.0, and 1.7 days, respectively, with less than 50 percent reduction in the maximum bromide concentration. The bacteriophage MS2 arrived at WP1 at about the same time as did bromide, and reached a maximum concentration slightly greater than 1×10^3 PFU/mL (fig. 9). The arrival time for MS2 at WP2 was greater than 20 hours, and the maximum concentration was about 1×10^3 PFU/mL. The MS2 breakthrough curves at WP1 and WP2 also indicated that the concentration of MS2 remained above about 5×10^1 PFU/mL throughout the first 6 days of the experiment. The breakthrough curves for PRD1 are shown for GP1 and GP2, since during the third tracer experiment no PRD1 was found below 1.0 m at a concentration greater than the detection limit (fig. 10).

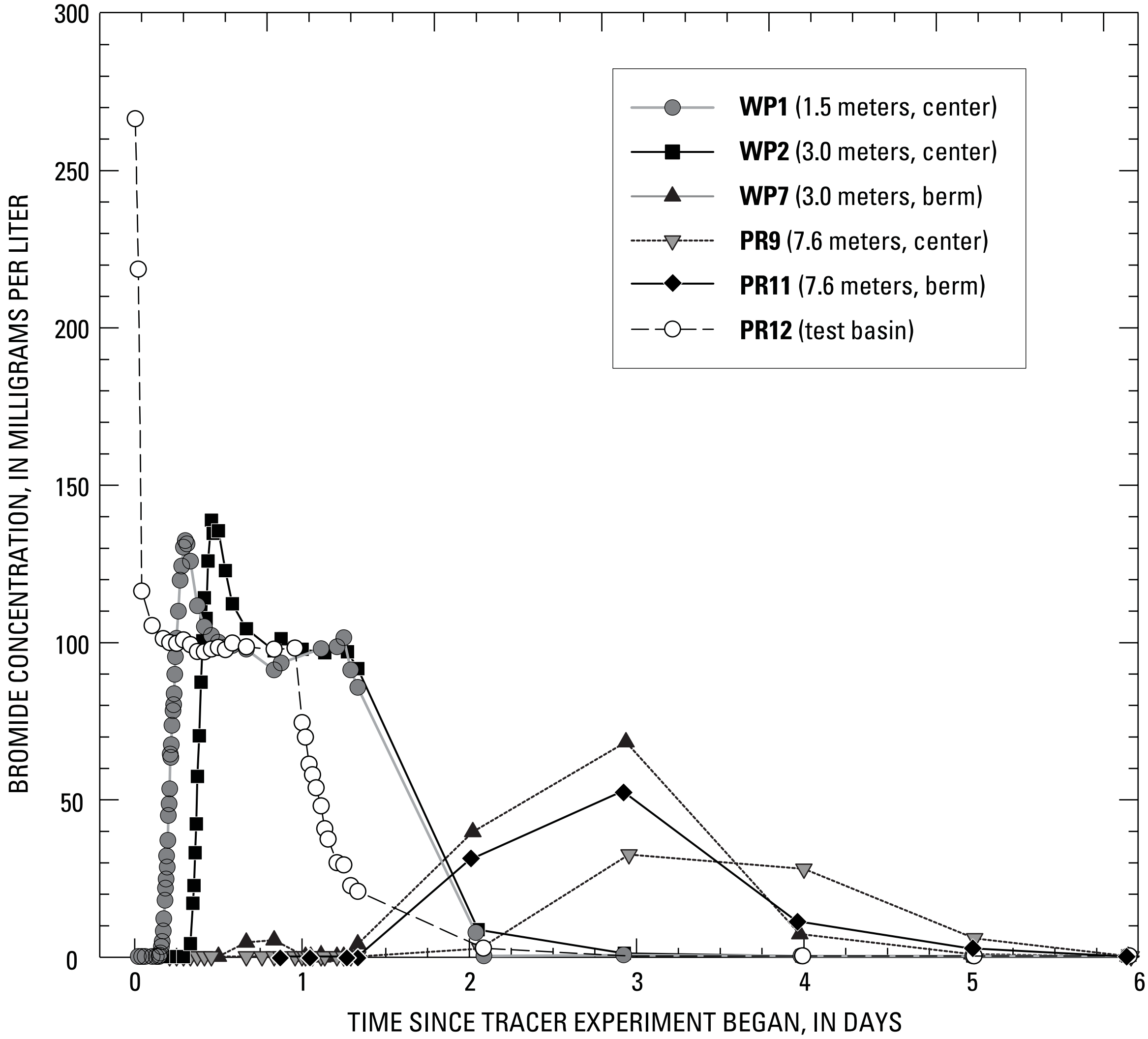

Figure 5. Bromide concentrations during the second tracer experiment, August–September 1998, from a research field site located in Los Angeles County, California.

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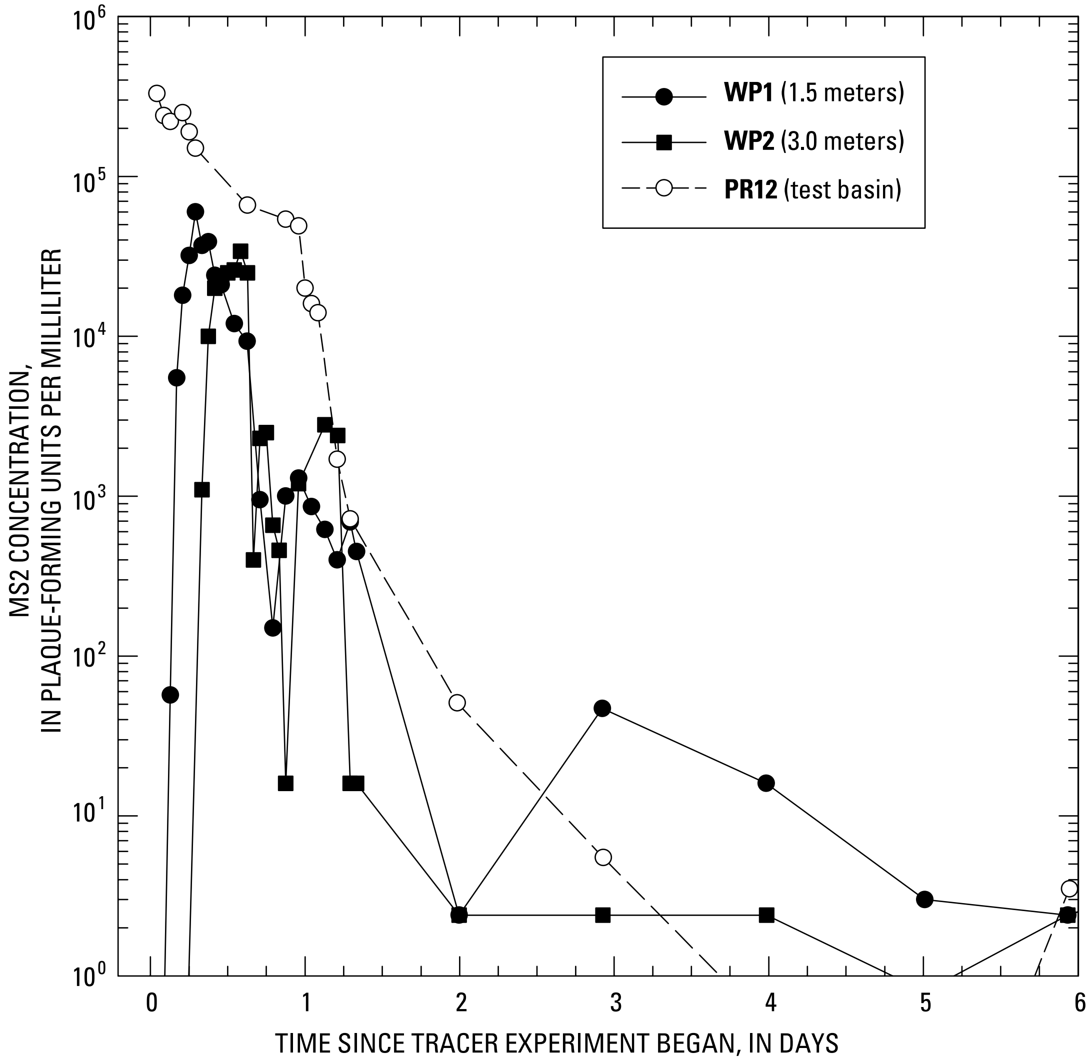

Figure 6. Bacteriophage MS2 concentrations during the second tracer experiment, August–September 1998, from a research field site located in Los Angeles County, California.

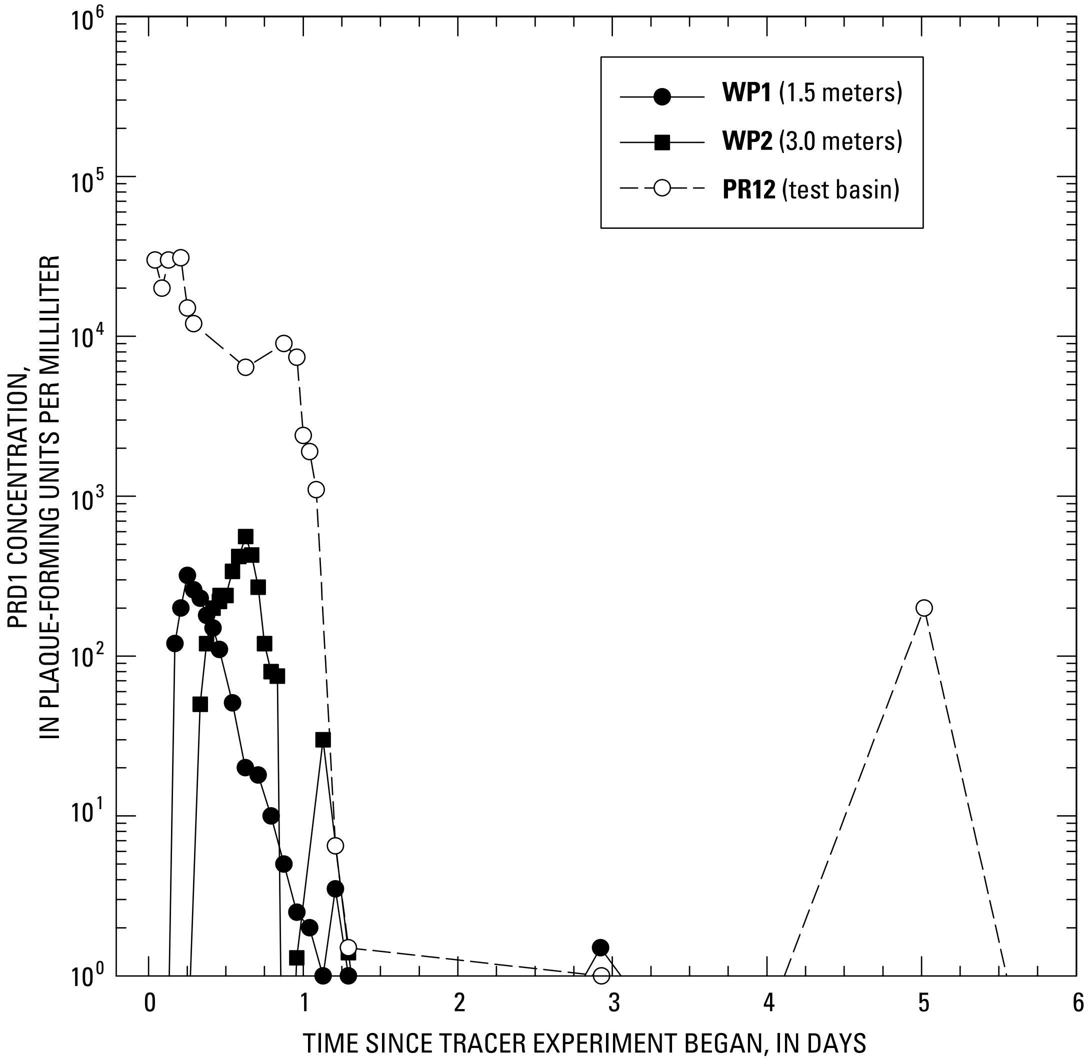

Figure 7. Bacteriophage PRD1 concentrations during the second tracer experiment, August–September 1998, from a research field site located in Los Angeles County, California.

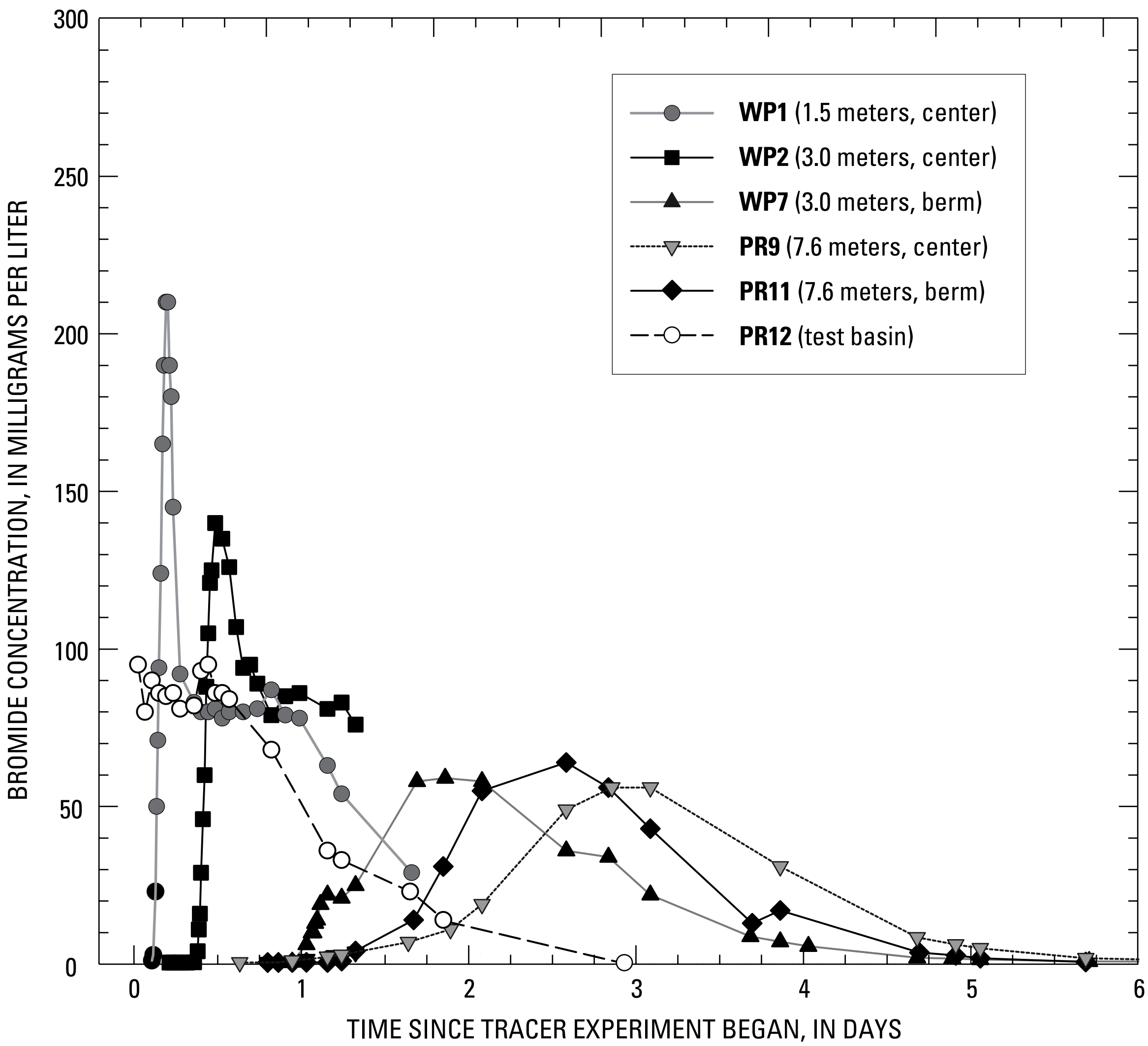

Figure 8. Bromide concentrations during the third tracer experiment, August 2000, from a research field site located in Los Angeles County, California.

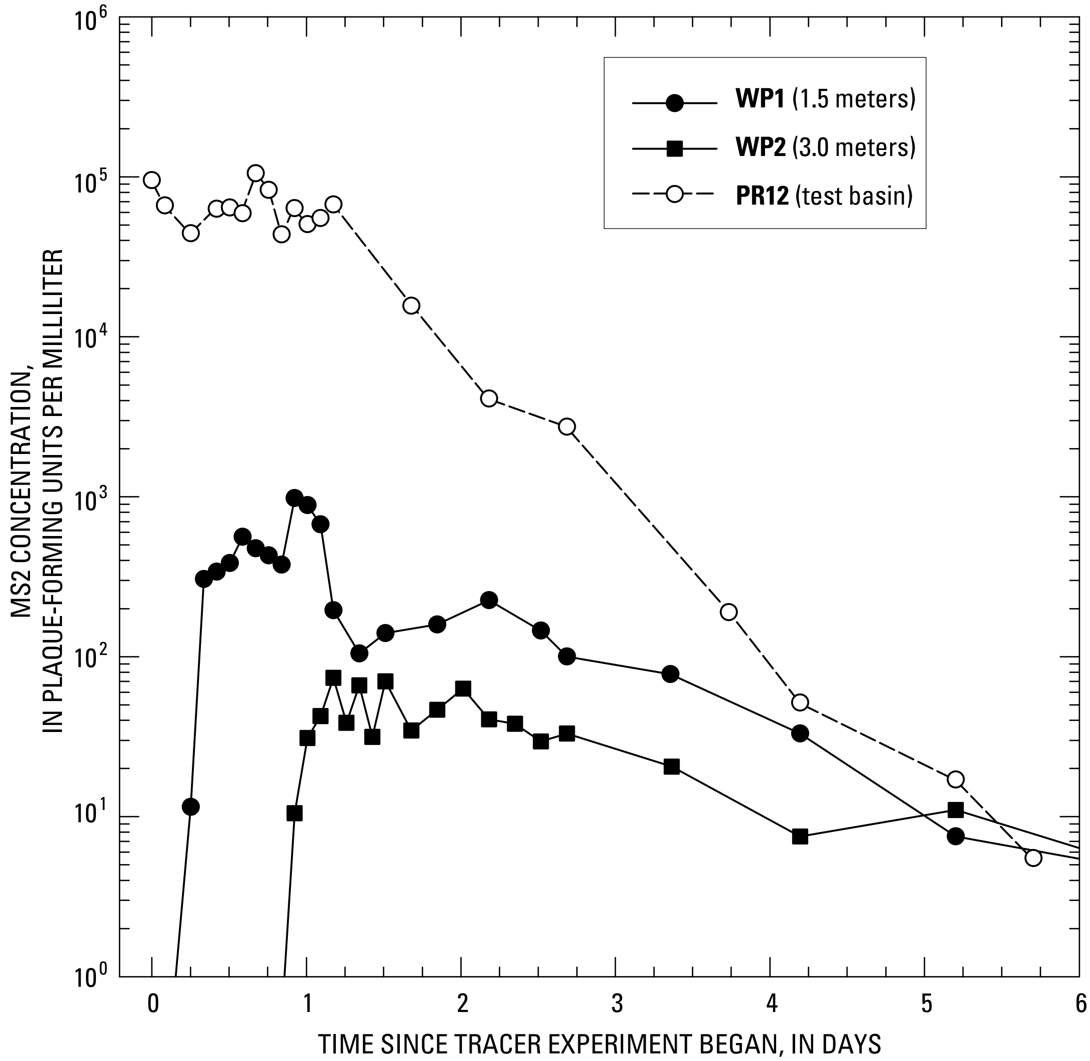

Figure 9. Bacteriophage MS2 concentrations during the third tracer experiment, August 2000, from a research field site located in Los Angeles County, California.

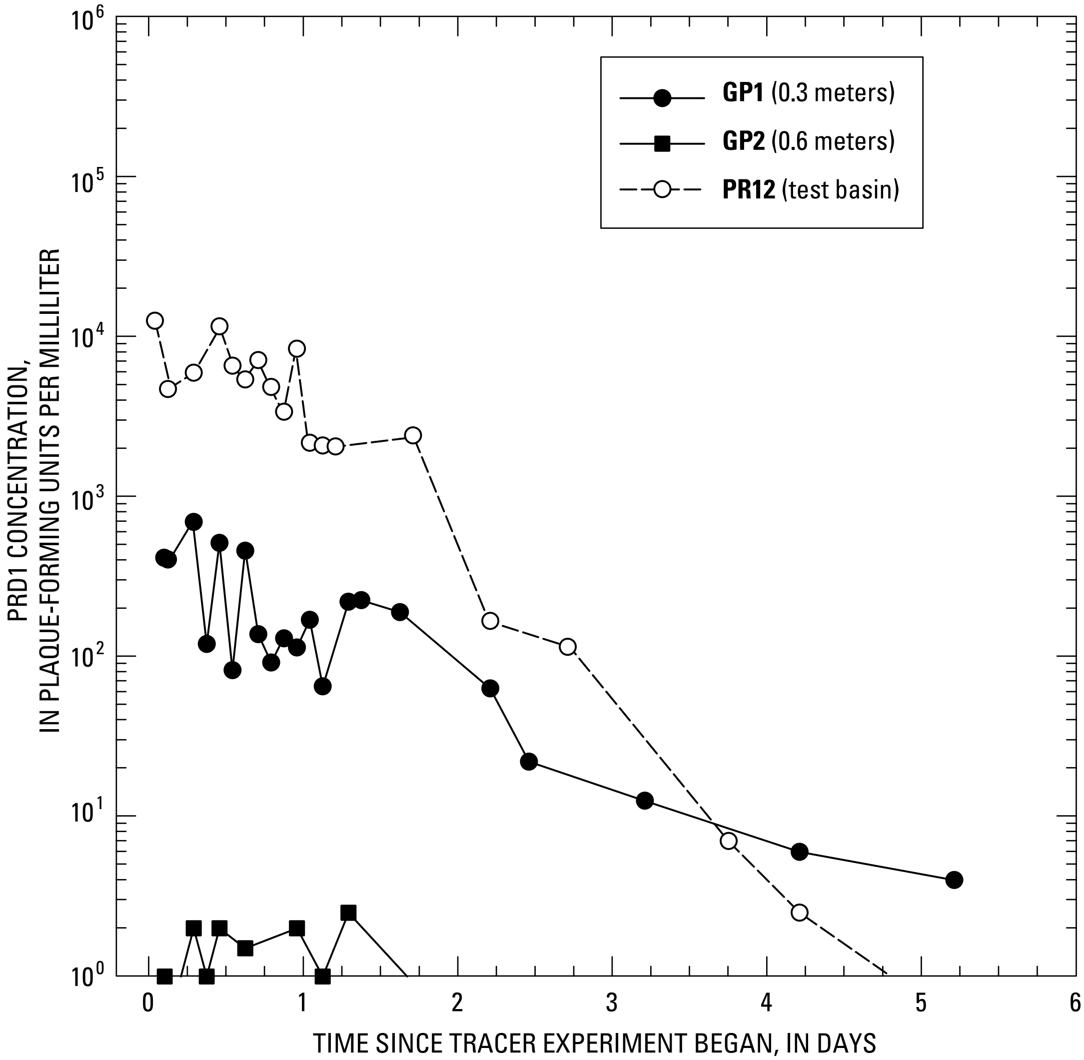

Figure 10. Bacteriophage PRD1 concentrations during the third tracer experiment, August 2000, from a research field site located in Los Angeles County, California.

Inactivation Rates

The rate of bacteriophage inactivation in the recycled water independent of any processes occurring in the subsurface was determined from measurements on water in the pond itself during the second and third tracer experiments. Assuming that virus inactivation is a first-order process (Yates and others, 1985), the rate of bacteriophage inactivation can be determined by linear-regression analysis of the observed normalized bacteriophage log-concentrations. For the second tracer experiment, during the 16-hour period when no additional recycled water or bacteriophage were being delivered to the test basin, inactivation rates were 0.07 hr^{-1} ($r^2 = 0.94$) for MS2 and 0.02 hr^{-1} ($r^2 = 0.36$) for PRD1 (fig. 11). These values indicate that the inactivation rate for MS2 was higher than for PRD1. However, for the 5-hour period when no recycled water or bacteriophage were delivered to the test basin during the third tracer experiment, inactivation rates were 0.02 hr^{-1} ($r^2 = 0.02$) and 0.2 hr^{-1} ($r^2 = 0.44$) for MS2 and PRD1, respectively (fig. 12). It is not clear what caused the increase in the inactivation rate of PRD1 during the third experiment. Temperature, an important factor that controls the degree of virus inactivation, was similar between the tracer experiments. Other factors that are known to influence the rate of inactivation in aquatic systems, such as Brownian coagulation of viruses (Grant, 1994) and (or) microbial activity (Janson and others, 1989) were not monitored.

It should be noted here that Sim and Chrysikopoulos (1996) have proposed that the inactivation rate coefficients should be time-dependent, which may explain the lower correlations. They suggested that virus transport data collected in the vicinity of the source of contamination at early times are most reliable for estimation of inactivation rate coefficients, and temporally variable inactivation rate coefficients can significantly affect the predicted virus migration in porous media. However, the inactivation rate coefficients measured during the tracer experiments can provide a conservative estimate for the adequate soil-retention time requirement for pathogen removal.

Attenuation Rates

In order to correct for the effect of dilution by antecedent soil moisture or regional ground water, bacteriophage concentrations were normalized with respect to bromide concentrations for samples collected during the second and third tracer experiments. Only a few bromide samples were analyzed during the first tracer experiment. For the second experiment, the bacteriophage to bromide ratios were calculated for samples from the test basin itself, and from 0.3, 0.6, 1.0, 1.5, and 3.0 m below the floor of the test basin. The resulting bacteriophage to bromide ratio plots at 3, 6, 9, and 21 hours after the addition of bacteriophage and bromide show the initial removal of MS2 and PRD1 during infiltration through the floor of the test basin at the soil-water interface, and then subsequent removal as the bacteriophage move through the percolation zone in the shallow part of the aquifer (fig. 13). Regression analysis of almost 125 bacteriophage to bromide ratios collected during the second tracer experiment was used to estimate the attenuation rates of MS2 and PRD1 during aquifer recharge. The attenuation rates are defined as the logarithmic reduction in the bacteriophage to bromide ratio, expressed as $\log_{10} (C_{virus}/C_{bromide})$, during percolation of the amended recycled water beneath the test basin. Regression analysis of the data collected during the second experiment yielded an attenuation rate of 0.37 $\log_{10}$ units per meter for MS2 and 0.55 $\log_{10}$ units per meter for PRD1 (fig.14). The low correlations, $r^2 = 0.14$ (n = 70) and $r^2 = 0.22$ (n = 54) for MS2 and PRD1, respectively, indicate substantial deviations from the regression line. Schijven and others (1999) suggested that such deviations are probably due to subsurface heterogeneities and (or) analytical variability.

For the third tracer experiment, regression analysis of data collected from the test basin itself and from 0.3, 0.6, 1.0, 1.2, 1.5, and 3.0 m below the floor of the test basin yielded an attenuation rate of 0.83 $\log_{10}$ units per meter and r^2 of 0.32 (n = 162) for MS2 and an attenuation rate of 3.0 $\log_{10}$ units per meter and r^2 of 0.71 (n = 53) for PRD1 (fig. 15). The third tracer experiment showed an increase in the attenuation rates and higher correlations for both MS2 and PRD1, especially for PRD1, due to increased removal and (or) inactivation.

Collision Efficiency

The average interstitial velocity, U, and the hydrodynamic dispersion coefficient, D, were determined by fitting the experimental bromide breakthrough curves using the computer program CXTFIT. During the second experiment, $U = 7.17 \times 10^{-5}$ m/s and $D = 1.34 \times 10^{-6}$ m^2/s at 1.5 m beneath the test basin. At 3.0 m, $U = 8.35 \times 10^{-5}$ m/s and $D = 1.18$ x 10^{-6} m2/s. During the third experiment, $U = 8.52 \times 10^{-5}$ m/s and $D = 1.38 \times 10^{-6}$ m^2/s at 1.5 m and $U = 7.11 \times 10^{-6}$ m/s and $D = 1.05 \times 10^{-6}$ m^2/s at 3.0 m. The slight increase in fluid velocities with depth during the second experiment and slight decease with depth during the third experiment indicate different hydraulic conditions existed beneath the test basin during these two experiments.

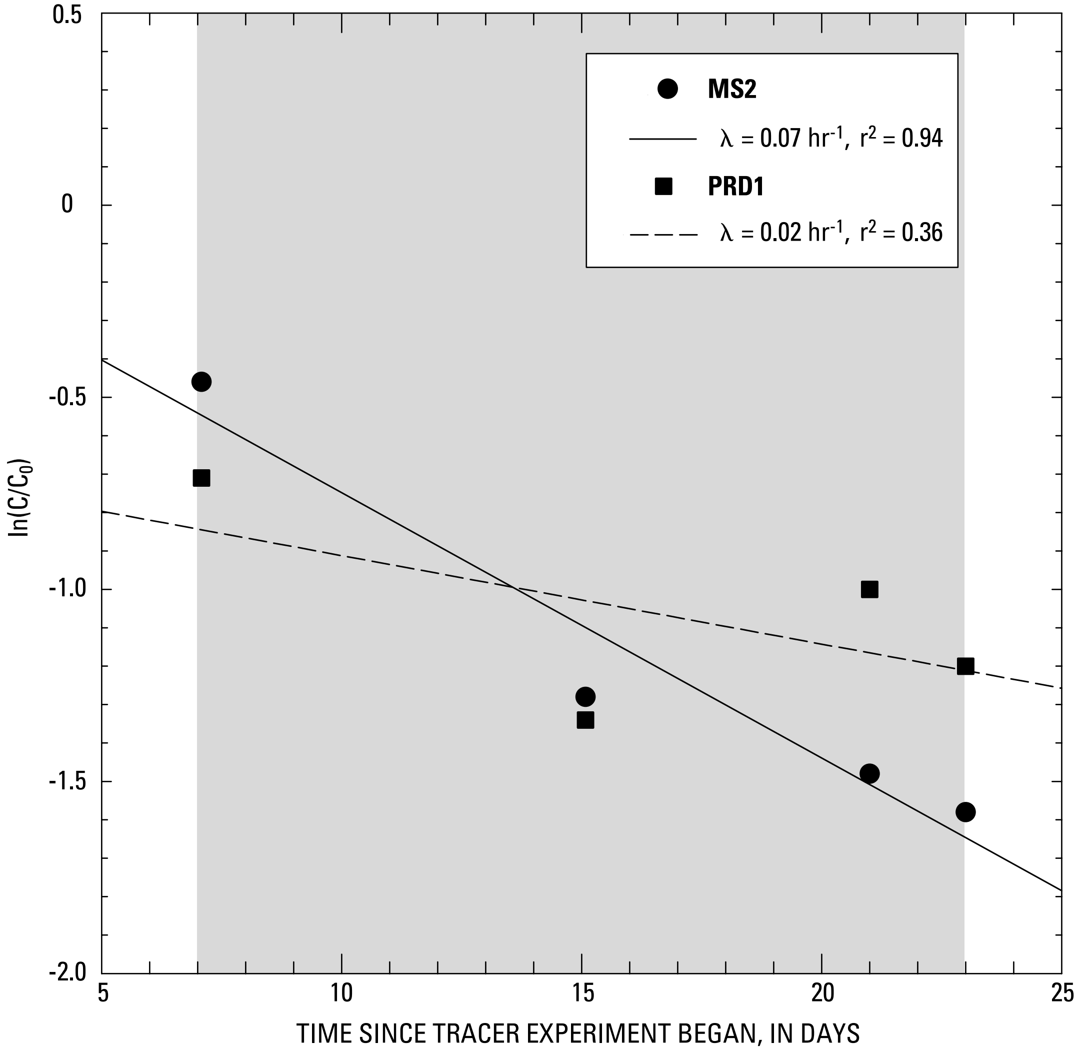

Figure 11. Normalized log-concentrations of MS2 (solid circles) and PRD1 (solid squares) in the test basin as a function of time for the second tracer experiment, August–September 1998. The slope of the fitted lines (solid line for MS2, and dashed line for PRD1) represents the corresponding inactivation rate coefficients, λ, for bacteriophage MS2 and PRD1. Shaded area is 16-hour period when no recycled water or tracer was being delivered to the test basin, Los Angeles County, California.

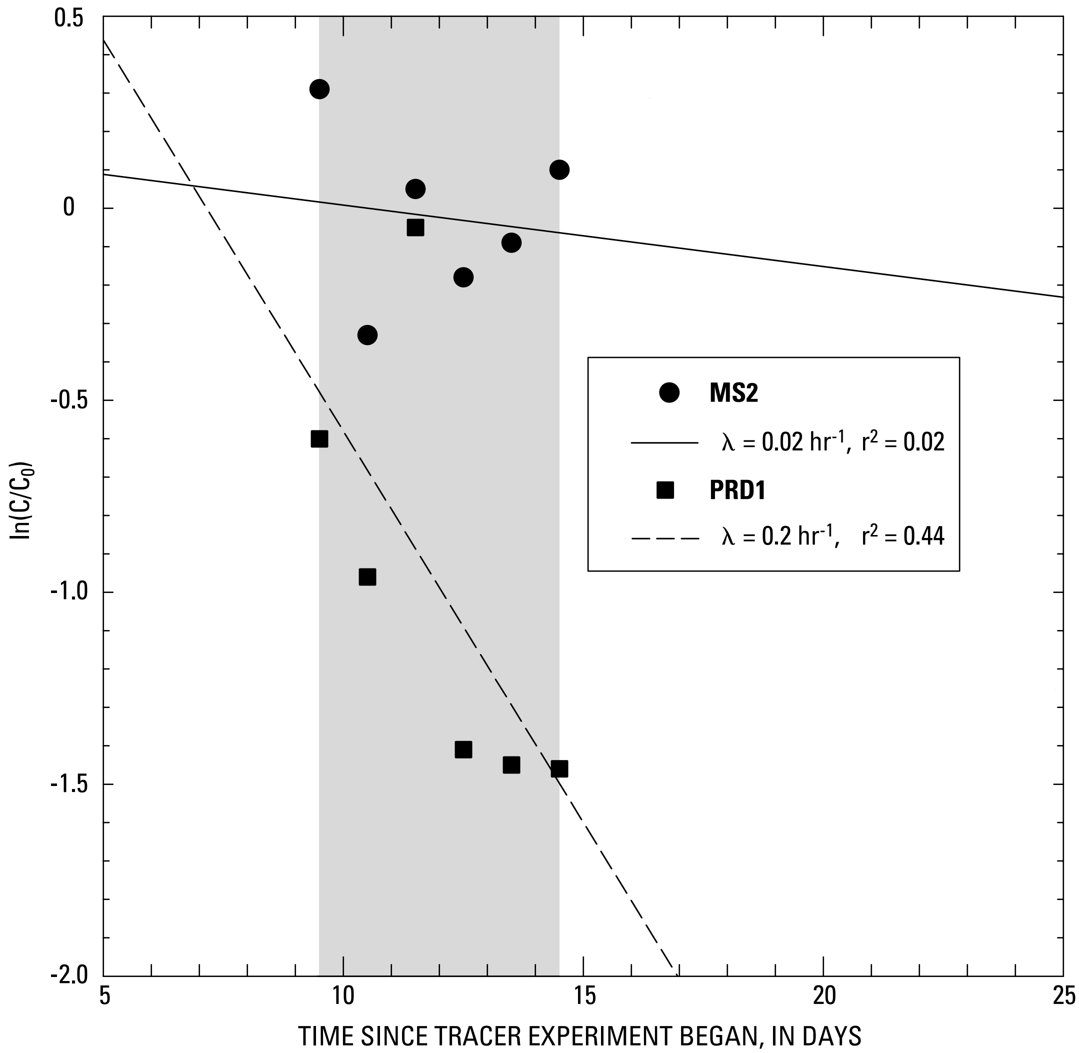

Figure 12. Normalized log-concentrations of MS2 (solid circles) and PRD1 (solid squares) in the test basin as a function of time for the third tracer experiment, August 2000. The slope of the fitted lines (solid line for MS2, and dashed line for PRD1) represents the corresponding inactivation rate coefficients, λ, for bacteriophage MS2 and PRD1. Shaded area is 5-hour period when no recycled water or tracer was being delivered to the test basin, Los Angeles County, California.

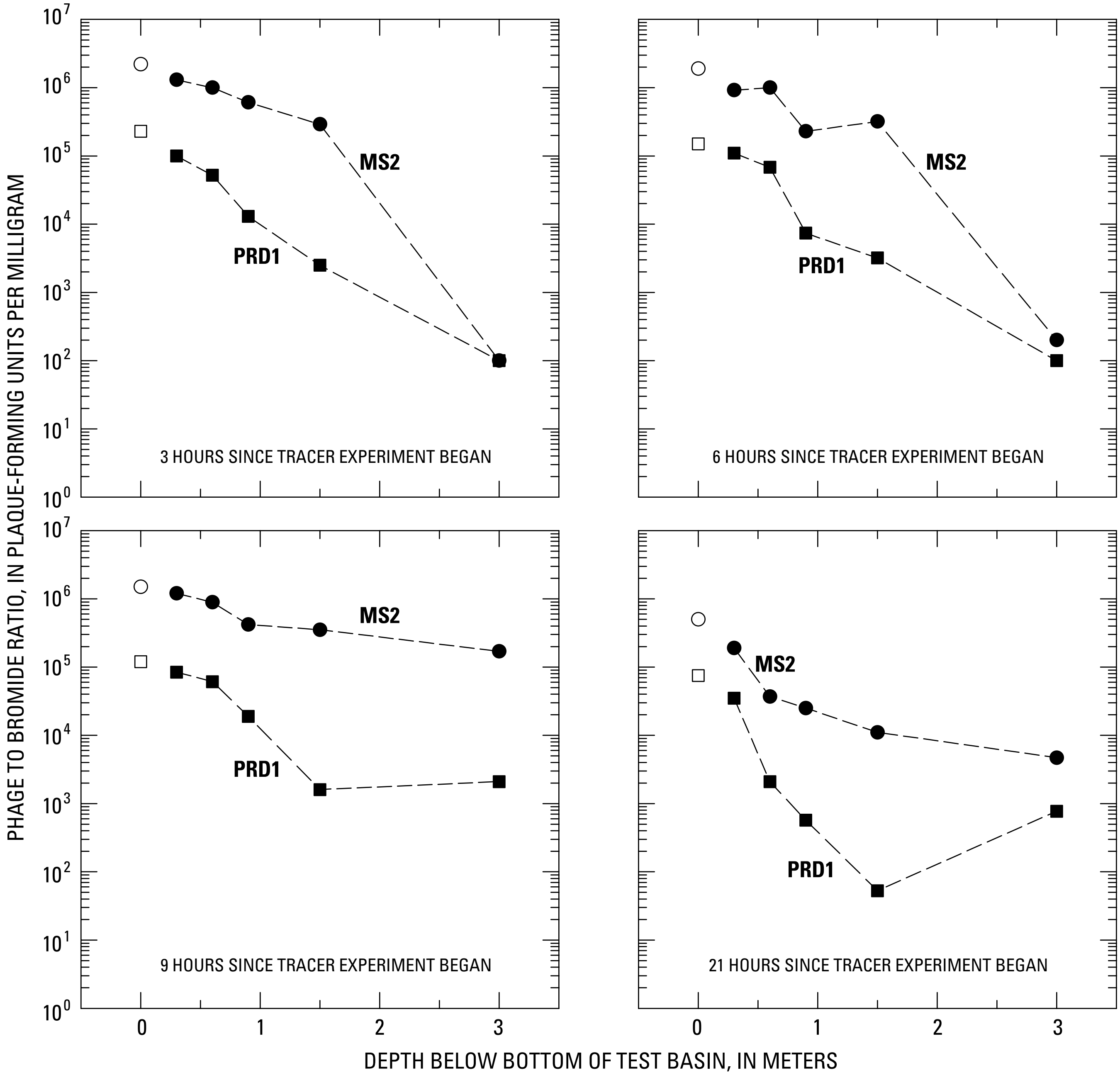

Figure 13. Bacteriophage to bromide ratio plots for the test basin (open symbols) and selected depths beneath the test basin (solid symbols) at 3, 6, 9, and 21 hours after the addition of bacteriophage and bromide during the second tracer experiment, August–September 1998, from a research field site located in Los Angeles County, California.

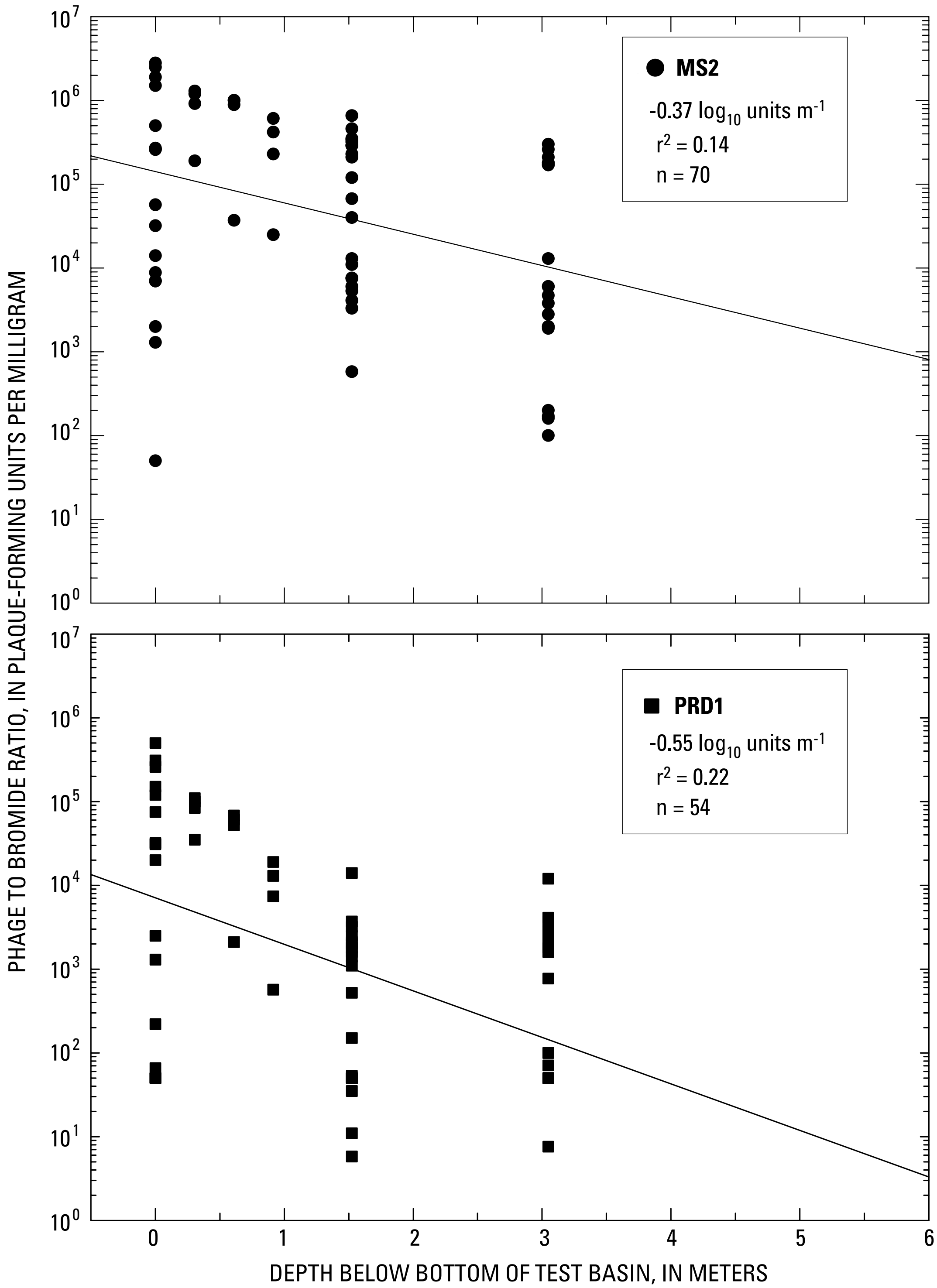

Figure 14. Attenuation rates, defined as the logarithmic reduction in the bacteriophage to bromide ratio (solid line), for MS2 (solid circles) and PRD1 (solid squares) during the second tracer experiment August–September 1998, from a research field site located in Los Angeles County, California.

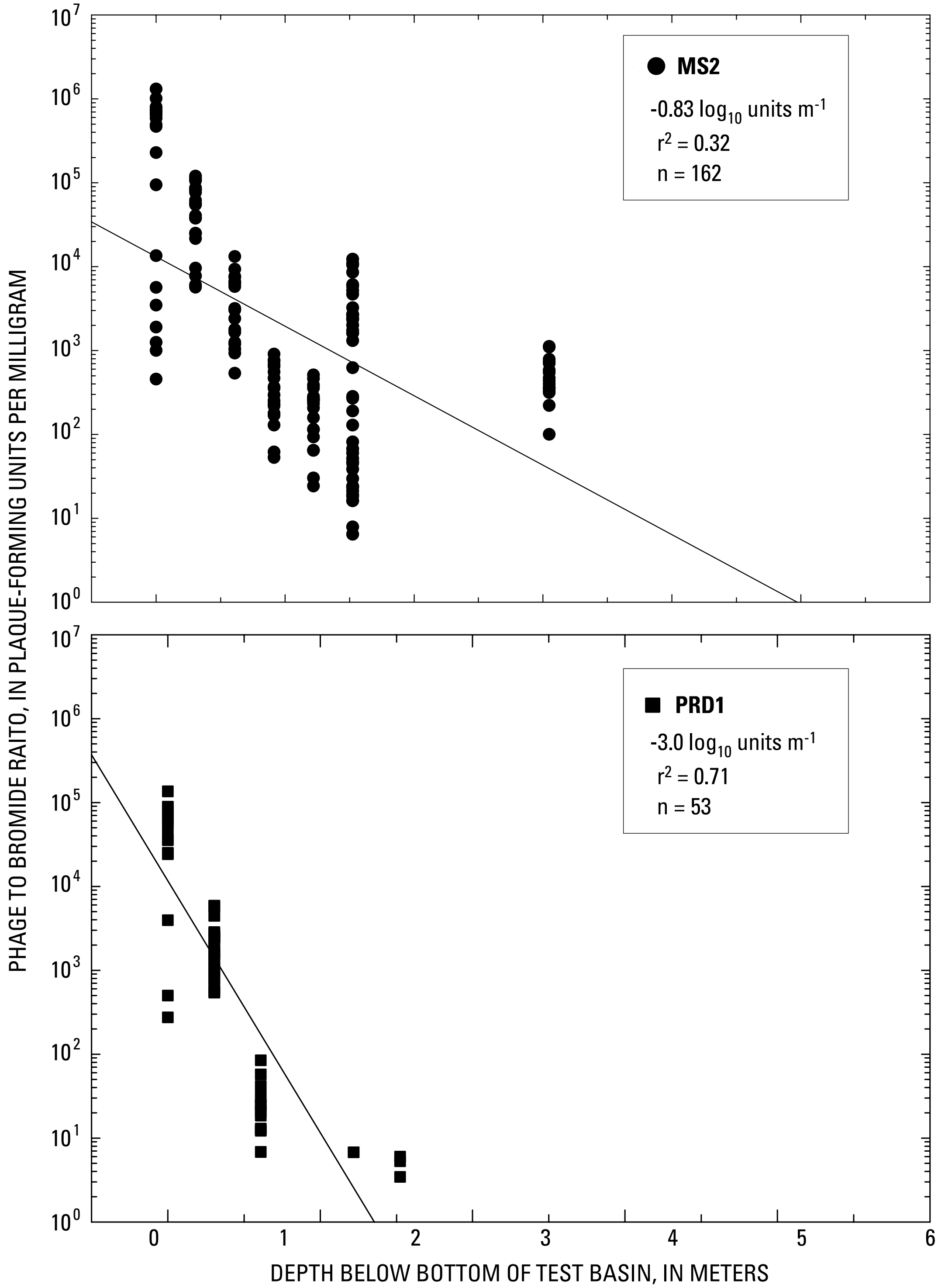

Figure 15. Attenuation rates, defined as the logarithmic reduction in the bacteriophage to bromide ratio (solid line), for MS2 (solid circles) and PRD1 (solid squares) during the third tracer experiment, August 2000, from a research field site located in Los Angeles County, California.

The *RB*s (equation 1) for MS2 after 1.5 m and 3.0 m of transport were 3.35×10^{-2} and 1.70×10^{-2}, respectively, for the second tracer experiment, and 4.33×10^{-3} and 7.35×10^{-4}, respectively, for the third experiment. The *RB*s for PRD1 after 1.5 m and 3.0 m of transport were 1.97×10^{-3} and 3.43×10^{-3}, respectively, for the second tracer experiment. Since measured PRD1 concentrations were never greater than the detection limit below 1.0 m during the third tracer experiment, *RB*s were determined from data for 0.3 m and 0.6 m of transport beneath the test basin. The corresponding *RB*s for PRD1 during the third tracer experiment were 1.99×10^{-2} at 0.3 m and 1.51×10^{-4} at 0.6 m.

The collision efficiency (equation 2) was determined for each bacteriophage during the second and third tracer experiments with the longitudinal dispersivity, α_L, calculated from fitted U and D values, the overall single collector efficiency, η, obtained from equation 3 and assigning a porosity, θ, of 0.3. The α_L values ranged from 0.014 to 0.019 m and indicate that the degree of soil formation heterogeneity beneath the test basin is slight. Table 3 contains additional parameter values used to calculate collision efficiencies for MS2 and PRD1 during the second and third tracer experiments. The α values for MS2 after 1.5 m and 3 m of transport were 1.37×10^{-3} and 8.94×10^{-4}, respectively, during the second tracer experiment, and 2.51×10^{-3} and 1.44×10^{-3}, respectively, during the third experiment. The α values for PRD1 during the second tracer experiment were 4.78×10^{-3} and 2.30×10^{-3} after 1.5 m and 3.0 m of transport, respectively. During the third tracer experiment, α values were 7.56×10^{-1} and 1.05×10^{-1} after 0.3 and 0.6 m of transport. The α values for PRD1 after 0.6 m of transport during the third experiment were not determined because PRD1 was only measured at the detection limit.

The collision efficiency for both bacteriophage indicates attachment conditions were more favorable for PRD1 than for MS2 during the tracer experiments. The more favorable attachment conditions (higher collision efficiency) for bacteriophage PRD1 are due to its lipid-containing structure and higher hydrophobicity, whereas a more hydrophilic virus such as MS2 behaves more conservatively (Kinoshita and others, 1993). For comparison, collision efficiencies have been reported in the literature under different physiochemical and hydrologic conditions. Pieper and others (1997) reported that $\alpha = 1.3 \times 10^{-2}$ in an uncontaminated aquifer zone and $\alpha = 1.4 \times 10^{-3}$ in a contaminated zone. The lower collision efficiency (less favorable attachment conditions) in the contaminated zone was attributed to the presence of high dissolved organic matter that enhances bacteriophage transport. Schroeder and others (2003) reported dissolved organic carbon concentrations of almost 10 mg/L in recycled water at the research field site.

Deborde and others (1999) calculated $\alpha = 4.0 \times 10^{-3}$ for MS2 and $\alpha = 1.4 \times 10^{-2}$ for PRD1 in a gravel-dominated floodplain aquifer. Although these α values are equal in magnitude to those obtained in our study, greater d_p values of 1.25 mm (coarse sand) and 12.0 mm (medium pebbles) at their site suggest less favorable attachment conditions existed due to higher ground-water velocities and lower specific conductance. Schijven and others (1999) studied the removal of viruses by dune recharge and found that α values ranged from 1.4 x 10^{-3} to 2.7×10^{-4} for MS2 and 2.4×10^{-3} to 4.3×10^{-4} for PRD1. Their very low α values reflect highly unfavorable conditions for attachment and are consistent with the concept that in sandy soils with pH values of 7.3–8.3, electrostatic repulsion is important in restricting attachment (Bales and others, 1993). Considering the slight difference in pH values reported by Schijven and others (1999) and Schroeder and others (2003), as well as the higher velocities during aquifer recharge and the presence of organic matter in recycled water, one would expect less-favorable conditions for attachment should have existed at the research site of our study.

Table 3. Parameter values used to calculate collision efficiencies for MS2 and PRD1 during the second and third tracer experiments in Los Angeles County, California

[Parameters: k_B, Boltzman constant; T, solute temperature; μ, fluid viscosity; d_v, virus diameter; d_p, average grain diameter; θ, porosity; A_s, Happel's sphere-in-cell model correction factor, where $\varepsilon = (1-\theta)^{1/3}$; Units: kg, kilogram; m, meter; s, second; K, degrees Kelvin]

Parameter	Values	Units
k_B	1.38×10^{-23}	$(kg \cdot m^2)/(s^2 \cdot K)$
T	298	K
μ	8.91×10^{-4}	$kg/(m \cdot s)$
d_p	2.5×10^{-4}	m
d_v	2.5×10^{-8} (MS2)	m
	6.2×10^{-8} (PRD1)	m
θ	.3	
ε	.89	
A_s	75.5	

The increased collision efficiency during the third tracer experiment for MS2 and PRD1 at the research field site, especially for PRD1, may be explained by changes in the attachment characteristics of each bacteriophage for the conditions present during the experiment. However, factors like temperature and ground-water quality that could affect the degree of attachment have been shown to be similar between tracer experiments, while other factors, such as viral surface properties or sediment surface charges, are not expected to change between experiments.

Another possible explanation for the increased collision efficiencies (more favorable attachment conditions) at the research field site is due to alterations in the surface structure as well as the porosity of the filtering media during the recharge experiment. This explanation seems reasonable considering the changes in water flux and hydraulic conductivities that can occur over time during artificial recharge because of the presence of entrapped air, sealing of the soil surface, and the effect of biofilms sealing the pores within the wetted zones. Furthermore, such an explanation would be consistent with the increased attenuation rates during the third tracer experiment.

Summary and Conclusions

The first tracer experiment established the feasibility of conducting such experiments under actual recharge conditions using recycled water seeded (augmented) with high concentrations of bacteriophage and bromide as tracers. On the basis of the results of the first tracer experiment, a second tracer experiment was designed to measure more precisely the fate and transport of surrogates for human viruses under actual recharge conditions. The third tracer experiment was completed to confirm the results obtained from the second tracer.

The attenuation rates for MS2 and PRD1 during the second and third tracer experiments indicate that rapid reduction occurs in the concentration of bacterial viruses released into the environment with recycled water during aquifer recharge. Furthermore, these tracer experiments indicate that adsorption, not inactivation, is the predominant removal mechanism for viruses during aquifer recharge.

Collision efficiencies for MS2 and PRD1 confirm that favorable attachment conditions existed for both bacteriophage, especially for PRD1. The increased collision efficiencies during the third tracer experiment are explained by changes in the inactivation rates and (or) attachment characteristics of each bacteriophage for the conditions present during the experiment although factors such as temperature, specific conductance, and pH that could affect the degree of virus inactivation and attachment were determined to be similar between experiments. Furthermore, factors such as viral surface properties or sediment surface charges are not expected to change between experiments. A plausible explanation is that different attachment conditions between experiments were created by temporal changes in water flux and hydraulic conductivities beneath the test basin.

Therefore, additional studies are needed to identify how these factors might contribute to variability in the collision efficiency between tracer experiments. Such information would also help quantify how to make effective use of the soil to protect public health in planned water-reuse programs and to design an optimal management scenario that maximizes the amount of recycled water applied to the spreading grounds while still maintaining favorable attachment conditions for virus removal. A management scenario that considers virus removal by attachment and (or) inactivation will ensure protection to the ground water supply. Finally, this study illustrates the importance of conducting field-scale tracer experiments at a specific site under actual recharge conditions with recycled water using surrogates for human viruses to establish setback requirements that ensure adequate pathogen removal.

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Appendixes

Appendix A. Water-quality data for selected wells at the research field site in Montebello Forebay, Los Angeles County, California, 1997–2000

[Number below the compound is the data parameter code, which is a 5-digit number used in the U.S. Geological Survey computerized data system, National Water Information System (NWIS), to uniquely identify a specific constituent or property; ft, feet below basin floor or land surface; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; <, actual value less than value shown; —, no data; MLS, multilevel sampler]

Station name (Local identifier)	Date	Time	Depth of well (ft) (72008)	Altitude of land surface (ft) (72000)	Oxygen, dissolved (mg/L) (00300)	pH, field (standard units) (00400)	Specific conductance, field (µS/cm) (00095)	Water temperature (°C) (00010)	Calcium, dissolved (mg/L as Ca) (00915)
2S/11-W18L27 (PR8)	08/25/1998	1230	49	160.93	0.2	7.4	689	21.6	50.9
2S/11-W18L28 (PR9)	08/25/1998	0945	25	161.04	.5	7.2	895	19.6	67.3
	08/28/1998	1130	25	161.04	—	7.2	982	24.7	69.5
	08/02/2000	1530	25	161.04	.1	7	959	28.5	59.5
2S/11-W18L29 (PR10)	08/25/1998	1130	60	171.91	0	7.3	632	20.8	45.6
2S/11-W18L30 (PR11)	08/25/1998	1030	36	171.87	.3	7.1	841	19.7	65.1
	08/28/1998	1000	36	171.87		7	1,010	26	63.5
	08/02/2000	1645	36	171.87	.2	7	936	28.9	58.8
Pond at Pico	08/27/1997	1134	—	—	—	—	—	—	—
	08/27/1997	1334	—	—	—	—	—	—	—
	08/27/1997	1504	—	—	—	—	—	—	—
	08/27/1997	1519	—	—	—	—	—	—	—
	08/27/1997	1719	—	—	—	—	—	—	—
	08/28/1997	1031	—	—	—	—	—	—	—
	08/25/1998	1300	—	—	8.6	7.3	1,000	28.8	53.4
	08/28/1998	1200	—	—		7.3	1,010	29	53.2
	08/02/2000	1730	—	—	2.1	7.1	990	28.4	56.1
	08/04/2000	0300	—	—	—	—	—	—	—
Sewage Effluent	08/25/1998	1800	—	—	—	7.1	1,080	28.6	55.1
2S/11-W18L31 (WP1)	08/27/1997	1225	7.13	161.88	—	—	—	—	—
	08/27/1997	1240	7.13	161.88	—	—	—	—	—
	08/27/1997	1255	7.13	161.88	—	—	—	—	—
	08/27/1997	1310	7.13	161.88	—	—	—	—	—
	08/27/1997	1325	7.13	161.88	—	—	—	—	—
	08/27/1997	1340	7.13	161.88	—	—	—	—	—
	08/27/1997	1355	7.13	161.88	—	—	—	—	—
	08/27/1997	1410	7.13	161.88	—	—	—	—	—
	08/27/1997	1510	7.13	161.88	—	—	—	—	—
	08/27/1997	1511	7.13	161.88	—	—	—	—	—
	08/27/1997	1610	7.13	161.88	—	—	—	—	—
	08/27/1997	1810	7.13	161.88	—	—	—	—	—
	08/28/1997	0930	7.13	161.88	—	—	—	—	—
	08/28/1997	1000	7.13	161.88	—	—	—	—	—
	08/28/1997	1030	7.13	161.88	—	—	—	—	—
	08/25/1998	1700	7.13	161.88	—	7.1	1,010	28.3	57.4
	08/28/1998	1055	7.13	161.88	—	7.2	1,020	29	55.7

Appendix A. Water-quality data for selected wells at the research field site in Montebello Forebay, Los Angeles County, California, 1997–2000—Continued

Station name (Local identifier)	Date	Time	Depth of well (ft) (72008)	Altitude of land surface (ft) (72000)	Oxygen, dissolved (mg/L) (00300)	pH, field (standard units) (00400)	Specific conductance, field (μS/cm) (00095)	Water temperature (°C) (00010)	Calcium, dissolved (mg/L as Ca) (00915)
2S/11-W18L32	08/28/1997	0930	12.25	161.43	—	—	—	—	—
(WP2)	08/28/1997	1000	12.25	161.43	—	—	—	—	—
	08/28/1997	1030	12.25	161.43	—	—	—	—	—
	08/25/1998	1100	12.25	161.43	0.2	7.1	992	28.6	56.9
	08/28/1998	1115	12.25	161.43	—	7.1	1,030	28.9	57.4
	08/04/2000	1030	12.25	161.43	—	—	—	—	—
2S/11-W18L42 (PR14)	08/25/1998	1600	60	172.4	—	7.4	641	21.1	47.7
2S/11-W18L43	08/25/1998	1730	35	172.4	.2	7.2	784	21.6	62
(PR15)	08/02/2000	1745	35	172.4	.3	6.7	891	21.5	67.5

Appendix A. Water-quality data for selected wells at the research field site in Montebello Forebay, Los Angeles County, California, 1997–2000—Continued

Station name (Local identifier)	Date	Time	Magnesium, dissoslved (mg/L as Mg) (00925)	Potassium, dissolved (mg/L as K) (90935)	Sodium, dissolved (mg/L as Na) (00930)	Acid neutralizing capacity, lab (mg/L as $CaCO_3$) (90410)	Alkalinity, fixed endpoint, field, (mg/L as $CaCO_3$) (39036)	Bromide, dissolved (mg/L as Br) (71870)	Chloride, dissolved (mg/L as Cl) (00940)
2S/11-W18L27 (PR8)	08/25/1998	1230	14.1	4.63	66.9	148	120	0.12	58
2S/11-W18L28 (PR9)	08/25/1998	0945	19.4	6.12	82.9	173	140	.13	93.2
	08/28/1998	1130	19.7	7.22	98.8	179	140	2.33	110
	08/02/2000	1530	15.7	12	101	—	185	.08	108
2S/11-W18L29 (PR10)	08/25/1998	1130	12.7	4.32	62.7	152	120	.1	46.8
2S/11-W18L30 (PR11)	08/25/1998	1030	18.9	6.01	76.6	167	140	.11	87.6
	08/28/1998	1000	17.7	8.4	107	172	140	31.3	113
	08/02/2000	1645	16.3	11.1	110	—	182	.08	108
Pond at Pico	08/27/1997	1134	—	—	—	—	—	67.2	120
	08/27/1997	1334	—	—	—	—	—	65.9	122
	08/27/1997	1504	—	—	—	—	—	78.7	121
	08/27/1997	1519	—	—	—	—	—	14.9	125
	08/27/1997	1719	—	—	—	—	—	11.1	130
	08/28/1997	1031	—	—	—	—	—	2.84	120
	08/25/1998	1300	16.5	14.4	110	137	140	.09	113
	08/28/1998	1200	16.2	14.9	108	147	140	.25	114
	08/02/2000	1730	16.6	12.9	108	—	188	.07	112
	08/04/2000	0300							
Sewage Effluent	08/25/1998	1800	16.7	10.7	107	121	170	.05	120
2S/11-W18L31 (WP1)	08/27/1997	1225	—	—	—	—	—	.13	126
	08/27/1997	1240	—	—	—	—	—	.47	124
	08/27/1997	1255	—	—	—	—	—	4.97	124
	08/27/1997	1310	—	—	—	—	—	19.1	124
	08/27/1997	1325	—	—	—	—	—	34.9	123
	08/27/1997	1340	—	—	—	—	—	49.9	125
	08/27/1997	1355	—	—	—	—	—	69.1	126
	08/27/1997	1410	—	—	—	—	—	22.5	121
	08/27/1997	1510	—	—	—	—	—	115	125
	08/27/1997	1511	—	—	—	—	—	115	123
	08/27/1997	1610	—	—	—	—	—	108	120
	08/27/1997	1810	—	—	—	—	—	85.9	123
	08/28/1997	0930	—	—	—	—	—	15.9	120
	08/28/1997	1000	—	—	—	—	—	5.51	122
	08/28/1997	1030	—	—	—	—	—	14.8	127
	08/25/1998	1700	16	12.4	108	147	140	.11	116
	08/28/1998	1055	16.1	20.2	112	162	150	7.79	115

Appendix A. Water-quality data for selected wells at the research field site in Montebello Forebay, Los Angeles County, California, 1997–2000—Continued

Station name (Local identifier)	Date	Time	Magnesium, dissoslved (mg/L as Mg) (00925)	Potassium, dissolved (mg/L as K) (90935)	Sodium, dissolved (mg/L as Na) (00930)	Acid neutralizing capacity, lab (mg/L as $CaCO_3$) (90410)	Alkalinity, fixed endpoint, field, (mg/L as $CaCO_3$) (39036)	Bromide, dissolved (mg/L as Br) (71870)	Chloride, dissolved (mg/L as Cl) (00940)
2S/11-W18L32	08/28/1997	0930	—	—	—	—	—	5.33	119
(WP2)	08/28/1997	1000	—	—	—	—	—	15.5	125
	08/28/1997	1030	—	—	—	—	—	4.72	130
	08/25/1998	1100	15.5	12.2	102	150	140	.09	109
	08/28/1998	1115	16.7	13.3	113	154	150	10.1	115
	08/04/2000	1030							
2S/11-W18L42 (PR14)	08/25/1998	1600	13.4	4.27	61.7	155	120	.09	48
2S/11-W18L43	08/25/1998	1730	18.9	6.11	67	162	130	.14	68.6
(PR15)	08/02/2000	1745	18.8	6.85	87.2	—	143	.17	95.2

Appendix A. Water-quality data for selected wells at the research field site in Montebello Forebay, Los Angeles County, California, 1997–2000—Continued

Station name (Local identifier)	Date	Time	Fluoride, dissolved (mg/L as F) (00950)	Iodine, dissolved (mg/L as I) (71865)	Silica, dissolved (mg/L as SiO_2) (00955)	Sulfate, dissolved (mg/L as SO_4) (00945)	Nitrogen, ammonia plus organic nitrogran, dissolved (mg/L as N) (00623)	Nitrogen, ammonia, dissolved (mg/L as N) (00608)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) (00631)
2S/11-W18L27 (PR8)	08/25/1998	1230	0.6	0.019	16.9	99	<0.1	0.03	0.91
2S/11-W18L28 (PR9)	08/25/1998	0945	.6	.024	16.9	115	.48	.03	2.22
	08/28/1998	1130	.7	.023	20.4	113	.67	.18	4.84
	08/02/2000	1530	.7	—	20.1	105	3	2.39	3.17
2S/11-W18L29 (PR10)	08/25/1998	1130	.7	.016	16.7	86.9	.12	.03	1.06
2S/11-W18L30 (PR11)	08/25/1998	1030	.5	.022	17.7	107	.34	.12	1.69
	08/28/1998	1000	.6	.016	21.7	112	.65	.22	3.46
	08/02/2000	1645	.6	—	20.3	105	1.3	.78	2.12
Pond at Pico	08/27/1997	1134	—	—	—	—	—	—	—
	08/27/1997	1334	—	—	—	—	—	—	—
	08/27/1997	1504	—	—	—	—	—	—	—
	08/27/1997	1519	—	—	—	—	—	—	—
	08/27/1997	1719	—	—	—	—	—	—	—
	08/28/1997	1031	—	—	—	—	—	—	—
	08/25/1998	1300	.6	.02	19.4	114	6.7	5.59	6.4
	08/28/1998	1200	.6	.017	19.8	108	6.9	5.58	5.71
	08/02/2000	1730	.6	—	21.9	105	8.8	<.02	<.05
	08/04/2000	0300	—	—	—	—	—	—	—
Sewage Effluent	08/25/1998	1800	.6	.077	20.5	105	16	15.4	4.62
2S/11-W18L31 (WP1)	08/27/1997	1225	—	—	—	—	—	—	—
	08/27/1997	1240	—	—	—	—	—	—	—
	08/27/1997	1255	—	—	—	—	—	—	—
	08/27/1997	1310	—	—	—	—	—	—	—
	08/27/1997	1325	—	—	—	—	—	—	—
	08/27/1997	1340	—	—	—	—	—	—	—
	08/27/1997	1355	—	—	—	—	—	—	—
	08/27/1997	1410	—	—	—	—	—	—	—
	08/27/1997	1510	—	—	—	—	—	—	—
	08/27/1997	1511	—	—	—	—	—	—	—
	08/27/1997	1610	—	—	—	—	—	—	—
	08/27/1997	1810	—	—	—	—	—	—	—
	08/28/1997	0930	—	—	—	—	—	—	—
	08/28/1997	1000	—	—	—	—	—	—	—
	08/28/1997	1030	—	—	—	—	—	—	—
	08/25/1998	1700	.5	.012	19.2	114	5.2	4.59	5.57
	08/28/1998	1055	.6	0.01	18.3	111	5.2	4.45	2.74

Appendix A. Water-quality data for selected wells at the research field site in Montebello Forebay, Los Angeles County, California, 1997–2000—Continued

Station name (Local identifier)	Date	Time	Fluoride, dissolved (mg/L as F) (00950)	Iodine, dissolved (mg/L as I) (71865)	Silica, dissolved (mg/L as SiO_2) (00955)	Sulfate, dissolved (mg/L as SO_4) (00945)	Nitrogen, ammonia plus organic nitrogran, dissolved (mg/L as N) (00623)	Nitrogen, ammonia, dissolved (mg/L as N) (00608)	Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) (00631)
2S/11-W18L32	08/28/1997	0930	—	—	—	—	—	—	—
(WP2)	08/28/1997	1000	—	—	—	—	—	—	—
	08/28/1997	1030	—	—	—	—	—	—	—
	08/25/1998	1100	0.6	0.021	19.8	113	5	4.38	5.3
	08/28/1998	1115	.6	.01	18.4	112	5.6	5.22	3.39
	08/04/2000	1030	—	—	—	—	—	—	—
2S/11-W18L42 (PR14)	08/25/1998	1600	.6	.017	16.9	87.7	<.1	.03	.43
2S/11-W18L43	08/25/1998	1730	.5	.031	17.8	121	<.1	.04	.09
(PR15)	08/02/2000	1745	.3		20.2	149	.13	<.02	.23

Appendix A. Water-quality data for selected wells at the research field site in Montebello Forebay, Los Angeles County, California, 1997–2000—Continued

Station name (Local identifier)	Date	Time	Nitrogen, nitrite, dissolved (mg/L as N) (00613)	Phosphorus, dissolved (mg/L as P) (00666)	Total organic carbon (mg/L) (00681)	Organic carbon, dissolved (mg/L) (00680	Boron, dissolved (mg/L as B) (01020)	Iron, dissolved (mg/L as Fe) (01046)	Manganese, dissolved (mg/L as Mn) (01056)
2S/11-W18L27 (PR8)	08/25/1998	1230	0.03		1.7		187	<10	934
2S/11-W18L28 (PR9)	08/25/1998	0945	.821	—	3.4	—	251	<10	1,420
	08/28/1998	1130	2.25	—	4.5	—	364	<10	1,370
	08/02/2000	1530	.378	1.46	—	4.5	438	18	4.5
2S/11-W18L29 (PR10)	08/25/1998	1130	.041	—	1.5	—	168	<10	920
2S/11-W18L30 (PR11)	08/25/1998	1030	.339	—	3.2	—	241	<10	1,010
	08/28/1998	1000	1.25	—	4.8	—	373	<10	<4
	08/02/2000	1645	.018	1.4	—	4.3	454	15	2.3
Pond at Pico	08/27/1997	1134	—	—	—	—	—	—	—
	08/27/1997	1334	—	—	—	—	—	—	—
	08/27/1997	1504	—	—	—	—	—	—	—
	08/27/1997	1519	—	—	—	—	—	—	—
	08/27/1997	1719	—	—	—	—	—	—	—
	08/28/1997	1031	—	—	—	—	—	—	—
	08/25/1998	1300	3.04	—	9	—	399	33	13.4
	08/28/1998	1200	2.73	—	8.8	—	372	29	4.3
	08/02/2000	1730	<.01	1.59	—	9.1	454	29	15.9
	08/04/2000	0300	—	—	—	9.5	—	—	—
Sewage Effluent	08/25/1998	1800	2.43	—	8.8	—	362	45	13.4
2S/11-W18L31 (WP1)	08/27/1997	1225	—	—	—	—	—	—	—
	08/27/1997	1240	—	—	—	—	—	—	—
	08/27/1997	1255	—	—	—	—	—	—	—
	08/27/1997	1310	—	—	—	—	—	—	—
	08/27/1997	1325	—	—	—	—	—	—	—
	08/27/1997	1340	—	—	—	—	—	—	—
	08/27/1997	1355	—	—	—	—	—	—	—
	08/27/1997	1410	—	—	—	—	—	—	—
	08/27/1997	1510	—	—	—	—	—	—	—
	08/27/1997	1511	—	—	—	—	—	—	—
	08/27/1997	1610	—	—	—	—	—	—	—
	08/27/1997	1810	—	—	—	—	—	—	—
	08/28/1997	0930	—	—	—	—	—	—	—
	08/28/1997	1000	—	—	—	—	—	—	—
	08/28/1997	1030	—	—	—	—	—	—	—
	08/25/1998	1700	2.57	—	6.6	—	400	284	55.7
	08/28/1998	1055	1.09	—	5.9	—	351	129	52.4
2S/11-W18L32 (WP2)	08/28/1997	0930	—	—	—	—	—	—	—
	08/28/1997	1000	—	—	—	—	—	—	—

Appendix A. Water-quality data for selected wells at the research field site in Montebello Forebay, Los Angeles County, California, 1997–2000—Continued

Station name (Local identifier)	Date	Time	Nitrogen, nitrite, dissolved (mg/L as N) (00613)	Phosphorus, dissolved (mg/L as P) (00666)	Total organic carbon (mg/L) (00681)	Organic carbon, dissolved (mg/L) (00680	Boron, dissolved (mg/L as B) (01020)	Iron, dissolved (mg/L as Fe) (01046)	Manganese, dissolved (mg/L as Mn) (01056)
	08/28/1997	1030	—	—	—	—	—	—	—
	08/25/1998	1100	2.6	—	5.8	—	369	24	21.3
	08/28/1998	1115	1.98	—	5.8	—	336	15	29.3
	08/04/2000	1030	—	—	—	4.6	—	—	—
2S/11-W18L42 (PR14)	08/25/1998	1600	.027	—	1.6	—	181	<10	828
2S/11-W18L43	08/25/1998	1730	<.01	—	2	—	194	<10	515
(PR15)	08/02/2000	1745	<.01	0.68	—	1.5	264	<10	2.3

Appendix B. Measured bacteriophage concentrations for water samples collected during the 1997 tracer experiment from a research field site located in Los Angeles County, California

[hr, hour; pfu/mL, plaque-forming units per millileter; <, actual value less than value shown; — no data; P2–P4, samples collected along perimeter of test basin]

Date and time collected		Elapsed time (hr)	PRD1 (pfu/mL)
	PR12		
08/27/1997	1104	0.23	1.9×10^4
08/27/1997	1119	0.48	2.8×10^4
08/27/1997	1134	0.73	2.1×10^4
08/27/1997	1149	0.98	2.4×10^4
08/27/1997	1204	1.23	2.3×10^4
08/27/1997	1219	1.48	2.1×10^4
08/27/1997	1234	1.73	2.6×10^4
08/27/1997	1249	1.98	1.7×10^4
08/27/1997	1304	2.23	2.1×10^4
08/27/1997	1319	2.48	2.1×10^4
08/27/1997	1334	2.73	2.3×10^4
08/27/1997	1349	2.98	2.7×10^4
08/27/1997	1404	3.23	2.7×10^4
08/27/1997	1419	3.48	2.1×10^4
08/27/1997	1434	3.73	1.9×10^4
08/27/1997	1449	3.98	2.2×10^4
08/27/1997	1504	4.23	1.7×10^4
08/27/1997	1519	4.48	3.8×10^2
08/27/1997	1534	4.73	4.0×10^2
08/27/1997	1549	4.98	2.0×10^2
08/27/1997	1604	5.23	9.9×10^1
08/27/1997	1619	5.48	1.6×10^2
08/27/1997	1634	5.73	1.6×10^2
08/27/1997	1649	5.98	1.6×10^2
08/27/1997	1704	6.23	1.1×10^2
08/27/1997	1719	6.48	9.0×10^1
08/27/1997	1734	6.73	1.3×10^2
08/27/1997	1749	6.98	1.1×10^2
08/27/1997	1804	7.23	1.2×10^2
08/28/1997	1030	23.67	4.2×10^1
08/28/1997	1330	26.67	2.4×10^1
	P2		
8/27/1997	11:02	0.20	2.6×10^2
8/27/1997	11:17	0.45	2.4×10^3
8/27/1997	11:32	0.70	2.5×10^3
	P3		
8/27/1997	11:47	0.95	1.4×10^3
8/27/1997	12:02	1.20	1.5×10^4

Date and time collected		Elapsed time (hr)	PRD1 (pfu/mL)	PRD1 (pfu/mL)
	WP1 (1.5 m)			**WP2 (3.0 m)**
08/27/1997	1140	0.83	<1	—
08/27/1997	1155	1.08	<1	—
08/27/1997	1201	1.18	<1	—
08/27/1997	1225	1.58	<1	—
08/27/1997	1240	1.83	1	—
08/27/1997	1255	2.08	15	—
08/27/1997	1310	2.33	50	—
08/27/1997	1325	2.58	88	—
08/27/1997	1340	2.83	100	—
08/27/1997	1355	3.08	130	—
08/27/1997	1410	3.33	85	—
08/27/1997	1425	3.58	120	—
08/27/1997	1440	3.83	110	—
08/27/1997	1455	4.08	93	—
08/27/1997	1510	4.33	87	—
08/27/1997	1525	4.58	66	—
08/27/1997	1540	4.83	140	—
08/27/1997	1555	5.08	62	—
08/27/1997	1610	5.33	120	—
08/27/1997	1625	5.58	45	—
08/27/1997	1640	5.83	67	—
08/27/1997	1655	6.08	57	—
08/27/1997	1710	6.33	60	—
08/27/1997	1725	6.58	58	<1
08/27/1997	1740	6.83	58	<1
08/27/1997	1755	7.08	46	<1
08/27/1997	1810	7.33	46	<1
08/28/1997	0900	22.17	6	<1
08/28/1997	0930	22.67	3	<1
08/28/1997	1000	23.17	7	<1
08/28/1997	1030	23.67	4	<1
08/28/1997	1100	24.17	6	<1
08/28/1997	1130	24.67	3	<1
08/28/1997	1200	25.17	6	<1
08/28/1997	1230	25.67	5	<1
08/28/1997	1300	26.17	3	<1
08/28/1997	1330	26.67	1	<1
08/28/1997	1400	27.17	6	<1
08/28/1997	1430	27.67	2	<1
08/28/1997	1500	28.17	6	<1

Appendix B. Measured bacteriophage for water samples collected during the 1997 tracer experiment from a research field site located in Los Angeles County, California—Continued

Date and time collected		Elapsed time (hr)	PRD1 (pfu/mL)
08/27/1997	1217	1.45	7.2×10^4
08/27/1997	1104	0.23	7.2×10^4
08/27/1997	1119	0.48	1.9×10^4
08/27/1997	1134	0.73	1.8×10^4
		P4	
08/27/1997	1149	0.98	2.8×10^4
08/27/1997	1204	1.23	2.0×10^4
08/27/1997	1219	1.48	1.6×10^4
08/27/1997	1108	0.30	3.0×10^0
08/27/1997	1123	0.55	4.0×10^0
08/27/1997	1138	0.80	9.0×10^0
08/27/1997	1157	1.12	7.0×10^0
08/27/1997	1208	1.30	1.6×10^1
08/27/1997	1223	1.55	1.1×10^1

Date and time collected		Elapsed time (hr)	PRD1 (pfu/mL)	PRD1 (pfu/mL)
08/28/1997	1530	28.67	2	<1
08/28/1997	1600	29.17	2	<1
08/28/1997	1700	30.17	4	<1
08/29/1997	1000	47.17	<1	<1

Appendix C. Measured bromide concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California

[hr, hour; mg/L, milligrams per liter; —, no data]

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
PR12	08/26/1998	1005	0.08	266.45
	08/26/1998	1030	.50	218.65
	08/26/1998	1100	1.00	116.40
	08/26/1998	1230	2.50	105.40
	08/26/1998	1405	4.08	101.25
	08/26/1998	1500	5.00	99.97
	08/26/1998	1600	6.00	99.78
	08/26/1998	1700	7.00	100.81
	08/26/1998	1800	8.00	99.33
	08/26/1998	1900	9.00	97.19
	08/26/1998	2000	10.00	97.04
	08/26/1998	2100	11.00	97.94
	08/26/1998	2200	12.00	98.42
	08/26/1998	2300	13.00	97.74
	08/26/1998	0000	14.00	99.88
	08/27/1998	0200	16.00	98.70
	08/27/1998	0600	20.00	97.92
	08/27/1998	0900	23.00	98.26
	08/27/1998	1000	24.00	74.50
	08/27/1998	1030	24.50	69.87
	08/27/1998	1100	25.00	61.28
	08/27/1998	1130	25.50	57.92
	08/27/1998	1200	26.00	53.82
	08/27/1998	1245	26.75	48.03
	08/27/1998	1315	27.25	40.75
	08/27/1998	1345	27.75	37.49
	08/27/1998	1500	29.00	29.95
	08/27/1998	1600	30.00	29.31
	08/27/1998	1700	31.00	22.69
	08/27/1998	1800	32.00	20.91
	08/28/1998	1200	50.00	2.88
	08/29/1998	0820	70.33	.40
	08/30/1998	0950	95.83	.40
	08/31/1998	1025	120.42	.40
	09/01/1998	0840	142.67	.40
	09/02/1998	0846	166.77	.40
	09/03/1998	0847	190.78	.40
	09/04/1998	0905	215.08	.40
P1	08/26/1998	1010	.17	—
	08/26/1998	1105	1.08	145.57
	08/26/1998	1405	4.08	103.11
	08/26/1998	1705	7.08	113.90

Appendix C. Measured bromide concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/27/1998	0700	21.00	98.21
P2	08/26/1998	1010	.17	133.07
	08/26/1998	1105	1.08	113.84
	08/26/1998	1405	4.08	97.93
	08/26/1998	1705	7.08	101.30
	08/27/1998	0700	21.00	98.51
P3	08/26/1998	1010	.17	116.89
	08/26/1998	1105	1.08	109.53
	08/26/1998	1405	4.08	102.50
	08/26/1998	1705	7.08	106.52
	08/27/1998	0700	21.00	98.94
P4	08/26/1998	1010	.17	55.33
	08/26/1998	1105	1.08	104.94
	08/26/1998	1405	4.08	97.95
	08/26/1998	1705	7.08	99.43
	08/27/1998	0700	21.00	99.96
WP1	08/26/1998	1030	0.50	.20
	08/26/1998	1100	1.00	.20
	08/26/1998	1130	1.50	.20
	08/26/1998	1230	2.50	.20
	08/26/1998	1305	3.08	.20
	08/26/1998	1330	3.50	.20
	08/26/1998	1335	3.58	.57
	08/26/1998	1340	3.67	1.31
	08/26/1998	1350	3.83	3.36
	08/26/1998	1355	3.92	4.98
	08/26/1998	1405	4.08	8.30
	08/26/1998	1410	4.17	12.19
	08/26/1998	1420	4.33	18.04
	08/26/1998	1425	4.42	21.87
	08/26/1998	1430	4.50	24.80
	08/26/1998	1435	4.58	32.13
	08/26/1998	1440	4.67	28.61
	08/26/1998	1445	4.75	37.13
	08/26/1998	1450	4.83	44.98
	08/26/1998	1455	4.92	48.67
	08/26/1998	1500	5.00	53.41
	08/26/1998	1505	5.08	64.49
	08/26/1998	1510	5.17	63.45
	08/26/1998	1515	5.25	67.45
	08/26/1998	1520	5.33	73.64
	08/26/1998	1530	5.50	78.30
	08/26/1998	1535	5.58	80.19
	08/26/1998	1540	5.67	83.65
	08/26/1998	1545	5.75	89.86

Appendix C. Measured bromide concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/26/1998	1550	5.83	95.50
	08/26/1998	1600	6.00	101.40
	08/26/1998	1615	6.25	109.97
	08/26/1998	1630	6.50	119.80
	08/26/1998	1645	6.75	124.30
	08/26/1998	1700	7.00	130.26
	08/26/1998	1715	7.25	132.37
	08/26/1998	1730	7.50	131.40
	08/26/1998	1800	8.00	125.82
	08/26/1998	1900	9.00	111.68
	08/26/1998	2000	10.00	105.06
	08/26/1998	2100	11.00	102.30
	08/26/1998	2200	12.00	100.11
	08/26/1998	2300	13.00	98.50
	08/27/1998	0000	14.00	99.02
	08/27/1998	0200	16.00	97.89
	08/27/1998	0600	20.00	91.31
	08/27/1998	0700	21.00	93.5
	08/27/1998	1245	26.75	98.09
	08/27/1998	1500	29.00	98.70
	08/27/1998	1600	30.00	101.54
	08/27/1998	1700	31.00	91.31
	08/27/1998	1800	32.00	85.69
	08/28/1998	1055	48.92	7.80
	08/28/1998	1205	50.08	.40
	08/29/1998	0810	70.17	.70
	08/30/1998	0935	95.58	.40
	08/31/1998	1012	120.20	.40
	09/01/1998	0825	142.42	.40
	09/02/1998	0930	167.50	.40
	09/03/1998	0842	190.70	.40
	09/04/1998	0855	214.92	.40
WP2	08/26/1998	1405	4.08	.20
	08/26/1998	1500	5.00	.20
	08/26/1998	1600	6.00	.20
	08/26/1998	1700	7.00	.20
	08/26/1998	1800	8.00	4.31
	08/26/1998	1820	8.33	17.15
	08/26/1998	1830	8.50	22.79
	08/26/1998	1840	8.67	33.22
	08/26/1998	1850	8.83	42.33
	08/26/1998	1900	9.00	57.48
	08/26/1998	1915	9.25	70.37
	08/26/1998	1930	9.50	87.42

Appendix C. Measured bromide concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/26/1998	1945	9.75	100.58
	08/26/1998	2000	10.00	114.28
	08/26/1998	2015	10.25	107.70
	08/26/1998	2030	10.50	125.96
	08/26/1998	2100	11.00	138.94
	08/26/1998	2115	11.25	134.75
	08/26/1998	2200	12.00	135.57
	08/26/1998	2300	13.00	122.93
	08/26/1998	0000	14.00	112.37
	08/27/1998	0200	16.00	104.45
	08/27/1998	0600	20.00	97.41
	08/27/1998	0700	21.00	101.24
	08/27/1998	1000	24.00	97.88
	08/27/1998	1315	27.25	96.80
	08/27/1998	1630	30.50	97.10
	08/27/1998	1800	32.00	91.79
	08/28/1998	1115	49.25	8.71
	08/29/1998	0815	70.25	1.26
	08/30/1998	0940	95.67	.40
	08/31/1998	1013	120.22	.40
	09/01/1998	0825	142.42	.40
	09/02/1998	0840	166.67	.40
	09/03/1998	0856	190.93	.40
	09/04/1998	0915	215.25	.40
WP7	08/26/1998	2200	12.00	.2
	08/27/1998	0200	16.00	4.73
	08/27/1998	0600	20.00	5.46
	08/27/1998	1030	24.50	.2
	08/27/1998	1115	25.25	.2
	08/27/1998	1245	26.75	.2
	08/27/1998	1500	29.00	.2
	08/27/1998	1600	30.00	.2
	08/27/1998	1700	31.00	.2
	08/27/1998	1800	32.00	4.18
	08/28/1998	1030	48.50	39.81
	08/29/1998	0830	70.50	68.40
	08/30/1998	0925	95.42	7.37
	08/31/1998	1006	120.10	.98
	09/01/1998	0830	142.50	.2
	09/02/1998	0955	167.92	.26
	09/03/1998	0835	190.58	.2
	09/04/1998	0900	215.00	.2
PR9	08/26/1998	1500	5.00	.2
	08/26/1998	1600	6.00	.2
	08/26/1998	1700	7.00	.2
	08/26/1998	1800	8.00	0.2

Appendix C. Measured bromide concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/26/1998	1900	9.00	.2
	08/26/1998	2000	10.00	.2
	08/26/1998	2100	11.00	.2
	08/27/1998	0200	16.00	.2
	08/27/1998	0415	18.25	.2
	08/27/1998	0600	20.00	.2
	08/27/1998	0700	21.00	.2
	08/27/1998	0900	23.00	.2
	08/27/1998	1000	24.00	.2
	08/27/1998	1030	24.50	.2
	08/27/1998	1100	25.00	.2
	08/27/1998	1130	25.50	.2
	08/27/1998	1245	26.75	.2
	08/27/1998	1315	27.25	.2
	08/27/1998	1500	29.00	.2
	08/27/1998	1600	30.00	.2
	08/27/1998	1700	31.00	.2
	08/27/1998	1800	32.00	.2
	08/28/1998	1130	49.50	2.73
	08/29/1998	855	70.92	32.59
	08/30/1998	1000	96.00	28.04
	08/31/1998	1030	120.50	5.98
	09/01/1998	0855	142.92	.19
	09/02/1998	0925	167.42	.2
	09/03/1998	0856	190.93	.2
	09/04/1998	0925	215.42	.2
PR11	08/27/1998	0700	21.00	<.3
	08/27/1998	1100	25.00	.5
	08/27/1998	1115	25.25	.5
	08/27/1998	1515	29.25	.6
	08/27/1998	1630	30.50	.5
	08/27/1998	1800	32.00	1
	08/28/1998	0925	47.42	4.2
	08/28/1998	1000	48.00	14
	08/29/1998	0800	70.00	31
	08/30/1998	0855	94.92	55
	08/31/1998	0935	119.58	64
	09/01/1998	0811	142.18	56
	09/02/1998	0821	166.35	43
	09/03/1998	0814	190.23	17
	09/04/1998	0830	214.50	3.7
GP1	08/26/1998	1320	3.33	108.90
	08/26/1998	1605	6.08	98.18
	08/26/1998	1915	9.25	95.50

Appendix C. Measured bromide concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/27/1998	0720	21.33	97.59
GP2	08/26/1998	1315	3.25	124.1
	08/26/1998	1610	6.17	98.40
	08/26/1998	1910	9.17	96.11
	08/27/1998	0735	21.58	97.9
GP3	08/26/1998	1310	3.17	179.00
	08/26/1998	1615	6.25	102.00
	08/26/1998	1905	9.08	96.30
GP3	08/26/1998	1310	3.17	179.00

Appendix D. Measured bacteriophage concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California

[hr, hour; pfu/L, plaque forming units per milliliter]

Sample	Date and time collected		Elapsed time (hr)	MS2 (pfu/mL)	PRD1 (pfu/mL)
PR12	08/26/1998	1005	0.08	6.5×10^{5}	6.9×10^{4}
	08/26/1998	1105	1.08	3.3×10^{5}	3.0×10^{4}
	08/26/1998	1205	2.08	2.4×10^{5}	2.0×10^{4}
	08/26/1998	1305	3.08	2.2×10^{5}	3.0×10^{4}
	08/26/1998	1405	4.08	2.9×10^{5}	3.1×10^{4}
	08/26/1998	1500	5.00	2.5×10^{5}	3.1×10^{4}
	08/26/1998	1605	6.08	1.9×10^{5}	1.5×10^{4}
	08/26/1998	1705	7.08	1.5×10^{5}	1.2×10^{4}
	08/27/1998	0105	15.08	6.6×10^{4}	6.4×10^{3}
	08/27/1998	0700	21.00	5.4×10^{4}	9.0×10^{3}
	08/27/1998	0900	23.00	4.9×10^{4}	7.4×10^{3}
	08/27/1998	1000	24.00	2.0×10^{4}	2.4×10^{3}
	08/27/1998	1100	25.00	1.6×10^{4}	1.9×10^{3}
	08/27/1998	1200	26.00	1.4×10^{4}	1.1×10^{3}
	08/27/1998	1505	29.08	1.7×10^{3}	6.5×10^{0}
	08/27/1998	1705	31.08	7.2×10^{2}	1.5×10^{0}
	08/28/1998	0937	47.62	5.1×10^{1}	$.0 \times 10^{0}$
	08/29/1998	0820	70.33	5.5×10^{0}	1.0×10^{0}
	08/30/1998	0950	95.83	5.0×10^{-1}	5.0×10^{-1}
	08/31/1998	1025	120.42	2.0×10^{-2}	2.0×10^{2}
	09/01/1998	0840	142.67	3.5×10^{0}	2.0×10^{-2}
	09/02/1998	0846	166.77	2.8×10^{0}	2.0×10^{-2}
	09/03/1998	0847	190.78	2.8×10^{0}	2.0×10^{-2}
	09/04/1998	0905	215.08	8.0×10^{-1}	2.0×10^{-2}
P1	08/26/1998	1010	.17	6.5×10^{5}	6.9×10^{4}
	08/26/1998	1105	1.08	3.3×10^{5}	3.0×10^{4}
	08/26/1998	1405	4.08	2.9×10^{5}	3.1×10^{4}
	08/26/1998	1705	7.08	1.5×10^{5}	1.2×10^{4}
	08/27/1998	0700	21.00	5.4×10^{4}	9.0×10^{3}
P2	08/26/1998	1010	.17	2.2×10^{4}	2.1×10^{3}
	08/26/1998	1105	1.08	4.1×10^{5}	3.8×10^{4}
	08/26/1998	1405	4.08	2.7×10^{5}	2.7×10^{4}
	08/26/1998	1705	7.08	6.3×10^{4}	6.8×10^{3}
	08/27/1998	0700	21.00	3.5×10^{4}	8.1×10^{3}
P3	08/26/1998	1010	.17	3.5×10^{5}	3.0×10^{4}
	08/26/1998	1105	1.08	3.5×10^{5}	4.2×10^{4}
	08/26/1998	1405	4.08	1.2×10^{5}	2.3×10^{4}
	08/26/1998	1705	7.08	9.4×10^{4}	1.5×10^{4}

Appendix D. Measured bacteriophage concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				(pfu/mL)	
	08/27/1998	0700	21.00	5.4×10^{4}	8.9×10^{3}
P4	08/26/1998	1010	.17	5.4×10^{4}	8.9×10^{3}
	08/26/1998	1105	1.08	5.9×10^{5}	4.2×10^{4}
	08/26/1998	1405	4.08	1.1×10^{5}	2.0×10^{4}
	08/26/1998	1705	7.08	1.2×10^{5}	8.9×10^{3}
	08/27/1998	0700	21.00	6.7×10^{4}	1.0×10^{4}
WP1	08/26/1998	1205	2.08	5.0×10^{-1}	$.0 \times 10^{0}$
	08/26/1998	1305	3.08	5.7×10^{1}	5.0×10^{-1}
	08/26/1998	1405	4.08	5.5×10^{3}	1.2×10^{2}
	08/26/1998	1500	5.00	1.8×10^{4}	2.0×10^{2}
	08/26/1998	1605	6.08	3.2×10^{4}	3.2×10^{2}
	08/26/1998	1705	7.08	6.0×10^{4}	2.6×10^{2}
	08/26/1998	1800	8.00	3.7×10^{4}	2.3×10^{2}
	08/26/1998	1900	9.00	3.9×10^{4}	1.8×10^{2}
	08/26/1998	2005	10.08	2.4×10^{4}	1.5×10^{2}
	08/26/1998	2105	11.08	2.1×10^{4}	1.1×10^{2}
	08/26/1998	2305	13.08	1.2×10^{4}	5.1×10^{1}
	08/27/1998	0105	15.08	9.3×10^{3}	2.0×10^{1}
	08/27/1998	0300	17.00	9.5×10^{2}	1.8×10^{1}
	08/27/1998	0500	19.00	1.5×10^{2}	1.0×10^{1}
	08/27/1998	0700	21.00	1.0×10^{3}	5.0×10^{0}
	08/27/1998	0900	23.00	1.3×10^{3}	2.5×10^{0}
	08/27/1998	1100	25.00	8.6×10^{2}	2.0×10^{0}
	08/27/1998	1305	27.08	6.2×10^{2}	1.0×10^{0}
	08/27/1998	1505	29.08	4.0×10^{2}	3.5×10^{0}
	08/27/1998	1705	31.08	6.9×10^{2}	1.0×10^{0}
	08/27/1998	1805	32.08	4.5×10^{2}	5.0×10^{-1}
	08/28/1998	0955	47.92	2.4×10^{0}	4.0×10^{-2}
	08/29/1998	0810	70.17	4.7×10^{1}	1.5×10^{0}
	08/30/1998	0935	95.58	1.6×10^{1}	6.0×10^{-2}
	08/31/1998	10:12	120.20	3.0×10^{0}	2.0×10^{-2}
	09/01/1998	0825	142.42	2.4×10^{0}	2.0×10^{-2}
	09/02/1998	0930	167.50	5.0×10^{0}	2.0×10^{-2}
	09/03/1998	0842	190.70	1.3×10^{0}	2.0×10^{-2}
	09/04/1998	0855	214.92	2.3×10^{-1}	2.0×10^{-2}
WP2	08/26/1998	1405	4.08	2.0×10^{-2}	2.0×10^{-2}
	08/26/1998	1500	5.00	4.0×10^{-2}	2.0×10^{-2}
	08/26/1998	1805	8.08	1.1×10^{3}	5.0×10^{1}
	08/26/1998	1902	9.03	1.0×10^{4}	1.2×10^{2}
	08/26/1998	2005	10.08	2.0×10^{4}	2.0×10^{2}
	08/26/1998	2105	11.08	2.3×10^{4}	2.2×10^{2}
	08/26/1998	2205	12.08	2.5×10^{4}	2.4×10^{2}
	08/26/1998	2305	13.08	2.6×10^{4}	3.4×10^{2}
	08/27/1998	0005	14.08	3.4×10^{4}	4.2×10^{2}
	08/27/1998	0105	15.08	2.5×10^{4}	5.6×10^{2}

Appendix D. Measured bacteriophage concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				(pfu/mL)	
	08/27/1998	0203	16.05	4.0×10^{2}	4.3×10^{2}
	08/27/1998	0300	17.00	2.3×10^{3}	2.7×10^{2}
	08/27/1998	0400	18.00	2.5×10^{3}	1.2×10^{2}
	08/27/1998	0500	19.00	6.6×10^{2}	8.0×10^{1}
	08/27/1998	0600	20.00	4.6×10^{2}	7.5×10^{1}
	08/27/1998	0700	21.00	1.6×10^{1}	2.0×10^{-2}
	08/27/1998	0900	23.00	1.2×10^{3}	1.3×10^{0}
	08/27/1998	1100	25.00	8.0×10^{2}	2.8×10^{0}
	08/27/1998	1305	27.08	2.8×10^{3}	3.0×10^{1}
	08/27/1998	1505	29.08	2.4×10^{3}	0.0×10^{0}
	08/27/1998	1705	31.08	1.6×10^{1}	1.4×10^{0}
	08/27/1998	1805	32.08	1.6×10^{1}	7.0×10^{-1}
	08/28/1998	0955	47.92	2.4×10^{0}	1.1×10^{-1}
	08/29/1998	0815	70.25	2.4×10^{0}	9.0×10^{-2}
	08/30/1998	0940	95.67	2.4×10^{0}	2.0×10^{-2}
	08/31/1998	1013	120.22	8.0×10^{-1}	2.0×10^{-2}
	09/01/1998	0825	142.42	2.4×10^{0}	2.0×10^{-2}
	09/02/1998	0840	166.67	5.0×10^{0}	2.0×10^{-2}
	09/03/1998	0856	190.93	8.0×10^{-1}	2.0×10^{-2}
	09/04/1998	0915	215.25	1.1×10^{0}	2.0×10^{-2}
WP7	08/27/1998	0700	21.00	>1/1000	<1/1000
	08/27/1998	1100	25.00	<1/1000	<1/1000
	08/27/1998	1505	29.08	<1/1000	<1/1000
	08/27/1998	1805	32.08	>1/1000	<1/1000
	08/28/1998	1000	48.00	>1/1000	<1/1000
	08/29/1998	0830	70.50	>1/1000	>1/1000
	08/30/1998	0925	95.42	>1/1000	<1/1000
	08/31/1998	1006	120.10	>1/1000	<1/1000
	09/01/1998	0830	142.50	>1/1000	<1/
	09/02/1998	0955	167.92	>1/1000	>1/1000
	09/03/1998	0835	190.58	>1/1000	>1/1000
	09/04/1998	0900	215.00	>1/1000	>1/1000
PR9	08/26/1998	1900	9.00	<1/100	<1/1000
	08/26/1998	2105	11.08	<1/100	<1/1000
	08/26/1998	2305	13.08	>1/100	<1/1000
	08/27/1998	0105	15.08	<1/100	<1/1000
	08/27/1998	0400	18.00	<1/100	<1/1000
	08/27/1998	0700	21.00	<1/100	<1/1000
	08/27/1998	1100	25.00	<1/100	<1/1000
	08/27/1998	1505	29.08	<1/100	<1/1000
	08/27/1998	1805	32.08	<1/100	<1/1000
	08/28/1998	1055	48.92	>1/100	<1/1000
	08/29/1998	0855	70.92	>1/100	<1/1000
	08/30/1998	1000	96.00	>1/100	<1/1000

Appendix D. Measured bacteriophage concentrations for water samples collected during the 1998 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				(pfu/mL)	
	08/31/1998	1030	120.50	>1/100	<1/1000
	09/01/1998	0855	142.92	>1/100	<1/
	09/02/1998	0925	167.42	>1/100	<1/1000
	09/03/1998	0856	190.93	>1/100	<1/1000
	09/04/1998	0925	215.42	>1/100	<1/1000
PR11	08/27/1998	0700	21.00	>1/1000	<1/1000
	08/27/1998	1100	25.00	>1/1000	<1/1000
	08/27/1998	1505	29.08	<1/1000	<1/1000
	08/27/1998	1805	32.08	<1/1000	<1/1000
	08/28/1998	0925	47.42	>1/1000	<1/1000
	08/29/1998	0800	70.00	>1/1000	>1/1000
	08/30/1998	0855	94.92	>1/1000	<1/1000
	08/31/1998	0935	119.58	>1/1000	<1/1000
	09/01/1998	0811	142.18	>1/1000	<1/
	09/02/1998	0821	166.35	>1/1000	<1/1000
	09/03/1998	0814	190.23	>1/1000	<1/1000
	09/04/1998	0830	214.50	>1/1000	<1/1000
GP1	08/26/1998	1320	3.33	1.4×10^5	1.1×10^4
	08/26/1998	1605	6.08	9.0×10^4	1.1×10^4
	08/26/1998	1915	9.25	1.1×10^5	8.0×10^3
	08/27/1998	0720	21.33	1.9×10^4	3.4×10^3
GP2	08/26/1998	1315	3.25	1.3×10^5	6.5×10^3
	08/26/1998	1610	6.17	9.8×10^4	6.7×10^3
	08/26/1998	1910	9.17	8.6×10^4	5.9×10^3
	08/27/1998	0735	21.58	3.6×10^3	2.1×10^2
GP3	08/26/1998	1310	3.17	1.1×10^5	2.4×10^3
	08/26/1998	1615	6.25	2.3×10^4	7.5×10^2
	08/26/1998	1905	9.08	4.1×10^4	1.9×10^3
	08/27/1998	0745	21.75	2.4×10^3	5.5×10^1

Appendix E. Measured bromide concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California

[hr, hour; mg/L, milligrams per liter]

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
PR12	08/03/2000	1600	0.50	185
	08/03/2000	1700	1.50	95
	08/03/2000	1800	2.50	80
	08/03/2000	1900	3.50	90
	08/03/2000	2000	4.50	86
	08/03/2000	2100	5.50	85
	08/03/2000	2200	6.50	86
	08/03/2000	2300	7.50	81
	08/04/2000	0000	8.50	80
	08/04/2000	0100	9.50	82
	08/04/2000	0200	10.50	93
	08/04/2000	0300	11.50	95
	08/04/2000	0400	12.50	86
	08/04/2000	0500	13.50	86
	08/04/2000	0600	14.50	84
	08/04/2000	1200	20.50	68
	08/04/2000	2000	28.50	36
	08/04/2000	2200	30.50	33
	08/05/2000	0000	32.50	29
	08/05/2000	0745	40.25	23
	08/05/2000	1230	45.00	14
	08/05/2000	1800	50.50	9.1
	08/06/2000	0600	62.50	4.9
	08/06/2000	1200	68.50	2.9
	08/06/2000	1800	74.50	2.2
	08/07/2000	1230	93.00	.7
	08/07/2000	1630	97.00	.6
	08/08/2000	0800	112.50	.5
	08/08/2000	1300	117.50	.4
	08/08/2000	1700	121.50	.5
	08/09/2000	0800	136.50	.5
	08/10/2000	1150	164.33	.5
WP1	08/03/2000	1630	1.00	<0.3
	08/03/2000	1900	3.50	1.1
	08/03/2000	1910	3.67	2.9
	08/03/2000	1922	3.87	9.2
	08/03/2000	1930	4.00	23
	08/03/2000	1940	4.17	50
	08/03/2000	1950	4.33	71
	08/03/2000	2000	4.50	94
	08/03/2000	2015	4.75	124
	08/03/2000	2030	5.00	165
	08/03/2000	2045	5.25	190

Appendix E. Measured bromide concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/03/2000	2100	5.50	210
	08/03/2000	2115	5.75	210
	08/03/2000	2130	6.00	190
	08/03/2000	2145	6.25	180
	08/03/2000	2200	6.50	145
	08/03/2000	2300	7.50	92
	08/04/2000	0000	8.50	81.3
	08/04/2000	0100	9.50	83
	08/04/2000	0200	10.50	80
	08/04/2000	0300	11.50	80
	08/04/2000	0400	12.50	81
	08/04/2000	0500	13.50	78
	08/04/2000	0600	14.50	80
	08/04/2000	0800	16.50	80
	08/04/2000	1000	18.50	81
	08/04/2000	1200	20.50	79
	08/04/2000	1400	22.50	79
	08/04/2000	1600	24.50	78
	08/04/2000	2000	28.50	63
	08/04/2000	2200	30.50	54
	08/05/2000	0000	32.50	42.3
	08/05/2000	0800	40.50	29
	08/05/2000	1800	50.50	14
	08/06/2000	0600	62.50	12
	08/06/2000	1800	74.50	3.1
	08/08/2000	0800	112.50	.7
	08/09/2000	0800	136.50	.8
WP2	08/03/2000	2130	6.00	<.3
	08/03/2000	2200	6.50	<.3
	08/03/2000	2300	7.50	.5
	08/04/2000	0000	8.50	.5
	08/04/2000	0100	9.50	.6
	08/04/2000	0130	10.00	4.1
	08/04/2000	0140	10.17	11
	08/04/2000	0150	10.33	16
	08/04/2000	0200	10.50	29
	08/04/2000	0215	10.75	46
	08/04/2000	0230	11.00	60
	08/04/2000	0245	11.25	88
	08/04/2000	0300	11.50	105
	08/04/2000	0315	11.75	121
	08/04/2000	0330	12.00	125
	08/04/2000	0400	12.50	140
	08/04/2000	0500	13.50	135
	08/04/2000	0600	14.50	126
	08/04/2000	0700	15.50	107

Appendix E. Measured bromide concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/04/2000	0800	16.50	94
	08/04/2000	0900	17.50	95
	08/04/2000	1000	18.50	89
	08/04/2000	1200	20.50	87
	08/04/2000	1400	22.50	85
	08/04/2000	1600	24.50	86
	08/04/2000	2000	28.50	81
	08/04/2000	2200	30.50	83
	08/05/2000	0000	32.50	76
	08/05/2000	1800	50.50	21
	08/06/2000	0600	62.50	10
	08/06/2000	1800	74.50	4.9
	08/08/2000	0800	112.50	1.4
	08/09/2000	0800	136.50	.7
	08/10/2000	1130	164.00	<.3
WP7	08/04/2000	1300	21.50	<0.3
	08/04/2000	1500	23.50	.7
	08/04/2000	1700	25.50	6.2
	08/04/2000	1745	26.25	10
	08/04/2000	1800	26.50	10
	08/04/2000	1815	26.75	13
	08/04/2000	1830	27.00	14
	08/04/2000	1900	27.50	19
	08/04/2000	2000	28.50	22
	08/04/2000	2200	30.50	21
	08/05/2000	0000	32.50	25
	08/05/2000	0845	41.25	58
	08/05/2000	1245	45.25	59
	08/05/2000	1800	50.50	58
	08/06/2000	0600	62.50	36
	08/06/2000	1158	68.47	34
	08/06/2000	1800	74.50	22
	08/07/2000	0815	88.75	8.8
	08/07/2000	1230	93.00	7.1
	08/07/2000	1630	97.00	5.7
	08/08/2000	0800	112.50	2
	08/08/2000	1300	117.50	1.8
	08/08/2000	1700	121.50	1.5
	08/09/2000	0830	137.00	.9
	08/10/2000	1115	163.75	.9
PR9	08/04/2000	0730	16.00	.5
	08/04/2000	1130	20.00	.5
	08/04/2000	1300	21.50	.6
	08/04/2000	1500	23.50	1.1

Appendix E. Measured bromide concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/04/2000	1700	25.50	1.5
	08/04/2000	2000	28.50	2.3
	08/04/2000	2030	29.00	2.3
	08/04/2000	2100	29.50	2.7
	08/04/2000	2200	30.50	2.9
	08/05/2000	0000	32.50	3.8
	08/05/2000	0730	40.00	7
	08/05/2000	1330	46.00	11
	08/05/2000	1800	50.50	19
	08/06/2000	0600	62.50	49
	08/06/2000	1230	69.00	56
	08/06/2000	1800	74.50	56
	08/07/2000	1230	93.00	31
	08/08/2000	0800	112.50	8.5
	08/08/2000	1330	118.00	6.2
	08/08/2000	1700	121.50	5
	08/09/2000	0800	136.50	1.9
	08/10/2000	1145	164.25	.5
PR11	08/04/2000	1130	20.00	<.3
	08/04/2000	1300	21.50	.5
	08/04/2000	1500	23.50	.5
	08/04/2000	1700	25.50	.6
	08/04/2000	2000	28.50	.5
	08/04/2000	2200	30.50	1
	08/05/2000	0000	32.50	4.2
	08/05/2000	0815	40.75	14
	08/05/2000	1230	45.00	31
	08/05/2000	1800	50.50	55
	08/06/2000	0600	62.50	64
	08/06/2000	1200	68.50	56
	08/06/2000	1800	74.50	43
	08/07/2000	1230	93.00	17
	08/08/2000	0820	112.83	3.7
	08/08/2000	1300	117.50	2.8
	08/08/2000	1700	121.50	1.9
	08/09/2000	0800	136.50	.7
	08/10/2000	1200	164.50	.4
GP1	08/03/2000	1630	1.00	140
	08/03/2000	1645	1.25	167
	08/03/2000	1700	1.50	155
	08/03/2000	1722	1.87	160
	08/03/2000	1800	2.50	152
	08/03/2000	1835	3.08	158
	08/03/2000	1900	3.50	156
	08/03/2000	1936	4.10	90
	08/03/2000	2000	4.50	80

Appendix E. Measured bromide concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/03/2000	2100	5.50	88
	08/03/2000	2200	6.50	80
	08/03/2000	2300	7.50	78
	08/04/2000	0000	8.50	81
	08/04/2000	0100	9.50	84
	08/04/2000	0200	10.50	82
	08/04/2000	0300	11.50	84
	08/04/2000	0400	12.50	85
	08/04/2000	0500	13.50	83
	08/04/2000	0600	14.50	83
	08/04/2000	0700	15.50	81
	08/04/2000	0800	16.50	79
	08/04/2000	0900	17.50	85
	08/04/2000	1000	18.50	82
	08/04/2000	1100	19.50	77
	08/04/2000	1200	20.50	74
	08/04/2000	1500	23.50	69
	08/04/2000	2100	29.50	39
	08/05/2000	0000	32.50	34
	08/05/2000	0600	38.50	23
	08/05/2000	1800	50.50	9.8
	08/06/2000	0600	62.50	4.8
	08/06/2000	1800	74.50	2.2
GP2	08/03/2000	1635	1.08	.6
	08/03/2000	1646	1.27	.4
	08/03/2000	1700	1.50	8.7
	08/03/2000	1726	1.93	60
	08/03/2000	1800	2.50	150
	08/03/2000	1838	3.13	130
	08/03/2000	1900	3.50	97
	08/03/2000	1934	4.07	95
	08/03/2000	2000	4.50	82
	08/03/2000	2100	5.50	81
	08/03/2000	2200	6.50	82
	08/03/2000	2300	7.50	81
	08/04/2000	0000	8.50	82
	08/04/2000	0100	9.50	79
	08/04/2000	0200	10.50	77
	08/04/2000	0300	11.50	80
	08/04/2000	0400	12.50	62
	08/04/2000	0500	13.50	77
	08/04/2000	0600	14.50	90
	08/04/2000	0700	15.50	81
	08/04/2000	0800	16.50	89

Appendix E. Measured bromide concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/04/2000	0900	17.50	91
	08/04/2000	1000	18.50	81
	08/04/2000	1100	19.50	82
	08/04/2000	1200	20.50	70
	08/04/2000	1500	23.50	73
	08/04/2000	2100	29.50	40
	08/05/2000	0000	32.50	37
	08/05/2000	0600	38.50	26
	08/05/2000	1800	50.50	12
	08/06/2000	0600	62.50	5.9
	08/06/2000	1800	74.50	2.5
GP3	08/03/2000	1800	2.50	<.3
	08/03/2000	1840	3.17	.8
	08/03/2000	1900	3.50	38.7
	08/03/2000	1932	4.03	85
	08/03/2000	2000	4.50	113.1
	08/03/2000	2100	5.50	93.9
	08/03/2000	2200	6.50	73
	08/03/2000	2300	7.50	71.5
	08/04/2000	0000	8.50	72
	08/04/2000	0100	9.50	68.4
	08/04/2000	0200	10.50	69.1
	08/04/2000	0300	11.50	72.1
	08/04/2000	0400	12.50	71.1
	08/04/2000	0600	14.50	72.8
	08/04/2000	0700	15.50	73.2
	08/04/2000	0800	16.50	72.3
	08/04/2000	0900	17.50	73.3
	08/04/2000	1000	18.50	79.8
	08/04/2000	1100	19.50	73.9
	08/04/2000	1200	20.50	73.8
	08/04/2000	1500	23.50	73.8
	08/04/2000	2100	29.50	75.4
	08/05/2000	0000	32.50	49
	08/05/2000	0600	38.50	35.7
	08/05/2000	1800	50.50	25.6
	08/06/2000	0600	62.50	6.5
	08/06/2000	1800	74.50	2.7
GP4	08/03/2000	1700	1.5	<.3
	08/03/2000	1800	2.5	<.3
	08/03/2000	1850	3.3	22.4
	08/03/2000	1900	3.5	49.5
	08/03/2000	1930	4	90.8
	08/03/2000	2000	4.5	144
	08/03/2000	2100	5.5	100.4
	08/03/2000	2200	6.5	75.3

Appendix E. Measured bromide concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/03/2000	2300	7.5	74.6
	08/04/2000	0000	8.5	75.3
	08/04/2000	0100	9.5	73.9
	08/04/2000	0200	10.5	74.1
	08/04/2000	0300	11.5	72.2
	08/04/2000	0400	12.5	68.1
	08/04/2000	0500	13.5	71.2
	08/04/2000	0600	14.5	71.4
	08/04/2000	0700	15.5	72.7
	08/04/2000	0800	16.5	64.3
	08/04/2000	0900	17.5	72.2
	08/04/2000	1000	18.5	78.3
	08/04/2000	1000	18.5	78.3
	08/04/2000	1100	19.5	69.9
	08/04/2000	1200	20.5	71
	08/04/2000	1500	23.5	69.9
	08/04/2000	2100	29.5	46
	08/05/2000	0000	32.5	35.1
	08/05/2000	0600	38.5	24.2
	08/05/2000	1800	50.5	12
	08/06/2000	0600	62.5	6.5
	08/06/2000	1800	74.5	2.8
GP5	08/03/2000	1800	2.5	<.3
	08/03/2000	1900	3.5	<.3
	08/03/2000	1924	3.9	13
	08/03/2000	2000	4.5	63.4
	08/03/2000	2100	5.5	141.4
	08/03/2000	2200	6.5	92.5
	08/03/2000	2300	7.5	77.4
	08/04/2000	0000	8.5	84.4
	08/04/2000	0100	9.5	85.5
	08/04/2000	0200	10.5	82.1
	08/04/2000	0300	11.5	82.1
	08/04/2000	0400	12.5	83.6
	08/04/2000	0500	13.5	83.2
	08/04/2000	0600	14.5	84.1
	08/04/2000	0700	15.5	83.8
	08/04/2000	0800	16.5	79.1
	08/04/2000	0900	17.5	77.6
	08/04/2000	1000	18.5	81.3
	08/04/2000	1100	19.5	77.5
	08/04/2000	1200	20.5	78.2
	08/04/2000	1400	22.5	76
	08/04/2000	1600	24.5	79.7

Appendix E. Measured bromide concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	Bromide (mg/L)
	08/04/2000	2200	30.5	63.5
	08/05/2000	0000	32.5	61.6
	08/05/2000	1800	50.5	13
	08/06/2000	0600	62.5	7.7
	08/06/2000	1800	74.5	3.7

Appendix F. Measured bacteriophage concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California

[hr, hour; MPN, most probable number; pfu/L, plaque forming units per liter]

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				MPN(pfu/L)	
PR12	08/03/2000	1600	0.5	9.50×10^7	1.26×10^7
	08/03/2000	1700	1.5	6.60×10^7	4.70×10^6
	08/03/2000	1900	3.5	4.42×10^7	5.95×10^6
	08/03/2000	2100	5.5	6.30×10^7	1.16×10^7
	08/03/2000	2200	6.5	6.40×10^7	6.60×10^6
	08/03/2000	2300	7.5	5.90×10^7	5.40×10^6
	08/04/2000	0000	8.5	1.05×10^8	7.15×10^6
	08/04/2000	0100	9.5	8.25×10^7	4.85×10^6
	08/04/2000	0200	10.5	4.35×10^7	3.40×10^6
	08/04/2000	0300	11.5	6.35×10^7	8.40×10^6
	08/04/2000	0400	12.5	5.05×10^7	2.17×10^6
	08/04/2000	0500	13.5	5.50×10^7	2.09×10^6
	08/04/2000	0600	14.5	6.70×10^7	2.06×10^6
	08/04/2000	1200	20.5	1.56×10^7	2.42×10^6
	08/04/2000	1800	26.5	4.10×10^6	1.67×10^5
	08/05/2000	0000	32.5	2.74×10^6	1.15×10^5
	08/05/2000	1230	45.0	1.90×10^5	7.00×10^3
	08/05/2000	1800	50.5	5.15×10^4	2.50×10^3
	08/06/2000	0600	62.5	1.70×10^4	<500
	08/06/2000	1200	68.5	5.50×10^3	<500
	08/06/2000	1800	74.5	1.00×10^3	<500
	08/07/2000	1230	93.0	<500	<500
	08/08/2000	1330	118.0	5.00×10^2	<500
	08/09/2000	0830	137.0	5.00×10^2	<500
P2	08/03/2000	1600	.5	5.5×10^7	7.50×10^6
	08/03/2000	1700	1.5	3.2×10^7	1.08×10^7
	08/03/2000	1900	3.5	3.4×10^7	9.60×10^6
P3	08/03/2000	1600	.5	1.1×10^8	2.44×10^7
	08/03/2000	1700	1.5	4.8×10^7	6.60×10^6
	08/03/2000	1900	3.5	5.1×10^7	5.65×10^6
P4	08/03/2000	1600	.5	5.8×10^7	1.23×10^7
	08/03/2000	1700	1.5	2.4×10^7	5.15×10^6
	08/03/2000	1900	3.5	3.4×10^7	1.01×10^7
WP1	08/03/2000	1900	3.5	1.2×10^4	<500
	08/03/2000	2000	4.5	3.1×10^5	5.0×10^2
	08/03/2000	2100	5.5	3.4×10^5	<500
	08/03/2000	2200	6.5	3.9×10^5	5.0×10^2
	08/03/2000	2300	7.5	5.6×10^5	<500
	08/04/2000	0000	8.5	4.8×10^5	<500
	08/04/2000	0100	9.5	4.3×10^5	5.0×10^2
	08/04/2000	0200	10.5	3.8×10^5	<500

Appendix F. Measured bacteriophage concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				MPN(pfu/L)	
	08/04/2000	0300	11.5	9.8×10^5	<500
	08/04/2000	0400	12.5	8.9×10^5	<500
	08/04/2000	0500	13.5	6.7×10^5	<500
	08/04/2000	0600	14.5	2.0×10^5	<500
	08/04/2000	0800	16.5	1.0×10^5	<500
	08/04/2000	1000	18.5	1.4×10^5	<500
	08/04/2000	1400	22.5	1.6×10^5	<500
	08/04/2000	1800	26.5	2.3×10^5	5.0×10^2
	08/04/2000	2200	30.5	1.5×10^5	<500
	08/05/2000	0000	32.5	1.0×10^5	<500
	08/05/2000	0800	40.5	7.8×10^4	<500
	08/05/2000	1800	50.5	3.3×10^4	<500
	08/06/2000	0600	62.5	7.5×10^3	<500
	08/06/2000	1800	74.5	5.0×10^3	<500
	08/10/2000	1120	163.8	<500	<500
WP2	08/03/2000	2300	7.5	<500	<500
	08/04/2000	0000	8.5	<500	<500
	08/04/2000	0100	9.5	<500	<500
	08/04/2000	0200	10.5	<500	<500
	08/04/2000	0300	11.5	1.1×10^4	<500
	08/04/2000	0400	12.5	3.1×10^4	<500
	08/04/2000	0500	13.5	4.3×10^4	<500
	08/04/2000	0600	14.5	7.4×10^4	<500
	08/04/2000	0700	15.5	3.9×10^4	<500
	08/04/2000	0800	16.5	6.6×10^4	<500
	08/04/2000	0900	17.5	3.2×10^4	<500
	08/04/2000	1000	18.5	7.0×10^4	<500
	08/04/2000	1200	20.5	3.5×10^4	<500
	08/04/2000	1400	22.5	4.7×10^4	<500
	08/04/2000	1600	24.5	6.3×10^4	<500
	08/04/2000	1800	26.5	4.1×10^4	5.0×10^2
	08/04/2000	2000	28.5	3.8×10^4	<500
	08/04/2000	2200	30.5	3.0×10^4	5.0×10^2
	08/05/2000	0000	32.5	3.3×10^4	<500
	08/05/2000	0805	40.6	2.1×10^4	<500
	08/05/2000	1800	50.5	7.5×10^3	<500
	08/06/2000	0600	62.5	1.1×10^4	<500
	08/06/2000	1800	74.5	5.5×10^3	<500
	08/10/2000	1130	164.0	<500	<500
WP7	08/04/2000	2000	28.50	>161	9.0×10^{-1}
	08/04/2000	2200	30.50	1.6×10^2	7.9×10^{-1}
	08/05/2000	0000	32.50	2.3×10^1	<.2
	08/05/2000	0600	38.50	>161	1.8×10^{-1}
	08/05/2000	1200	44.50	>161	1.8×10^{-1}
	08/05/2000	1800	50.50	>161	1.8×10^{-1}

Appendix F. Measured bacteriophage concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				MPN(pfu/L)	
	08/06/2000	0715	63.75	3.5×10^{3}	<.2
	08/06/2000	1200	68.50	7.9×10^{2}	<.2
	08/06/2000	1800	74.50	>161	<.2
	08/07/2000	0815	88.75	2.3×10^{2}	2.0×10^{-1}
	08/07/2000	1245	93.25	2.3×10^{2}	<.2
	08/07/2000	1630	97.00	1.6×10^{3}	<.2
	08/08/2000	0800	112.50	>1610	<.2
	08/08/2000	1330	118.00	1.3×10^{2}	<.2
	08/08/2000	1700	121.50	2.4×10^{2}	<.2
	08/09/2000	0830	137.00	1.3×10^{2}	<.2
	08/10/2000	1115	163.75	1.3×10^{3}	<.2
PR9	08/04/2000	2000	28.50	>161	4.1×10^{0}
	08/04/2000	2200	30.50	>161	2.4×10^{1}
	08/05/2000	0000	32.50	>161	1.4×10^{0}
	08/05/2000	0600	38.50	3.6×10^{1}	4.0×10^{-1}
	08/05/2000	1200	44.50	>161	3.7×10^{-1}
	08/05/2000	1800	50.50	4.9×10^{0}	2.0×10^{-1}
	08/06/2000	0630	63.00	7.9×10^{1}	<.2
	08/06/2000	1200	68.50	1.3×10^{1}	<.2
	08/06/2000	1800	74.50	5.4×10^{1}	<.2
	08/07/2000	0800	88.50	5.4×10^{1}	6.0×10^{-1}
	08/07/2000	1245	93.25	1.6×10^{2}	<.2
	08/07/2000	1630	97.00	1.6×10^{2}	4.9×10^{0}
	08/08/2000	0820	112.83	5.4×10^{1}	<.2
	08/08/2000	1330	118.00	3.5×10^{1}	<.2
	08/08/2000	1700	121.50	5.4×10^{1}	<.2
	08/09/2000	0845	137.25	2.4×10^{1}	<.2
	08/10/2000	1145	164.25	2.8×10^{1}	<.2
PR11	08/04/2000	2000	28.50	>161	2.1×10^{0}
	08/04/2000	2200	30.50	>161	1.3×10^{1}
	08/05/2000	0000	32.50	>161	2.0×10^{0}
	08/05/2000	0600	38.50	>161	3.7×10^{-1}
	08/05/2000	1200	44.50	3.5×10^{1}	<.2
	08/05/2000	1800	50.50	4.9×10^{0}	5.0×10^{-1}
	08/06/2000	0700	63.50	9.3×10^{0}	<.2
	08/06/2000	1200	68.50	2.0×10^{0}	<.2
	08/06/2000	1800	74.50	3.5×10^{1}	<.2
	08/07/2000	0830	89.00	2.4×10^{1}	8.0×10^{-1}
	08/07/2000	1245	93.25	5.4×10^{1}	2.0×10^{-1}
	08/07/2000	1630	97.00	3.0×10^{1}	7.0×10^{-1}
	08/08/2000	0835	113.08	3.5×10^{1}	<.2
	08/08/2000	1330	118.00	2.0×10^{1}	<.2
	08/08/2000	1700	121.50	7.9×10^{0}	<.2

Appendix F. Measured bacteriophage concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				MPN(pfu/L)	
	08/09/2000	0900	137.50	3.5×10^{1}	5.0×10^{-1}
	08/10/2000	1200	164.50	1.7×10^{1}	<.2
GP1	08/03/2000	1645	1.2	4.2×10^{6}	4.2×10^{5}
	08/03/2000	1700	1.5	3.4×10^{6}	4.1×10^{5}
	08/03/2000	1900	3.5	8.5×10^{6}	7.0×10^{5}
	08/03/2000	2000	4.5	8.7×10^{6}	1.2×10^{5}
	08/03/2000	2100	5.5	5.0×10^{6}	5.2×10^{5}
	08/03/2000	2200	6.5	9.1×10^{6}	8.2×10^{4}
	08/03/2000	2300	7.5	6.4×10^{6}	4.6×10^{5}
	08/04/2000	0000	8.5	9.7×10^{6}	1.4×10^{5}
	08/04/2000	0100	9.5	7.3×10^{6}	9.2×10^{4}
	08/04/2000	0200	10.5	8.7×10^{6}	1.3×10^{5}
	08/04/2000	0300	11.5	6.5×10^{6}	1.1×10^{5}
	08/04/2000	0400	12.5	7.0×10^{6}	1.7×10^{5}
	08/04/2000	0500	13.5	5.1×10^{6}	6.5×10^{4}
	08/04/2000	0700	15.5	3.1×10^{6}	2.2×10^{5}
	08/04/2000	0800	16.5	3.2×10^{6}	2.3×10^{5}
	08/04/2000	1100	19.5	2.9×10^{6}	1.9×10^{5}
	08/04/2000	1800	26.5	8.2×10^{5}	6.3×10^{4}
	08/04/2000	2100	29.5	3.8×10^{5}	2.2×10^{4}
	08/05/2000	0600	38.5	5.8×10^{5}	1.3×10^{4}
	08/05/2000	1800	50.5	7.6×10^{4}	6.0×10^{3}
	08/06/2000	0600	62.5	2.9×10^{4}	4.0×10^{3}
	08/06/2000	1800	74.5	1.3×10^{4}	5.0×10^{3}
GP2	08/03/2000	1645	1.25	4.5×10^{3}	1.0×10^{3}
	08/03/2000	1700	1.50	2.7×10^{4}	5.0×10^{2}
	08/03/2000	1800	2.50	1.6×10^{5}	<500
	08/03/2000	1900	3.50	6.2×10^{5}	2.0×10^{3}
	08/03/2000	2000	4.50	6.3×10^{5}	1.0×10^{3}
	08/03/2000	2100	5.50	6.1×10^{5}	2.0×10^{3}
	08/03/2000	2300	7.50	7.6×10^{5}	1.5×10^{3}
	08/04/2000	0100	9.50	5.3×10^{5}	<500
	08/04/2000	0300	11.50	1.1×10^{6}	2.0×10^{3}
	08/04/2000	0500	13.50	4.9×10^{5}	1.0×10^{3}
	08/04/2000	0700	15.50	4.7×10^{5}	2.5×10^{3}
	08/04/2000	0900	17.50	1.1×10^{5}	<500
	08/04/2000	1000	18.50	4.4×10^{4}	<500
	08/04/2000	1100	19.50	2.5×10^{5}	<500
	08/04/2000	1500	23.50	2.3×10^{5}	5.0×10^{2}
	08/04/2000	1800	26.50	1.0×10^{5}	5.0×10^{2}
	08/04/2000	2100	29.50	7.1×10^{4}	5.0×10^{2}
	08/05/2000	0600	38.50	4.3×10^{4}	<500
	08/05/2000	1800	50.50	1.5×10^{4}	5.0×10^{2}
	08/06/2000	0600	62.50	5.5×10^{3}	5.0×10^{2}
	08/06/2000	1800	74.50	6.0×10^{3}	<500

Appendix F. Measured bacteriophage concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				MPN(pfu/L)	
GP3	08/03/2000	1700	1.50	<500	<500
	08/03/2000	1800	2.50	<500	<500
	08/03/2000	1900	3.50	2.5×10^4	<500
	08/03/2000	2000	4.50	7.0×10^3	<500
	08/03/2000	2100	5.50	5.0×10^3	<500
	08/03/2000	2200	6.50	1.3×10^4	<500
	08/03/2000	2300	7.50	1.8×10^4	<500
	08/04/2000	0000	8.50	5.5×10^4	<500
	08/04/2000	0100	9.50	5.2×10^4	<500
	08/04/2000	0200	10.50	6.3×10^4	<500
	08/04/2000	0300	11.50	4.9×10^4	<500
	08/04/2000	0500	13.50	5.1×10^4	<500
	08/04/2000	0700	15.50	2.6×10^4	<500
	08/04/2000	0800	16.50	5.5×10^4	<500
	08/04/2000	1100	19.50	1.3×10^4	<500
	08/04/2000	1500	23.50	9.5×10^3	<500
	08/04/2000	1800	26.50	1.6×10^4	<500
	08/04/2000	2100	29.50	1.7×10^4	<500
	08/05/2000	0000	32.50	1.8×10^4	<500
	08/05/2000	0600	38.50	1.1×10^4	<500
	08/05/2000	1800	50.50	1.2×10^4	<500
	08/06/2000	0600	62.50	1.5×10^3	<500
	08/06/2000	0075	74.50	1.5×10^3	<500
GP4	08/03/2000	1700	1.50	<500	<500
	08/03/2000	1800	2.50	<500	<500
	08/03/2000	1900	3.50	1.5×10^3	<500
	08/03/2000	2000	4.50	3.5×10^3	<500
	08/03/2000	2100	5.50	6.5×10^3	<500
	08/03/2000	2200	6.50	2.0×10^4	<500
	08/03/2000	2300	7.50	2.1×10^4	<500
	08/04/2000	0000	8.50	2.0×10^4	<500
	08/04/2000	0100	9.50	8.5×10^3	5.0×10^2
	08/04/2000	0200	10.50	2.0×10^4	<500
	08/04/2000	0300	11.50	3.7×10^4	<500
	08/04/2000	0500	13.50	2.8×10^4	<500
	08/04/2000	0700	15.50	1.2×10^4	<500
	08/04/2000	0800	16.50	1.5×10^4	<500
	08/04/2000	1100	19.50	4.5×10^3	<500
	08/04/2000	1500	23.50	6.5×10^3	<500
	08/04/2000	1800	26.50	6.5×10^3	<500
	08/04/2000	2100	29.50	1.3×10^4	<500
	08/05/2000	0000	32.50	4.0×10^3	<500
	08/05/2000	0600	38.50	5.0×10^3	<500
	08/05/2000	1800	50.50	3.0×10^3	<500

Appendix F. Measured bacteriophage concentrations for water samples collected during the 2000 tracer experiment from a research field site located in Los Angeles County, California—Continued

Sample	Date and time collected		Elapsed time (hr)	MS2	PRD1
				MPN(pfu/L)	
	08/06/2000	0600	62.50	3.0×10^3	<500
	08/06/2000	0075	74.50	1.0×10^3	<500
GP5	08/03/2000	1800	2.50	<500	<500
	08/03/2000	1900	3.50	<500	<500
	08/03/2000	2000	4.50	5.0×10^2	<500
	08/03/2000	2100	5.50	3.0×10^3	<500
	08/03/2000	2200	6.50	1.5×10^3	<500
	08/03/2000	2300	7.50	4.0×10^3	<500
	08/04/2000	0000	8.50	2.4×10^4	<500
	08/04/2000	0100	9.50	2.0×10^3	<500
	08/04/2000	0200	10.50	1.5×10^3	<500
	08/04/2000	0300	11.50	5.5×10^3	<500
	08/04/2000	0400	12.50	5.0×10^3	<500
	08/04/2000	0500	13.50	2.0×10^3	<500
	08/04/2000	0600	14.50	2.5×10^3	<500
	08/04/2000	0700	15.50	2.0×10^3	<500
	08/04/2000	0800	16.50	1.5×10^4	<500
	08/04/2000	1100	19.50	3.5×10^3	<500
	08/04/2000	1400	22.50	1.1×10^4	<500
	08/04/2000	1600	24.50	5.0×10^2	<500
	08/04/2000	1800	26.50	1.5×10^3	<500
	08/04/2000	2000	28.50	<500	<500
	08/04/2000	2200	30.50	6.5×10^3	<500
	08/05/2000	0000	32.50	3.0×10^3	<500
	08/05/2000	0600	38.50	1.0×10^3	<500
	08/05/2000	1800	50.50	5.0×10^2	<500
	08/06/2000	0025	62.50	<500	<500
	08/06/2000	0075	74.50	1.0×10^3	<500