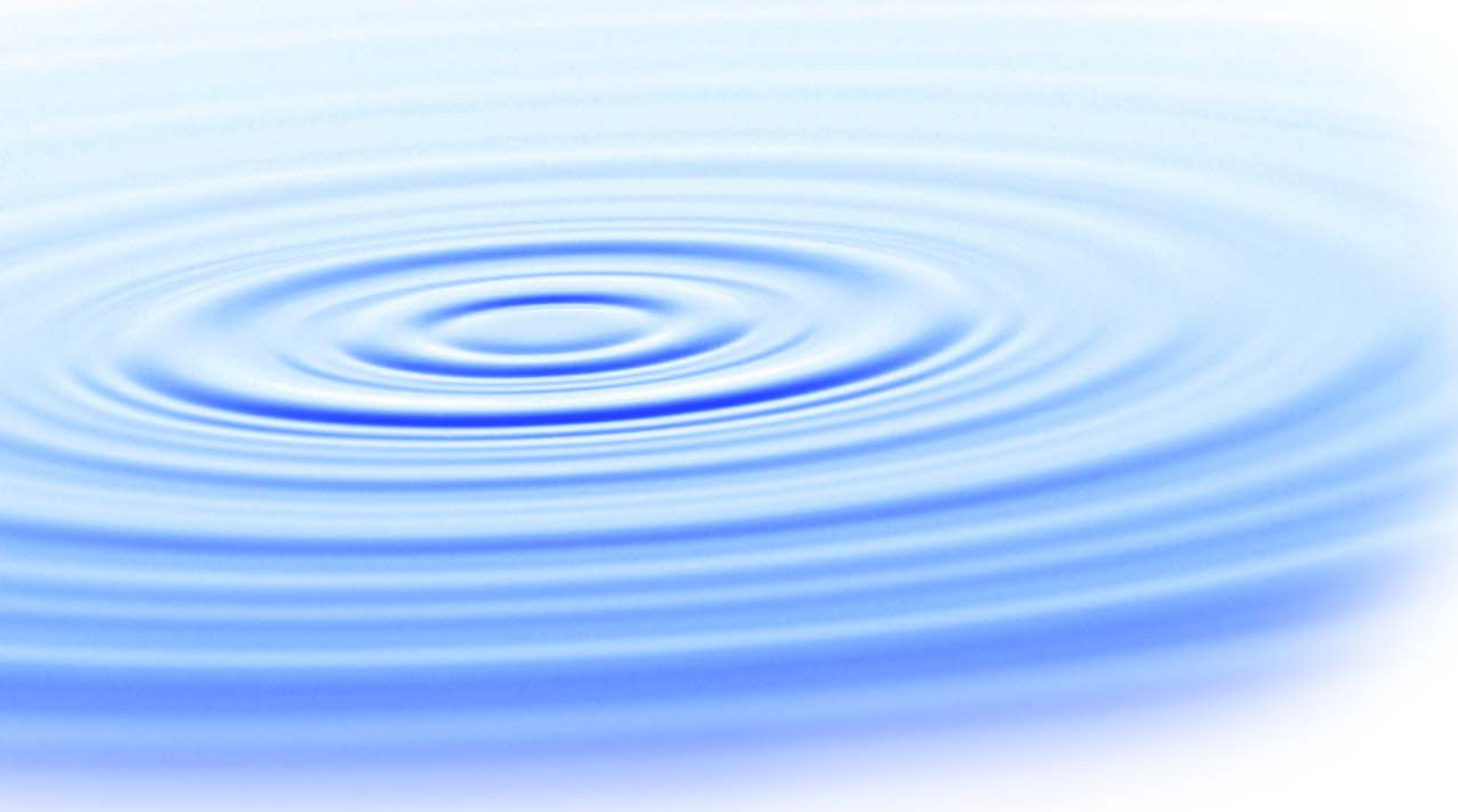




**Selection and Testing of Tracers
for Measuring Travel Times in
Groundwater Aquifers Augmented
with Reclaimed Water**



**WaterReuse
Foundation**

**Selection and Testing of
Tracers for Measuring Travel
Times in Groundwater
Aquifers Augmented with
Reclaimed Water**

About the WateReuse Foundation

The mission of the WateReuse Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high quality water through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

The Foundation's funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the Southwest Florida Water Management District, the California Energy Commission, and the California Department of Water Resources. Funding is also provided by the Foundation's Subscribers, water and wastewater agencies, and other interested organizations. The Foundation also conducts research in cooperation with the Global Water Research Coalition.

Selection and Testing of Tracers for Measuring Travel Times in Groundwater Aquifers Augmented with Reclaimed Water

Wontae Lee, Ph.D., P.E.
HDR Engineering, Inc.

Cosponsors

Bureau of Reclamation
City of Phoenix
Fountain Hills Sanitary District
Town of Gilbert



Published by the WaterReuse Foundation
Alexandria, VA

Disclaimer

This report was sponsored by the WateReuse Foundation. The Foundation, its Board Members, and the project cosponsors assume no responsibility for the content reported in this publication or for the opinions or statements of facts expressed in the report. The mention of trade names of commercial products does not represent or imply the approval or endorsement of the WateReuse Foundation, its Board Members, or the cosponsor. This report is published solely for informational purposes.

For more information, contact:

WateReuse Foundation
1199 North Fairfax Street, Suite 410
Alexandria, VA 22314
703-548-0880
703-548-5085 (fax)
www.WateReuse.org/Foundation

© Copyright 2009 by the WateReuse Foundation. All rights reserved. Permission to reproduce must be obtained from the WateReuse Foundation.

WateReuse Foundation Project Number: WRF-05-007
WateReuse Foundation Product Number: 05-007-01

ISBN: 978-1-934183-18-2
Library of Congress Control Number: 2009925041

Printed in the United States of America

 Printed on Recycled Paper

CONTENTS

List of Figures	vii
List of Tables.....	viii
Acronyms and Abbreviations	ix
Foreword	xi
Acknowledgments.....	xii
Executive Summary	xiii
Chapter 1. Introduction	1
1.1 Background	1
1.2 Objectives.....	1
1.3 Research Approach	1
Chapter 2. Overview of Recharge Systems and Tracers.....	3
2.1 Introduction	3
2.2 Artificial Recharge Methods Using Reclaimed Water	4
2.2.1 Types of Artificial Recharge Systems.....	4
2.2.2 Growth of Reclaimed Water Recharge in the United States	6
2.2.3 Health Aspects of Groundwater Recharged with Reclaimed Water	8
2.3 Tracers for Recharged Water Flow	9
2.3.1 Inorganic Anions.....	11
2.3.2 SF ₆	12
2.3.3 Dyes	13
2.3.4 Isotopes	14
2.4 Tracers for Wastewater Constituents.....	14
2.4.1 Biological Constituents	15
2.4.2 Chemical and Organic Constituents.....	18
2.5 Summary	20
Chapter 3. Materials and Methods	23
3.1 Site Description.....	23
3.1.1 Direct Recharge Well Site.....	23
3.1.2 Vadose Zone Recharge Well Site.....	26
3.1.3 Recharge Basin Site	27
3.2 Microbial Survival Test.....	28
3.3 Tracer Injection and Sampling	29
3.3.1 Tracer Preparation	29
3.3.2 Tracer Injection	30
3.3.3 Sampling	31

3.4	Sample Handling And Analysis	31
3.4.1	Bacteriophages	31
3.4.2	Caffeine	32
3.4.3	SF ₆	33
3.5	Travel Time Determination	33
Chapter 4. Results and Discussion		35
4.1	Bacteriophage Survival	35
4.2	Direct Recharge Well Site	36
4.3	Vadose Zone Recharge Well Site	40
4.4	Recharge Basin Site	44
4.5	Discussion	47
Chapter 5. Protocols for Tracer Tests in Recharge Systems		51
5.1	Background and Purpose	51
5.2	Aquifer Recharge Using Reclaimed Water	51
5.2.1	Recharge Basins	51
5.2.2	Vadose Zone Recharge Wells	52
5.2.3	Direct Recharge Wells	52
5.3	Typical Setup and Operation of a Tracer Test	52
5.4	State Permit Requirements for Tracer Tests	55
5.4.1	Arizona	56
5.4.2	California	56
5.4.3	Colorado	57
5.4.4	Florida	58
5.4.5	Nevada	58
5.4.6	Texas	59
5.4.7	Washington State	59
5.5	Field Testing and Analysis Procedures	60
5.5.1	Preparation Task Checklist	60
5.5.2	Field Testing Checklist	61
5.5.3	Sampling Procedure	61
5.6	Determination of Travel Time	61
5.7	Other Considerations and Limitations	63
References		65

FIGURES

Figure 2-1. Engineered groundwater recharge methods.....	4
Figure 2-2. Underground storage facilities recharging reclaimed water in the Phoenix AMA.....	7
Figure 3-1. Engineered recharge systems for reclaimed water.....	23
Figure 3-2. Schematic of the injection and monitoring well for the Direct Injection Well Site.....	25
Figure 3-3. Schematic of the injection and monitoring well for the Vadose Zone Recharge Site.....	27
Figure 3-4. Schematic of the Recharge Basin Site.....	28
Figure 4-1. Survival of bacteriophages PRD1 and MS2 in groundwater from the monitoring well.....	36
Figure 4-2. Breakthrough curve results of tracers at the Direct Recharge Well Site monitoring well.....	38
Figure 4-3. Conductivity, sulfate, and nitrate monitoring results at the Direct Recharge Well Site monitoring well.....	39
Figure 4-4. UVA254 and TTHM monitoring results at the Direct Recharge Well Site monitoring well.....	39
Figure 4-5. Breakthrough curve results of tracers at the Vadose Zone Recharge Well Site monitoring well.....	42
Figure 4-6. Conductivity, sulfate, and nitrate monitoring results at the Vadose Zone Recharge Well Site monitoring well.....	43
Figure 4-7. UVA254 and TTHM monitoring results at the Vadose Zone Recharge Well Site monitoring well.....	43
Figure 4-8. Evolution of nitrate levels in reclaimed water and groundwater samples from the Vadose Zone Recharge Well Site monitoring well.....	44
Figure 4-9. Breakthrough curve results of tracers at the Recharge Basin Site monitoring well.....	45
Figure 4-10. Conductivity, sulfate, and nitrate monitoring results at the Recharge Basin Site monitoring well.....	46
Figure 4-11. UVA254 and TTHM monitoring results at the Recharge Basin Site monitoring well.....	46
Figure 5-1. Typical setup of injection and monitoring wells for a tracer test.....	54
Figure 5-2. Tracer test setup and monitoring in longitudinal cross-section view.....	54
Figure 5-3. Illustration of tracer dispersion along groundwater flowpath.....	62
Figure 5-4. An example of a tracer test breakthrough curve (bromide).....	63

TABLES

Table 2-1. Comparison of major engineering factors for three common groundwater recharge methods, modified from Guidelines (2004)	5
Table 2-2. Utilities in five U.S. states recharging groundwater with reclaimed water	7
Table 2-3. Comparison of various tracers for water movement	10
Table 2-4. Use of microbial tracers in recent recharge and recovery experiments, adapted from Harvey (1997).....	16
Table 2-5. Characteristics of bacteriophages PRD1 and MS2	16
Table 3-1. Summary of test site characteristics.....	24
Table 3-2. Characteristics of bacteriophages PRD1 and MS2	29
Table 3-3. Target concentrations of tracers in recharging water	31
Table 3-4. Sample handling and analysis	32
Table 4-1. Pseudo-first order equations for the decay rates of bacteriophages in groundwater from the monitoring well	35
Table 4-2. Summary of travel time at the Direct Recharge Well Site	38
Table 4-3. Water quality of groundwater samples from the monitoring wells prior to tracer injection	40
Table 4-4. Summary of travel time at the Vadose Zone Recharge Well Site.....	42
Table 4-5. Summary of travel time at the Recharge Basin Site	45
Table 5-1. Permits required for tracer tests in select U.S. states	55

ACRONYMS AND ABBREVIATIONS

AAC	Arizona Administrative Code
ADEQ	Arizona Department of Environmental Quality
AFY	Acre-Feet per Year
AKART	All Known And Reasonable Technologies
AMA	Active Management Area
APHA	American Public Health Association
ASR	Aquifer Storage and Recovery
ATCC	American Type Culture Collection
bls	below land surface
BWPC	Bureau of Water Pollution Control
DBPs	Disinfection Byproducts
DDT	Dichlorodiphenyltrichloroethane
DOC	Dissolved Organic Carbon
EDCs	Total Dissolved Solids
FAC	Florida Administrative Code
GC	Gas Chromatography
GC/MS	Gas Chromatography–Mass Spectroscopy
GF/F	Glass Fiber Filter
gpm	gallons per minute
IC	Ion Chromatography
ICP	Inductively Coupled Plasma
IEP	Isoelectric Point
MDL	Method Detection Limit
MW	Monitoring Well
NAC	Nevada Administrative Code
NTU	Nephelometric Turbidity Units
PBS	Phosphate-Buffered Saline
PCB	Polychlorinated Biphenyl
PFU	Plaque-Forming Units
redox	Oxidation–Reduction

SAT	Soil Aquifer Treatment
TAC	Texas Administrative Code
TCEQ	Texas Commission For Environmental Quality
TDS	Total Dissolved Solids
THM	Trihalomethane
TSA	Tryptic Soy Agar
TTHM	Total Trihalomethane
UIC	Underground Injection Control
USAID	U.S. Agency for International Development
USDW	Underground Sources of Drinking Water
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UVA	Ultraviolet Absorbance
UVA254	Ultraviolet Absorbance at 254 nm
WAC	Washington Administrative Code

FOREWORD

The WateReuse Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide high-quality water, protect public health, and improve the environment.

A Research Plan guides the Foundation's research program. Under the plan, a research agenda of high-priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities including water professionals, academics, and Foundation Subscribers. The Foundation's research focuses on a broad range of water reuse research topics including:

- Definition and addressing of emerging contaminants;
- Public perceptions of the benefits and risks of water reuse;
- Management practices related to indirect potable reuse;
- Groundwater recharge and aquifer storage and recovery;
- Evaluation and methods for managing salinity and desalination; and
- Economics and marketing of water reuse.

The Research Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project and provide technical review and oversight. The Foundation's RAC and PACs consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

The Foundation's primary funding partners include the Bureau of Reclamation, California State Water Resources Control Board, the Southwest Florida Water Management District, the California Energy Commission, Foundation Subscribers, water and wastewater agencies, and other interested organizations. The Foundation leverages its financial and intellectual capital through these partnerships and funding relationships.

This publication is the result of a study sponsored by the Foundation and is intended to communicate the results of this research project. The primary objective of this project was to identify, select, and test environmentally acceptable tracers for measuring travel times of reclaimed water and its constituents in recharge systems. The secondary objective was to develop a protocol for conducting tracer tests on recharge systems that are augmented with reclaimed water.

David L. Moore
President
WateReuse Foundation

G. Wade Miller
Executive Director
WateReuse Foundation

ACKNOWLEDGMENTS

This project was funded by the WaterReuse Foundation in cooperation with the Bureau of Reclamation, the City of Phoenix, Fountain Hills Sanitary District, and the Town of Gilbert.

The research team thanks the WaterReuse Foundation and Bureau of Reclamation for funding this research project. We also extend our appreciation to the participating utilities for their in-kind contributions. The participating utilities remain unrevealed mainly because of confidentiality agreements.

We also thank Project Advisory Committee members (as identified below) and the WaterReuse Foundation's project manager, Burnett King, for their insights, efforts, and dedication to the project.

Principal Investigator and Project Manager

Wontae Lee, Ph.D., P.E., *HDR Engineering, Inc.*

Research Project Team

Jordan F. Clark, Ph.D., *University of California, Santa Barbara*

Morteza Abbaszadegan, Ph.D., *Arizona State University, Tempe*

Peter Fox, Ph.D., *Arizona State University, Tempe*

Hodon Ryu, Ph.D., *Arizona State University, Tempe*

John Koreny, R.G., *HDR Engineering, Inc.*

Guy Carpenter, P.E., *HDR Engineering, Inc.*

Project Advisory Committee

Warren Frizell, *Bureau of Reclamation*

Jon Loveland, *Malcolm Pirnie*

Mohsen Mehran, Ph.D., *Rubicon Engineering Corporation*

Bahman Sheikh, Ph.D., P.E., *Water Reuse Consultant*

EXECUTIVE SUMMARY

RESEARCH OBJECTIVES

The primary objective of this project was to identify, select, and test environmentally acceptable tracers for measuring travel times of reclaimed water and its constituents in recharge systems. The secondary objective was to develop a protocol for conducting tracer tests on recharge systems that are augmented with reclaimed water.

APPROACH

The project included the following major activities: 1) compare and select tracers for recharge systems augmented with reclaimed water, 2) evaluate the performance of tracers in three common recharge systems (recharge basin, vadose zone recharge well, and direct recharge well), and 3) develop a protocol for conducting tracer tests in recharge systems.

The tracers used included two nonreactive tracers (bromide and sulfur hexafluoride), two microbial tracers (PRD1 and MS2), and one reactive organic compound (caffeine). Each tracer was injected via a recharge basin, a direct recharge well, and a vadose zone recharge well.

FINDINGS AND CONCLUSIONS

This research report provides a summary of the literature related to conservative and surrogate tracers for reclaimed water constituent transport in the subsurface (Chapter 2), the materials and methods used for evaluation of tracers (Chapter 3), the results from tracer experiments on three common recharge systems augmented with reclaimed water (Chapter 4), and information on the process for regulatory approval of the use of tracers for reclaimed water recharge systems and of field methods for conducting tracer tests (Chapter 5).

Deliberate experiments using conservative (nonreactive and nonretarding) tracers are the best methods to estimate the travel time of recharged water in recharge systems. Commonly used tracers for groundwater flow within aquifers include anions, trace gases, fluorescent dyes, and isotopes. Bromide and chloride are considered ideal conservative tracers for water movement and are thus widely used. Gas tracers, such as sulfur hexafluoride, can be a useful tracer for larger tracer experiments when a large volume of water needs to be tagged. The use of isotopes as deliberate tracers in groundwater recharge systems augmented with reclaimed water tends to be limited by public health concerns and complexity in the injection, monitoring, and analysis of isotopes.

The travel time of recharged reclaimed water obtained by the conservative tracer test, however, does not necessarily resemble the movement of chemical and microbial constituents of the reclaimed water. An alternative method of investigating the transport of constituents present in reclaimed water is to find the best available surrogates for the specific compounds of each investigation. DOC, UVA254, and excitation–emission fluorescence have been used as indicators of organic compounds; chloride, sulfate, conductivity, and TDS have been used

as indicators of salts; nitrate, ammonium, and phosphate have been used as indicators of nutrients; and bacteriophages have been injected into aquifers as microbial tracers.

Bromide and sulfur hexafluoride exhibited very similar results for the direct recharge well site, while the sulfur hexafluoride detections were sporadic relative to bromide detections for the vadose zone recharge and recharge basin sites. The gas was lost from the recharged water during percolation through the vadose zone as we expected, based on solubility consideration. It is also likely that the caffeine was lost within the vadose zone, although it is not possible to determine if the loss was caused by sorption or degradation. The microbial tracers (PRD1 and MS2) were not detected in the monitoring wells for all three recharge systems. The microbial tracers may have been inactivated at a very early stage by the residual chlorine in the reclaimed water. Microbial survival tests in the reclaimed water indicated that the bacteriophages cannot be used as tracers in recharge systems augmented with reclaimed water, which is generally chlorinated.

At the direct recharge well site, levels of reclaimed water constituents (conductivity, sulfate, nitrate, organics, and trihalomethanes) gradually increased as recharge progressed. Because these constituents were continuously introduced at an almost constant dosage during the recharge, recharge of reclaimed water can be considered a step input tracer test. Mean travel times of the reclaimed water constituents were close to the mean travel time of bromide tracer. This indicated monitoring of reclaimed water constituents or in situ water quality could be a potential method of estimating the travel time of reclaimed water in the direct recharge well site. However, water quality data showed no clear trends in the vadose zone recharge and recharge basin sites. The impact of reclaimed water constituents on the groundwater quality was presumably reduced by the high dilution with the native groundwater and by in situ biogeochemical reactions and filtration, which are collectively referred to as soil aquifer treatment.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Aquifer recharge using reclaimed water is an increasingly popular water management technique to augment limited water supplies in the arid western United States. A recharge project typically requires information on the travel time of recharge water through the aquifer. This is usually done by analytical calculations from aquifer testing data or from travel time data obtained through tracer tests.

Although the constituents present that may be of concern in reclaimed water are usually removed through advance treatment processes prior to the point of recharge, augmentation of the groundwater aquifer with reclaimed water has the potential to cause public health and environmental concerns. Tracking the migration of contaminants, pathogens, and disinfection byproducts (DBPs) in groundwater aquifers is crucial in assessing potential health/environmental impacts, preventing pollution problems, and designing/constructing cost-effective remediation systems. Information and the method of testing and analysis to determine the travel time of biophysicochemical constituents of reclaimed water in aquifers are useful for the design and permitting of reclaimed water aquifer recharge projects. Some projects may evaluate the transport of typical reclaimed water constituents in the datum collection and analysis phase of a project. Since it is generally not possible to test the travel times of these compounds in situ because of environmental concerns, testing inert or harmless surrogate compounds may be an environmentally acceptable alternative. This study evaluated methods and procedures to accomplish in situ injection of surrogate tracers.

This first WateReuse Foundation project on groundwater tracers is intended to improve the ability to measure the travel times of reclaimed water and its constituents in recharge systems using conservative and surrogate tracers.

1.2 OBJECTIVES

The primary objective of this project was to identify, select, and test environmentally acceptable tracers to measure the travel times of reclaimed water and its constituents in recharge systems. A secondary objective was to develop a protocol for conducting tracer tests in recharge systems that are augmented with reclaimed water.

1.3 RESEARCH APPROACH

To accomplish the project objectives, the research project involved the following tasks:

- Compare and select tracers for recharge systems augmented with reclaimed water. This project provides methods for using typical conservative tracers (bromide and sulfur hexafluoride [SF_6]) as well as environmentally acceptable microbial tracers (PRD1 and MS2), and one organic compound (caffeine).

- Evaluate the performance of tracers in three common aquifer recharge systems: 1) recharge basin, 2) vadose zone recharge well, and 3) direct recharge well. These tests were conducted in the field at facilities currently operating in Arizona.
- Develop protocols for conducting tracer tests in recharge systems augmented with reclaimed water and provide information on the regulatory approvals needed.

CHAPTER 2

OVERVIEW OF RECHARGE SYSTEMS AND TRACERS

2.1 INTRODUCTION

Recharge (augmentation or replenishment) of aquifers using reclaimed water is gaining widespread acceptance among water resource managers as a method to augment limited water supplies, especially in the arid western United States. The most common and widely accepted engineered methods for aquifer recharge with reclaimed water include surface spreading, subsurface infiltration, and direct aquifer injection (Fox, 1999; *Guidelines*, 2004; Dillon, 2005). However, there is significant public concern and regulatory attention regarding contaminants in the recharged reclaimed water that may degrade groundwater quality. The introduction of infectious microorganisms, DBPs, and other contaminants (e.g., endocrine disruptors, pharmaceuticals, and personal care products) into groundwater supplies is a significant concern to water reuse communities (National Research Council, 1998; Asano and Cotruvo, 2004; Daughton, 2004; National Research Council, 2008). Higgins et al. (2002) surveyed the users and providers of recycled water in Australia and reported that nearly four out of five respondents (79%) have concerns about aspects of reclaimed water quality. Their primary concerns are focused on microbiological components (viruses, pathogens, parasites, and bacteria); potential salinity effects; aggregate components (pH and solids); nutrients; and organic compounds, including pharmaceuticals, endocrine disrupting chemicals (EDCs), pesticides, and DBPs. For these reasons, almost all reclaimed water recharge projects require advanced treatment (essentially treating to drinking water standards) to All Known And Reasonable Technologies (AKART) Standards and regular monitoring to ensure that the treatment is effective.

However, despite the advanced treatment that ensures the removal of constituents of potential concern in reclaimed water, additional information on the fate and transport of biological and chemical constituents of reclaimed water in aquifers may be helpful for project design and regulatory approval. Such information may be helpful to determine the travel time of reclaimed water and its constituents from the point of augmentation to downgradient receptors (i.e., wells), discharge points (i.e., wetlands, rivers, or lakes), or other water users. The permitting process of most aquifer recharge projects requires information on the fate and transport characteristics of biological and chemical constituents that may be present in wastewater. The proposed California state criteria for artificial recharge with reclaimed water stipulate that 1) for a surface spreading project, all the recycled water 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 ft of the point of recharge and 2) for a subsurface recharge project, all the recycled water shall be retained underground for a minimum of 12 months prior to extraction for use as a drinking water supply and shall not be extracted within 2000 ft of the point of recharge (California Department of Public Health, 2007). The proposed regulations do allow for an exemption of the travel distance requirement if the water agency can document a “tracer experiment” finding that the required retention time can be achieved at the proposed reduced distance. Although some U.S. states have established provisions to protect groundwater resources from recharged reclaimed water, the information on the fate and transport of many wastewater constituents within aquifers near recharge sites is limited (Anders and Chrysikopoulos, 2005).

Use of tracers is a simple way to investigate the travel time of recharged reclaimed water within the subsurface and to establish hydraulic connections between recharge locations and specific wells. Results from tracer tests can be used to provide adequate retention times to satisfy drinking water standards and regulations. This document reviews the practice of artificial recharge using reclaimed water in the United States and discusses tracer techniques used to determine the travel times of reclaimed water and its constituents in recharge systems.

2.2 ARTIFICIAL RECHARGE METHODS USING RECLAIMED WATER

2.2.1 Types of Artificial Recharge Systems

Three common methods for groundwater recharge augmented with reclaimed water are 1) surface spreading or percolation (recharge basins), 2) subsurface infiltration (vadose zone recharge wells), and 3) direct aquifer injection (direct recharge wells). Figure 2-1 illustrates different means of distribution of reclaimed water including the three recharge methods, and Table 2-1 summarizes major engineering factors for the three recharge methods.

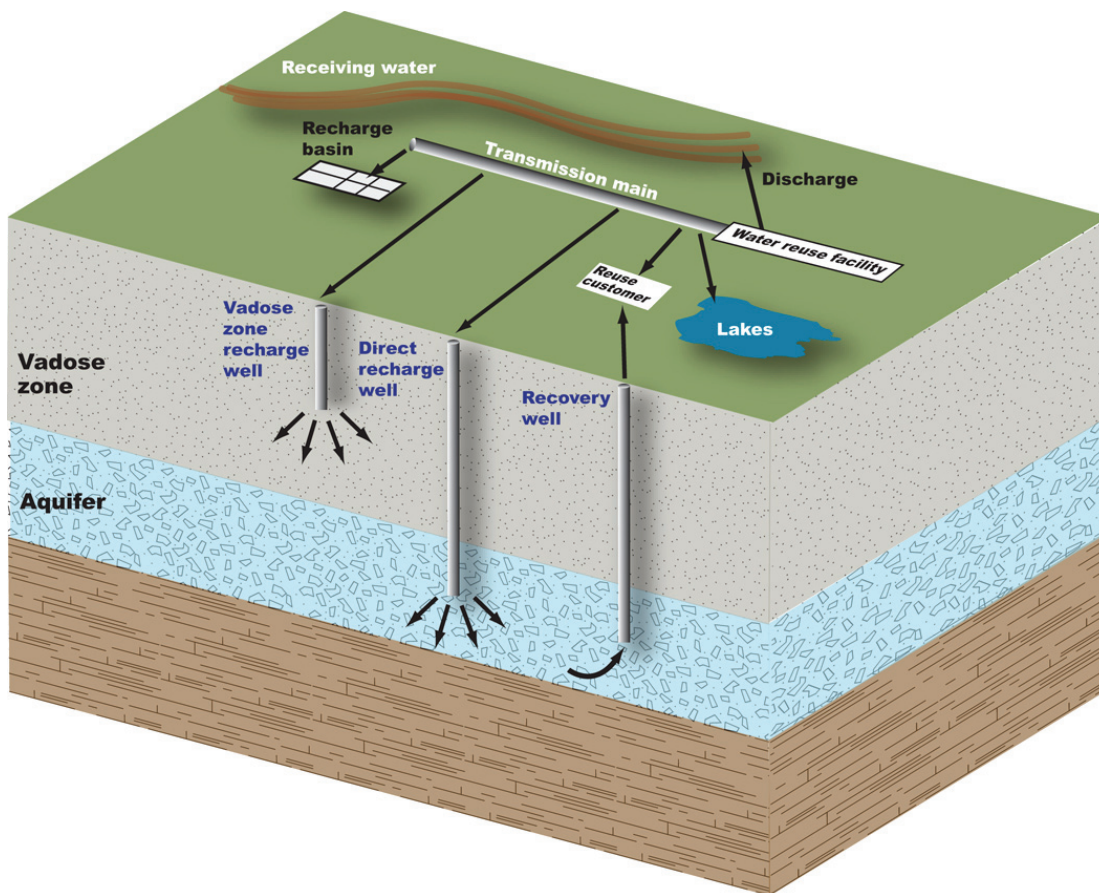


Figure 2-1. Engineered groundwater recharge methods.

Table 2-1. Comparison of major engineering factors for three common groundwater recharge methods, modified from *Guidelines* (2004)

Aspect	Aspects of:		
	Recharge basin	Vadose zone recharge well	Direct recharge well
Aquifer type	Unconfined	Unconfined	Unconfined or confined
Pretreatment requirements	Low technology	Removal of solids	High technology
Capacity	100–20,000 m ³ /hectare-day (12–2400 acre-ft/acre-year)	1000–3000 m ³ /day 180–550 gpm per well	2000–6000 m ³ /day 360–1100 gpm per well
Estimated major capital costs (US\$)	Depending on land and distribution system size	\$25,000–\$75,000 per well	\$150,000–\$500,000 per well
Maintenance requirements	Drying and scraping	Drying and disinfection	Disinfection and flow reversal
Estimated life cycle	>100 years	5–20 years	25–50 years
Advantages	Simple technology	Shallow wells	Injection possible into confined aquifers; wells can be pumped to remove sediments and remediate clogged wells
Disadvantages	Can be used only for unconfined aquifer with high-permeability deposits close to surface, requires regular sediment removal	Clogging may be a problem that can be hard to reverse, requires high-permeability deposits close to surface	Deep, expensive-to-install wells are usually required

Recharge Basins

Surface spreading through recharge basins is the most common and widely accepted method of aquifer recharge. They can be used only for situations where highly permeable deposits are present near the surface, overlying an unconfined aquifer that would allow water to easily infiltrate into the aquifer. Recharge basins require a large area of land and only simple maintenance. The primary limitations are the depth to groundwater and the permeability of the near-surface and aquifer deposits. The estimated costs associated with recharge basins are highly variable because they depend on infiltration rates, frequency of cleaning (removal of clogging material), and land values. Infiltration rates are a function of the hydraulic conductivity of the soil. Those calculating average infiltration rates must consider the cyclic operation of the recharge basins, which includes both wetting and drying periods. Average infiltration rates can vary from 8 to >150 cm/day depending on the soil type and the maturity of clogging layers (Fox, 1999; Avisar and Clark, 2005). Some limited treatment may occur as the water percolates through the basins and the vadose zone and then some distance laterally through the aquifer. Recharge basins are usually constructed far from drinking water wells, based on the local permitting requirements and the anticipated travel time. For example, the proposed California state criteria for artificial recharge with reclaimed water stipulate that, for

a surface spreading project, all the recycled water 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 ft of the point of recharge (California Department of Public Health, 2007).

Direct Recharge Wells

Another method of groundwater recharge is direct recharge into the aquifer. Direct recharge wells allow for recharge in confined aquifers and require a higher level of pretreatment than does surface spreading. Groundwater recharge by direct recharge using deep wells has been practiced where groundwater is deep or where the topography or existing land use makes surface spreading impractical or too expensive (Bouwer, 1988; Asano and Cotruvo, 2004). Aquifer storage and recovery (ASR) allows for injection of water into an aquifer during low-demand periods and withdrawal during periods of peak demand.

Vadose Zone Recharge Wells

An emerging method of groundwater recharge is the use of vadose zone recharge wells, which are analogous to trenches. Vadose zone recharge wells provide some of the advantages of both recharge basins and direct recharge wells (Fox, 1999; Fox, 2002). However, they are subject to clogging and may not be pumped back to remove suspended solids, as is the case for direct injection wells.

2.2.2 Growth of Reclaimed Water Recharge in the United States

The WateReuse Foundation surveyed water reclamation/reuse facilities throughout the United States and established a database (National Database of Water Reuse Facilities). The database had 1274 records as of April 2007. Among the utilities in the database, 1042 utilities (82%) are located in five states: Arizona, California, Florida, Texas, and Washington (Table 2-2). Based on the database, about one-third (34%) of utilities are practicing groundwater recharge with reclaimed water. Among the utilities practicing recharge, the majority (83%) adopted the surface spreading method for their artificial recharge system. However, the percentage varies by state and region, depending on characteristics of aquifer layers (i.e., depth and lateral extent), hydraulic regimen, local topography, the permeability and geochemistry of the aquifer sediment, location, and weather. Also, some utilities are equipped with two or three different types of recharge system. For example, the Phoenix Active Management Area (AMA), located in central Arizona, had 28 groundwater recharge facilities as of December 2006 (Arizona Department of Water Resources, 2006), and 15 of the 28 facilities were recharging reclaimed water by surface spreading (Figure 2-2). Among these 15 facilities, three facilities were recharging by both surface spreading and vadose zone recharge, and one facility was recharging by both surface spreading and direct recharge. The numbers of facilities with vadose zone recharge and direct recharge are 9 and 10, respectively, and two facilities are equipped with both vadose zone recharge and direct recharge. The recharge capacity of most facilities (75%) is less than 10,000 AFY, and no distinct preference of recharge type per recharge volume was observed (Figure 2-2).

Table 2-2. Utilities in five U.S. states recharging groundwater with reclaimed water^a

State	No. of utilities in the database	No. of utilities that responded	No. of utilities recharging	No. of utilities with surface spreading	No. of utilities with recharge wells	No. of utilities with subsurface infiltration
Arizona	107	14	4	3	1	-
California	286	136	15	10	4	1
Florida	308	289	143	123	3	17
Texas	330	41	3	1	2	-
Washington	11	5	2	1	-	1
Total	1042	485	167	138	10	19

^aSummarized from National Database of Water Reuse Facilities.

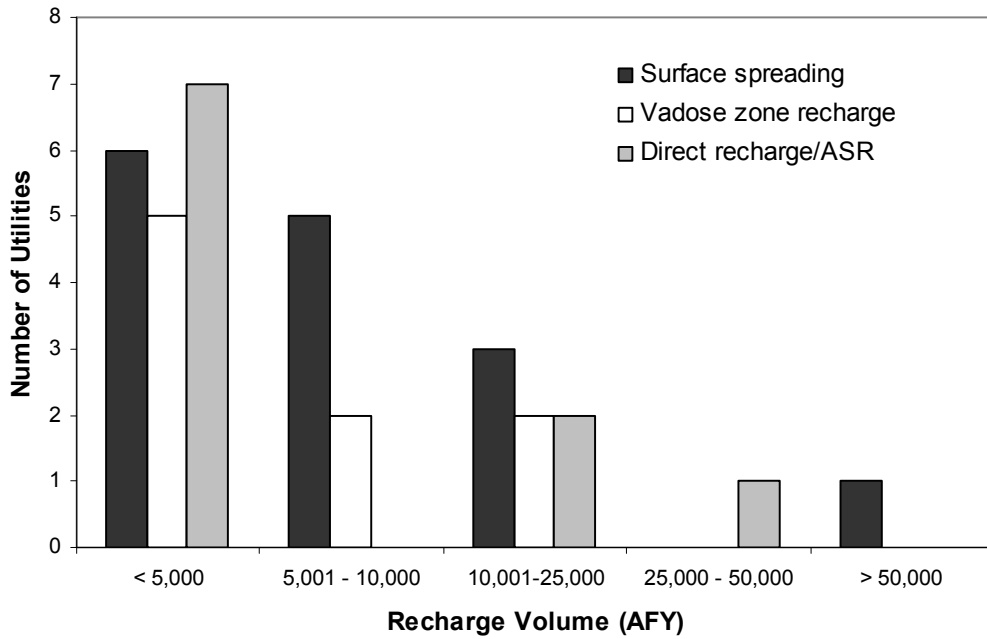


Figure 2-2. Underground storage facilities recharging reclaimed water in the Phoenix AMA.

2.2.3 Health Aspects of Groundwater Recharged with Reclaimed Water

It is essential that water extracted from a groundwater basin for domestic use be of acceptable physical, chemical, microbiological, and radiological quality. The proposed California state criteria for groundwater recharge with reclaimed water focus on traditional wastewater quality parameters such as SS, NTU, BOD, TOC, total coliform, and pathogenic microorganisms (*Proposed*, 1992). The water quality of a recharged aquifer is a function of the quality of the recharge source water, the recharge method used, the physical characteristics of the vadose zone and aquifer layers, the permeability and geochemistry of the aquifer sediment, water residence time, the amount of blending with other sources, the quality of the “background” groundwater, the history of recharge, and the hydraulic regimen resulting from natural gradients and pumping performances (Asano and Cotruvo, 2004; Massmann et al., 2004).

Numerous studies have shown that the quality of recharged wastewater improves during transit in the subsurface (Gerba et al., 1991; Amy et al., 1993; Karimi et al., 1998; Litwiller et al., 2000; Fox et al., 2001; Drewes et al., 2002a; Fox, 2002; Heberer et al., 2004; Mansell and Drewes, 2004; Fox et al., 2005). This water quality improvement is achieved by in situ biogeochemical reactions and filtration, which are collectively referred to as soil aquifer treatment (SAT) (Fox et al., 2001; Fox, 2002). Reduction in organic matter and other contaminants takes place mainly in the vadose zone, with time scales on the order of days; removal of organic matter continues at a lower rate in the saturated zone since most easily biodegradable organics have been removed and/or electron acceptor concentrations have decreased (Wilson et al., 1995; Vengosh and Keren, 1996; Fox et al., 2001). The effectiveness of the vadose zone at removing organic matter depends on biogeochemistry, travel time, surface area, oxygen, and other parameters. Organic matter is a mixture of different compounds, some of which rapidly degrade. These compounds readily degrade before the recharge water crosses the water table. The biodegradation of trace organic compounds often occurs slowly, and sufficient time is required to achieve the full benefits of aquifer storage.

Alluvial aquifers, comprised mostly of sand and gravel, contain abundant surface area, which permits ample contact with the water traveling through it. This surface area mediates many biogeochemical reactions that can improve water quality. Such water quality transformations are less likely in fractured and karst aquifers, where preferential flow through cracks and fissures limits contact between the water and aquifer material. Flowpaths also affect transformations during subsurface storage. Flowpaths surrounding dual-purpose wells, those used for both injection and recovery, have highly variable travel times and the most unpredictable effects on water quality. Subsurface storage systems with different recharge and recovery points can have defined flowpaths and associated travel times. Such systems have more consistent and predictable water quality transformations.

Monitoring the efficacy of the purification processes in the vadose zone and adjacent aquifer is essential for evaluating the quality of groundwater impacted by artificial recharge of treated wastewater (Vengosh and Keren, 1996). Documentation of water quality changes with pilot studies often needs to be verified for compliance with local regulations. The major issues surrounding the need to recycle municipal wastewater for a wide spectrum of uses (perhaps with the ultimate objective of achieving true, direct recycling of sewage as a dependable source of drinking water) have been discussed in a growing body of literature. An overview of water reuse, perspectives regarding public concerns, and future research needs is available in numerous articles such as National Research Council (1998, 2008), Higgins et al. (2002), and *Guidelines* (2004). Main concerns are that adverse health risks could result from

introduction of pathogens (e.g., bacteria, protozoans, and viruses) and toxic chemicals (e.g., endocrine disrupting compounds [EDCs], pharmaceutically active compounds, and DBPs) into groundwater that is eventually to be consumed by the public (National Research Council, 1994; Asano and Cotruvo, 2004; Daughton, 2004; National Research Council, 2008).

Control of pathogens in reclaimed water is important even though such product water may meet microbiological standards set for drinking water, e.g., less than or equal to one total coliform bacterium/100 mL or no detectable *Escherichia coli* bacteria per 100 mL. The principal reason is that reclaimed water is derived directly from municipal wastewater in which pathogen concentrations are higher than in even heavily polluted natural waters, and the typical microbiological indicators alone are inadequate for drinking water application. Thus, more extensive regimens for controlling and monitoring of microbial agents must be applied, and additional standards are required (Asano and Cotruvo, 2004).

Alluvial recharge systems effectively filter bacteria and protozoans, leaving viruses as the major concern for pathogen transport during subsurface flow. In fact, the survival of viruses has been used as travel-time criteria for systems designed for potable water production. In California, the minimum travel time requirement is 6 months, while 50 and 70 days are required in Germany and the Netherlands, respectively. Higher levels of microbial activity in an aquifer decrease the survival of pathogenic viruses since the viruses are subject to predation. This is one reason for the discrepancy between criteria in different parts of the world.

To ensure a safe potable supply, it is important to place the extraction (or production) wells at an appropriate distance from the recharge point, according to an adequate understanding of the hydrogeology and water quality of the aquifer system. These separations in space and time allow the recharged reclaimed water to mix with native groundwater and, more important, to degrade biological and chemical constituents of reclaimed water. For recharge basins and vadose zone recharge wells, the recharged water will occupy the upper portion of the aquifer. Wells screened over a wide depth will produce a mixture of reclaimed water and recharge water dependent on the well productivity as a function of depth. This is an important consideration in successful reuse of reclaimed water to facilitate public acceptance. Knowledge of the migration of contaminants in groundwater aquifers is crucial in assessing the potential health/environmental impacts, preventing pollution problems, and designing or constructing cost-effective remediation systems. Although recent advances (including modeling techniques) for evaluating the transport processes in these natural water systems provide predictive tools for measuring travel times, tracer studies are uniquely applicable for direct measurement of travel times, velocities, and hydraulic connections.

2.3 TRACERS FOR RECHARGED WATER FLOW

Different geochemical techniques can be used to evaluate flow pathways, velocities and travel times, and hydrodynamic dispersion, including geochemical fingerprinting, age dating, and deliberate tracer experiments. The techniques are based on different principles, so they provide complementary information about the flow and mixing between artificially recharged water and native groundwater. Use of conservative (nonreactive and nonretarding) deliberate tracers is one of the best methods for estimating the travel time of recharged water from a recharge point because the tracers directly measure the direction and travel time of groundwater flow (see Table 2-3).

Table 2-3. Comparison of various tracers for water movement

Tracer	Analytical method	Advantages	Disadvantages	References
Inorganic anions (Br ⁻ , Cl ⁻)	Ion-selective electrode, ion chromatography (IC)	Easy quantification; inexpensive chemicals; no toxicological problems unless an excessive amount applied	A potential precursor for DBPs; relatively high background concentrations; large mass must be added	Sposito, 1989; Domenico and Schwartz, 1990; Flury and Papritz, 1993; Seaman et al., 1996
Gas (SF ₆)	Gas chromatography (GC) equipped with an electron capture detector	Nontoxic; low background concentration; economical	Loss due to gas exchange; a minor greenhouse gas	Lester and Greenberg, 1950; Wilson and Mackay, 1993; Busenberg and Plummer, 2000; Gamlin et al., 2001; Clark et al., 2004; Avisar and Clark, 2005
Dyes	Fluorometer; fiber optics spectroscopy (in situ), fluorescence spectroscopy	Detectable at low concentrations; easy quantification; sighting; inexpensive	Large molecules; sorption and decay; toxicity; complicated chemical interactions (e.g., pH-dependent charge and color changes); complex formation	Williams and Bridges, 1964; Smart, 1984; Nielsen et al., 1991; Flury and Wai, 2003
Isotopes	GC, ICP, isotope ratio analyzer, or elemental analyzer, coupled with mass spectrometer	Naturally occurring tracer; difference between the composition of the source water and that of native groundwater; dating (age determination); labeling of pollution sources	Public health concerns (radiation risk); sophisticated instrumentation for quantification; expensive analysis and sample collection	Davis et al., 1980; Sidle, 1998; Miljevic, 2003; Babcock et al., 2006

Ideally, a tracer will have transport characteristics the same as or very similar to those of groundwater, and such a tracer is termed “conservative” because it flows at the same speed

and with the same characteristics as groundwater (Davis et al., 1980). A perfect water tracer would flow through the aquifer at the same direction and rate of speed as groundwater, have a low background concentration in the native groundwater, be insensitive to changes in solution chemistry (pH, alkalinity, or ionic strength), be measurable simply and cheaply at low concentrations, and generate a low toxicological impact on the environment (Davis et al., 1980; McLaughlin, 1982; Flury and Wai, 2003). The movement of the tracer should match that of the water flow regimen, so it should not be affected by sorption (i.e., retardation) by physical or biological processes. The tracer should not affect the water flow regimen by changing fluid density or viscosity. The tracer should be stable for the duration of the test but not be retained as residual material in the longer term. However, there is no perfect water tracer (Church, 1974; Davis et al., 1980). Commonly used tracers for groundwater flow within aquifers include anions (e.g., Br⁻, Cl⁻), fluorescent dyes (e.g., rhodamine), isotopes (e.g., ²H₂O, ¹⁰B, ⁸²Br), and trace gases (e.g., He, SF₆) (Flury and Wai, 2003; Clark et al., 2004; Quast et al., 2006). Deliberate tracer tests consist of introducing a tracer into a volume of water, which is injected into the groundwater flow field and subsequently monitored at selected downgradient sampling points.

Selection of a conservative tracer compound may require laboratory testing to prove almost ideal tracer behavior. Aspects of environmental and administrative law must also be considered; often this limits field application of tracers. In most countries only a few compounds—such as salt tracers and some fluorescent dye tracers—can be used for injection in field experiments and require permitting. In the United States, most states do not authorize in any tracer study the use of any radioactive material, hazardous substance, carcinogen, or chemicals reasonably anticipated to be carcinogens [e.g., chemicals listed by the secretary of the Department of Health and Human Services pursuant to United States Code Section 24(b)(4), 40 Code of Federal Regulations Section 251.33(e)]. In Germany, it is practically impossible to use radioactive tracers and rhodamine compounds (except amidorhodamine G) within field experiments. When new tracers (especially the reactive compounds) not yet known to the administration are proposed, lengthy and tedious procedures to obtain permission for their use are often required (Ptak et al., 2004).

2.3.1 Inorganic Anions

Inorganic anions are the most commonly used tracers because they are relatively inexpensive. Inorganic anions can be easily mixed on site and injected into the aquifer. In addition to deuterium (²H), bromide (Br⁻) and chloride (Cl⁻) are considered almost ideal conservative tracers for water movement and are thus widely used (Domenico and Schwartz, 1990; Flury and Wai, 2003). Bromide and chloride transport is generally not retarded because these anions are repulsed by the negative charge on soil particles (Flury and Wai, 2003). The pH of the soil environment mainly governs anion adsorption and exclusion, because pH affects the net proton charge of soil particles. Anions like phosphate (PO₄³⁻) and fluoride (F⁻) are less affected by anion exclusion but sorb to the soil particles by ligand exchange. Iodide (I⁻) sorbs to some degree to soil minerals, has a low oxidation potential, and oxidizes under aerobic conditions (Davis et al., 1980; Bowman, 1984). Therefore, these anions (PO₄³⁻, F⁻, and I⁻) are unsuitable as water tracers. If the soil material possesses a dominant positive charge such as saprolytic soils, electrostatic adsorption of anions may occur, leading to considerable retardation of anions (Sposito, 1989; Seaman et al., 1996).

Compared with chloride, bromide may be a more suitable tracer for artificial recharge systems using reclaimed water because chloride concentrations are relatively high in aquifers as well as in reclaimed water. The concentrations of bromide in natural waters are

approximately 300 times lower (by weight) than those of chloride (Davis et al., 1980; Davis et al., 1998). In addition, the toxicity of bromide is low; unless an excessive amount is applied, no toxicological problems should arise (Flury and Papritz, 1993). Flury and Papritz proposed a quality criterion of 1 mg/L of groundwater on the basis of bromide toxicity data (Flury and Papritz, 1993).

2.3.2 SF₆

SF₆ is a synthetic gas used primarily in the electrical industry as a dielectric; it is a nontoxic, colorless, and odorless gas (Wilson and Mackay, 1993). SF₆ has been used as a tracer in the atmosphere and in surface water for more than 2 decades, and more recently it has been used as a conservative tracer in groundwater systems (Dillon et al., 1999; Gamlin et al., 2001; Wilson et al., 2002; Clark et al., 2004; Clark et al., 2005). SF₆ can be a useful tracer in groundwater recharge systems because: 1) SF₆ is nontoxic (Lester and Greenberg, 1950) and permission has been granted to use it as a tracer in potable aquifers in California, Arizona, and southern Australia; 2) background concentrations of SF₆ in natural waters are extremely low (<0.2 pmol/L; 1 pmol = 10⁻¹² mole) (Busenberg and Plummer, 2000); 3) laboratory-scale experiments have shown that breakthrough curves of SF₆ and Br⁻ are identical in saturated porous media, which have high contents of organic material or clays, demonstrating that SF₆ is not retarded (Wilson and Mackay, 1993; Wilson and Mackay, 1996; Vulava et al., 2002); and 4) SF₆ is less expensive than other tracers, so it can be used in larger systems for longer periods (Gamlin et al., 2001; Clark et al., 2004; Avisar and Clark, 2005; Clark et al., 2005). This economic factor is important and often limits the size of experiments because the cost of the tracer can be a particular problem when large volumes of water need to be tagged, as is often the case near artificial recharge operations. SF₆ can be used to tag volumes of 10⁶ m³ or more.

SF₆ differs from ionic and dye tracers in that it is a gas and is lost from solution to the atmosphere across the air-water interface. Thus, it is important to monitor the SF₆ concentrations in the recharge water to determine the amount of tracer lost to gas exchange prior to infiltration. This is especially true if the artificial recharge is taking place in a spreading pond. Insufficient monitoring of spatial variability can lead to erroneous interpretations of travel times (Avisar and Clark, 2005). Also, because SF₆ gas is a greenhouse gas (Busenberg and Plummer, 2000), the injection of SF₆ should be conducted carefully to minimize loss to the atmosphere.

Recent results from gas tracer experiments conducted at three managed artificial recharge sites in California (Orange County, Montebello Forebay, and El Rio) indicate that gas lost during percolation is minimal and that therefore, the flow, or at least a portion of it, is saturated (Clark et al., 2004; Avisar and Clark, 2005; Clark and Hudson, 2005; Quast et al., 2006). Clark and coworkers hypothesized that the bulk of the tracer and, therefore, of the recharge water passed through saturated columns that exist below these basins and were transported across the water table without interacting with soil air (Clark et al., 2004). This finding contradicts conventional wisdom, observations of dissolved noble gases (Clark and Hudson, 2005; Clark et al., 2005), and gas tracer experiments performed at two other locations, the Big Bear pilot basins (Clark and Avisar, unpublished data) and the Sandy Hollow Reservoir experimental basin (Heilweil et al., 2004). These experiments indicate that trapped air exists beneath spreading basins and its amount can be sufficient to retard the transport or completely remove the gases from the recharge water. In the presence of trapped air, gases will partition strongly into the immobile air volume, retarding their transport and reducing their concentrations in the infiltrating water. These effects have been documented

previously in laboratory column experiments (Fry et al., 1995; Donaldson et al., 1997; Vulava et al., 2002).

2.3.3 Dyes

The most comprehensive catalogue of dye tracers is the Colour Index (Society of Dyers and Colourists, 1999), which lists information on several thousand different dyes, including chemical structures, selected physical and chemical properties, manufacturers, commercial and generic names, and methods of application. Flury and Wai (2003) recently reviewed dye tracers. Many types of dyes were tested for their suitability as soil water and groundwater tracers. Because of their low cost, easy detection to low limits with a fluorometer, and the potential for viewing, the tracers used most frequently for groundwater tracing are sulforhodamine B, rhodamine B, fluorescein/uranine, and rhodamine WT (Flury and Wai, 2003). The most prominent vadose zone tracers include erio floxine 2G, brilliant blue FCF, rhodamine WT, methylene blue, lissamine yellow FF, and pyranine (Flury and Wai, 2003). Some of these tracers are also frequently used in surface water investigations. In contrast to groundwater tracers, vadose zone tracers are often employed so that one can view the spatial flow patterns of water or solutes. Therefore, a tracer's visibility in soils and other subsurface materials is important. While methylene blue (C.I. 52015) was once extensively used for viewing preferential flow pathways in clayey soils (Bouma et al., 1977), owing to its strong sorption to soil material, it is infrequently used today. Brilliant blue FCF has become the most prominent dye tracer in vadose zone hydrology (Steenhuis et al., 1990; Flury and Wai, 2003).

However, dyes can sorb to the aquifer soil. Most dyes are relatively large organic molecules with various functional groups attached to the molecular kernel. Dyes interact to some degree with the solid matrix in vadose zones and aquifers (Davis et al., 1980; McLaughlin, 1982). In general, organic dyes have both hydrophobic and hydrophilic properties. In addition, the functional groups of organic dyes can protonate and deprotonate depending on pH, thereby changing the net charge of the molecule (Smart and Laidlaw, 1977; Viriot and Andre, 1989). Because of these characteristics, interaction of the dye molecule with soil is rather complex (Flury and Wai, 2003). For instance sodium fluorescein, rhodamine WT, lissamine yellow FF, and amino G acid are sorbed rather easily on soil materials and have been found to suffer losses in groundwater (Rahe et al., 1979). In addition to chemical loss, the fluorescence of dyes can be quenched by a variety of mechanisms, including redox reactions within the subsurface involving the electron-donating anions, such as I^- and Br^- , or the electron-accepting anions, such as NO_3^- (Williams and Bridges, 1964). Dye tracers may not be suitable for artificial recharge systems using reclaimed water with elevated ions such as NO_3^- .

In addition, dyes can react with naturally occurring compounds or contaminants to form toxic compounds. Chlorination of water containing dye tracers can form chlorophenol compounds (Smart, 1984). Rhodamine dyes (rhodamine B and rhodamine WT) can react with nitrite to form the carcinogenic compound diethylnitrosamine (Abidi, 1982; Steinheimer and Johnson, 1986). Unfortunately, toxicological reviews of dyes used as hydrological tracers are rare and exist only for some fluorescent dyes (Smart and Laidlaw, 1977; Smart, 1984), and regulations for the use of dyes as subsurface tracers are few in the United States (Flury and Wai, 2003). In comparison, the German Federal Environmental Agency (Umweltbundesamt) recently assessed the toxicological and ecotoxicological impacts of water tracers (Behrens et al., 2001). Eleven fluorescent dye tracers, primarily groundwater tracers, were tested for genotoxicology and ecotoxicology. Among the eleven, seven dyes were reported toxicologically safe (fluorescein/uranine, eosine, sulforhodamine G, pyranine, sodium naphthionate, tinopal CBS-X, and tinopal ABP). The other four dyes (sulforhodamine B, rhodamine WT, rhodamine B, and rhodamine 6G) caused either genotoxicologically or

ecotoxicologically adverse effects and were deemed unsafe as tracers (Behrens et al., 2001). Overall, synthetic dyes should be considered toxic to the environment (Flury and Wai, 2003).

2.3.4 Isotopes

The tracer closest to ideal is the water molecule itself, which is composed of five stable isotopes: ^1H , ^2H or D , ^{16}O , ^{17}O , and ^{18}O (Davis et al., 1980; Flury and Wai, 2003). The stable isotope composition of water ($^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/^1\text{H}$) varies throughout the water cycle because of the slight mass differences between molecules containing ^2H and ^{18}O and the most common form: $^1\text{H}_2^{16}\text{O}$. When the difference between the composition of the source water and that of native groundwater is large ($>3\%$ in $\delta^{18}\text{O}$) compared to their local spatial and temporal variability, the plume of recharge water can be easily mapped and the mixing fraction between the two water types can be calculated (Muir and Coplen, 1981; Ma and Spalding, 1996; Clark et al., 2004). Isotopes of water are almost always used as intrinsic tracers of the groundwater flowpath and are rarely used during deliberate tracer experiments because it is difficult to add sufficient enriched water to alter the isotope composition of the recharge water.

Other isotopes commonly used as tracers include the stable isotopes ^{11}B , ^{13}C , ^{15}N , ^{34}S , and ^{87}Sr and the radioactive isotopes ^3H , ^{14}C , ^{35}S , and ^{222}Rn (Davis et al., 1980; Cook and Herczeg, 2000). Similar to the stable isotopes of water, these isotopes are almost always used as intrinsic tracers because of some event that has caused their presence to occur in an aquifer. Reclaimed waters contain elevated levels of boron in comparison to most groundwaters. Since most boron in detergents comes from one source, ^{11}B has been used as an intrinsic tracer in reclaimed water, similar to ^2H or ^{18}O (Bassett et al., 1995). While some short-lived isotopes such as selenate (^{75}Se), as well as stable deuterium (^2H), have been used during deliberate tracer experiments (Dunnivant et al., 1998; Flury and Wai, 2003), their application is limited. A complicating factor for the use of isotope tracers is the sophisticated instrumentation needed for analysis and quantification and the high cost of analysis. More discussion on the application of environmental isotopes in evaluating the velocity of groundwater and on the identification of isotopic fingerprints is available in other references (Sidle, 1998; Miljevic, 2003).

2.4 TRACERS FOR WASTEWATER CONSTITUENTS

The travel time of recharged reclaimed water from a recharge point can be directly measured by conservative tracers. Artificial recharge projects with reclaimed water also require information on the transport of biological and chemical constituents that are present in reclaimed water. Therefore, surrogate tracers are needed for this purpose that would approximate the transport characteristics of constituents in reclaimed water.

The travel time of recharged water obtained by conservative tracer tests does not necessarily resemble the movement of biological and chemical wastewater constituents because of sorption (retardation), biogeochemical reactions including degradation, and changes in water chemistry (e.g., pH and salinity) (Ptak et al., 2004). Although these constituents are removed prior to injection in a reclaimed water project, it is helpful to know their transport characteristics. One must use environmentally acceptable surrogate tracers for these constituents to provide the fate and transport data necessary for designing and evaluating the performance of recharge projects using reclaimed water. A prime example is the use of nonpathogenic microorganisms as indicators of the fate and transport of pathogenic microorganisms in the subsurface (Burge and Enkiri, 1978; Gerba, 1984; Harvey et al., 1988; Harvey, 1997). However, tracer testing with chemical constituents originating from

wastewater is challenging (i.e., legally unfeasible or requiring greater efforts to obtain permits in most states) because injection of those substances into the subsurface is not allowed by most regulatory agencies, mainly because of public health concerns. For this reason, most studies have focused on the fate of constituents already contained in the reclaimed water instead of deliberate tracer experiments with a subset of constituents (see Section 2.4.2). An important part of these studies is to define the hydraulic connection and travel time between the recharge location and wells using conservative deliberate tracer experiments or intrinsic tracers. Once these hydraulic parameters have been established, biogeochemical reactions can be inferred by comparing time series measurements of the recharge water to those of groundwater.

2.4.1 Biological Constituents

The presence of pathogenic microorganisms in reclaimed water, especially human enteric viruses, is one of the primary concerns in water reuse. Biological constituents such as bacteria, viruses, and protozoans are a human health concern, and all reclaimed water recharge projects should include advanced treatment to ensure they are removed or inactivated prior to recharging the aquifer. Viruses are the major concern for pathogen transport during subsurface flow because they are not effectively filtered through vadose zone as compared with bacteria and protozoans. Viruses can travel long distances and survive for many months before becoming inactive in the subsurface prior to entering drinking water wells (Gerba et al., 1975; Yates et al., 1985). The use of nonpathogenic indicators of fecal contamination has served as an important tool in public health studies involving groundwater resources. The three main classes of microorganism indicators are yeasts, bacteria, and bacteriophages (Skilton and Wheeler, 1988). Yeasts are poor surrogate tracers because they are orders of magnitude larger than pathogenic microorganisms and, therefore, interact much differently with soil matrices. Bacteria are more frequently used as tracers in groundwater studies, but it is difficult to select and culture pure strains for use as surrogate tracers, and field handling and injection are complicated. Bacteria may die or reproduce in situ, yielding false results. Bacteria cannot be used as surrogates for viral transport because they are much larger (Skilton and Wheeler, 1988). Bacteriophages (viruses that infect bacteria) have been used for viral surrogates because of their availability, ease of assay, and lack of pathogenicity and have been determined to be the most representative microbial tracers (Gerba, 1984; VanDuin, 1988; Bales et al., 1991; Emerick et al., 1997; Schijven et al., 1999).

Bacteriophages are not known to cause disease in humans, animals, or plants. They are easily distinguishable from each other because of their specificity for specific bacterial hosts; therefore, several may be used at the same time without interference (Bales et al., 1993). They are unlikely to be present in groundwater unless it is highly polluted with domestic sewage, and they are incapable of multiplication within these environments, limiting background levels. Their smallness and physical composition permit them to be potential tracers of human enteroviral behavior. Finally, bacteriophages have high detection limits and can be prepared inexpensively in small volumes with easy field handling procedures (Skilton and Wheeler, 1988).

Table 2-4 summarizes microbial tracers used in selected recent tracer studies. Bacteriophages have been injected into aquifers at very high concentrations (e.g., 10^{13} phages/mL) and monitored through many log units of dilution (Harvey, 1997). Commonly employed bacteriophages are PRD1 and MS2, which are single-stranded RNA and double-stranded DNA bacteriophages, respectively (Table 2-5). Both bacteriophages have been previously found to adsorb poorly to soils (Bales et al., 1991; Yahya et al., 1993) and have been

extensively used as viral surrogates (VanDuin, 1988; Bales et al., 1991; Emerick et al., 1997; Schijven et al., 1999).

Table 2-4. Use of microbial tracers in recent recharge and recovery experiments, adapted from Harvey (1997)^a

Medium type	Microorganism	Distance (m)	Retardation factor	Reference
Clay-rich till	PRD1 and MS2 (bacteriophage)	4	0.01	McKay et al., 1993
Alluvial sand	f2 (bacteriophage)	5	n/a	Bales et al., 1989
Alluvial gravel	<i>E. coli</i> PB922 (rifampin-resistant)	42	n/a	Sinton, 1986
Well-sorted sand and gravel	Indigenous bacterial community	6	1.0	Harvey and Garabedian, 1991
Well-sorted sand and gravel	PRD1 (bacteriophage)	12	1.0	Bales et al., 1995
Well-sorted sand and gravel	P32-labeled PRD1	4	1.0	Pieper et al., 1997
Well-sorted sand and gravel	Indigenous flagellates (protozoan)	1	4.7	Harvey et al., 1995

^a Retardation factor = $V_{\text{bromide}}/V_{\text{microbe}}$, where V_{bromide} and V_{microbe} are the observed average velocities of the peak concentrations of bromide and microbe, respectively, that appear at a downgradient well.

Table 2-5. Characteristics of bacteriophages PRD1 and MS2

Bacteriophage	Bacterial host	Size	Isoelectric point	Genetic structure	References
MS2 (ATCC 15597-B1)	<i>E. coli</i> (ATCC 15597)	24–27 nm	3.5–3.9	Single-stranded RNA	Schijven et al., 2002; Gerba et al., 2003; Schulze-Makuch et al., 2003
PRD1 (ATCC BAA-769-B1)	<i>Salmonella typhimurium</i> LT2 (ATCC 19585)	62–65 nm	3.0–4.2	Double-stranded DNA	Sokolova et al., 2001; Schijven et al., 2002; Gerba et al., 2003

A variety of factors have been reported to influence the transport of microorganisms in soil and aquifers. The critical factors include porosity (Barton and Ford, 1995), mineralogy (Mills and Powelson, 1996), and groundwater chemistry (Shields and Farrah, 1987). The porosity of sediments or the fissures in rocks are heterogeneous phenomena and can range from very small (straining off bacterial movement) openings to large spacing, where dissolved solutes move more quickly through channels and preferred flowpaths (DeMarsily, 1986). The tendency of bacteria to collect on sediment and rock surfaces is enhanced by adhesive polymers on cell surfaces or by similar mechanisms (Mills and Powelson, 1996). However, these are not significant factors in determining the transport of the cells in complex porous media. In addition to the physical parameters mentioned previously, the main mechanism for virus removal appears to be adsorption and charge neutralization. The adsorption of viruses is a complex process, the underlying mechanisms of which are still poorly understood (Burge and Enkiri, 1978; Goyal and Gerba, 1979; Singh et al., 1986; Shields and Farrah, 1987; Dowd et al., 1998). It is believed that the isoelectric point (IEP), surface charge, and ionic strength are key factors that influence virus adsorption (Shields and Farrah, 1987).

It has been suggested that the IEP is the predominant factor controlling virus adsorption (Dowd et al., 1998). A virus with a higher IEP should demonstrate a higher degree of adsorption since it has a weaker repulsive force against the negatively charged matrix of water and soil in which it exists. For example, the IEP of bacteriophage FR is relatively high (8.9–9.0), meaning that its surface is positively charged in most naturally occurring pH ranges (6–8). This enables FR to adsorb to the surface of negatively charged particles such as natural organic matter. In the same pH range, other bacteriophages such as PRD1 and MS2 (IEPs of 3.5–3.9 and 3.0–4.2, respectively) will be negatively charged, thereby allowing them to adsorb to positively charged particles.

In terms of surface charge, some bacteriophages such as phi-X174 are not as negatively charged as either MS2 or PRD1 (Schijven et al., 2002); in neutral-pH water, phi-X174 has essentially no charge (Fujito and Lytle, 1996; Dowd et al., 1998). The relatively weak surface charge of phi-X174 should hinder its ability to adsorb to surfaces. On the other hand, size becomes the overriding factor for particles greater than 60 nm in diameter (Dowd et al., 1998). The pore sizes of sand and gravel sediments are too large in diameter to impede virus transport by physical straining. Electrostatic adsorption to the sand and gravel grains is the primary virus removal mechanism; however, virus-specific IEPs may be too weak to significantly attenuate transport (Woessner et al., 2001).

The ionic strength of the background electrolyte has been shown to be a critical factor in influencing pathogen fate and transport in porous media. Duboise et al. (1976) found that a burst of poliovirus released from a soil column coincided with a drop in the electrical conductivity of the percolate. This finding was supported by Bales et al. (1993), who observed the release of MS2 and poliovirus during transport through silica columns was enhanced upon changing the eluent ionic strength from 0.5 to 0.005 M. The deposition rates of bacteriophages MS2 and λ on quartz grains increased with the ionic strength in the range of 0.01 to 0.1 M NaCl at a pH of 5 (Penrod et al., 1996). The findings of Chu et al. (2000) indicated that MS2 was largely removed during transport in a high-ionic-strength phosphate buffer solution through a sand column but that the virus particles moved through the column in buffer solutions that had low ionic strength (both phosphate buffer and artificial groundwater). In addition, redox conditions have a significant influence on the transport rate and deactivation of viruses in aquifers (Holzbecher et al., 2006).

2.4.2 Chemical and Organic Constituents

Results from tracer tests with conservative tracers (bromide and SF₆) may reflect the transport of some water-soluble chemicals (e.g., inorganic ions). However, it is difficult to estimate the travel time of most wastewater constituents from these experiments because the constituents are often affected by biogeochemical reaction and sorption in the subsurface. The direct injection of wastewater contaminants into the subsurface is not acceptable because of public health concerns. Based on extensive literature review and interviews with leading researchers, an ideal tracer for chemical and organic constituents (or contaminants) in reclaimed water is nonexistent.

An alternative approach is to find the best available surrogates for the specific purpose of the investigation. Possible wastewater “indicator” tracers include (according to Ronen et al., 1987; Garabedian et al., 1991; Rettinger et al., 1991; Barber et al., 1997; Schroeder et al., 1997; Ding et al., 1999; Corbett et al., 2002; Anders and Schroeder, 2003; Massmann et al., 2004; Lin and Banin, 2006):

- DOC, UVA254, excitation–emission fluorescence: organic compounds
- Chloride (Cl⁻), sulfate (SO₄²⁻): salts, anions
- Sodium (Na⁺): salts, cations
- Conductivity, TDS: salts
- Nitrate (NO₃⁻), ammonium (NH₄⁺), phosphate (PO₄³⁻): nutrients
- Boron (B): washing powder additive (detergent)

Transport and attenuation of these constituents can be affected by site-specific conditions, including the porous medium matrix, mineralogy, biochemical activity, groundwater chemistry, redox conditions, types of organic carbon present, saturation, and history of use (LeBlanc, 1996; Vengosh and Keren, 1996; Ding et al., 1999; Anders and Schroeder, 2003; Mansell and Drewes, 2004). Among these conditions, saturation is one of the most important factors governing retention of chemical and organic constituents. The recharge of a relatively high-salinity reclaimed water into groundwater results in ion-exchange and adsorption reactions during the first stages of reclaimed water arrival, but once the exchangeable and absorbed sites become saturated, cations and/or anions can be retained in the reclaimed water and behave conservatively, similar to the chloride ion (Vengosh and Keren, 1996; Anders and Schroeder, 2003). Degradation of much of the organic matter is rapid and takes place mainly in the unsaturated zone, and refractory organic matter tends to be slowly removed during the flow of contaminated groundwater in the saturated zone (Fox et al., 2001; Fox et al., 2005; Yoo et al., 2006). The approximately conservative behavior of organic matter in the groundwater may be an artifact of its composition; the fraction that remains after transport through the unsaturated zone is the slowly reacting resistant species (Fox et al., 2001). As discussed in previous sections, the effectiveness of the vadose zone at removing organic matter stems not only from the biogeochemistry but also from other parameters such as the availability of electron acceptors.

Other potential chemical markers for tracing the transport of wastewater constituents in groundwater are pharmaceuticals and EDCs (Masters et al., 2004; Soliman et al., 2007). The occurrence of pharmaceuticals and EDCs in the environment has received considerable attention from regulators and consumers, now that many have been detected in surface waters

and groundwaters, municipal wastewater, and drinking water systems (Kolpin et al., 2002; Snyder et al., 2003; Masters et al., 2004). Some U.S. states such as California and Florida have shown interest in the occurrence of pharmaceutically active compounds in drinking water supplies and are considering adopting regulations that would require annual monitoring of EDCs at groundwater recharge systems augmented with reclaimed water (Masters et al., 2004). The fate and transport of pharmaceuticals and EDCs are widely discussed in a *Ground Water Monitoring & Remediation* special issue (Vol. 24[2], 2004).

EDCs include natural hormones and pharmaceuticals such as birth control pills, estrogen replacement products, or steroids. EDCs can also be organochlorine compounds found in pesticides and industrial chemicals such as polychlorinated biphenyls (PCBs) and dichlorodiphenyl-trichloroethane (DDT) (Masters et al., 2004). Pharmaceuticals observed in the aquatic environment include antibiotics, analgesics/anti-inflammatory drugs, antiepileptics, blood lipid regulators, blood viscosity-affecting agents, beta-blockers, diagnostic agents, antidiabetic agents, and antidepressants (Stan and Heberer, 1997; Halling-Sorensen et al., 1998; Ternes, 1998; Buser et al., 1999; Daughton and Ternes, 1999; Kolpin et al., 2002; Drewes et al., 2003). These human-derived contaminants have the potential to serve as tracers of domestic water in surface water and groundwater (Kolpin et al., 2002; Drewes et al., 2003; Giger et al., 2003; Anderson et al., 2004; Ashton et al., 2004; Clara et al., 2004; Kolpin et al., 2004; Masters et al., 2004; Weigel et al., 2004; Glassmeyer et al., 2005).

The chemical that has received the most interest as an indicator tracer for domestic wastewater contamination in surface water and groundwater is caffeine (Seiler et al., 1999; Standley et al., 2000; Chen et al., 2002; Gardinali and Zhao, 2002; Buerge et al., 2003; Weigel et al., 2004; Ferreira et al., 2005; Peeler et al., 2006; Rabiet et al., 2006). Caffeine (1,3,7-trimethylxanthine) is a nonprescription pharmaceutical used both as a cardiac, cerebral, and respiratory stimulant and as a diuretic. It is also a constituent of a variety of beverages and of numerous food products. The average caffeine consumption in the United States is 210 mg per person per day, and the global average consumption is about 70 mg per person per day (Buerge et al., 2003). If one considers its uptake with beverages, foods, and drugs, caffeine is probably the most widely consumed drug in the world (Ogunseitan, 1996; Buerge et al., 2003).

Caffeine's usefulness as an indicator for pharmaceuticals is limited because it is apparently nonconservative (i.e., biodegradable) under some conditions, and the presence of prescription pharmaceuticals is unpredictable (Seiler et al., 1999; Chen et al., 2002). Caffeine is metabolized through a specific biphasic pathway driven by oxygen-demanding enzymes (Ogunseitan, 2002). Degradation by-products of caffeine metabolized by the bacterial isolate include other xanthine derivatives (Ogunseitan, 1996). Nevertheless, scientists using caffeine have successfully detected groundwater contamination by domestic wastewaters (Seiler et al., 1999; Chen et al., 2002; Peeler et al., 2006; Rabiet et al., 2006).

Caffeine is not sufficiently metabolized by wastewater microorganisms. Its mean rate coefficient for biodegradation in surface water is estimated at $\sim 0.004 \text{ day}^{-1}$ at 20 °C and $< 0.003 \text{ day}^{-1}$ at less than 10 °C (Ogunseitan, 1996; Buerge et al., 2003). Additionally, the occurrence of microorganisms capable of degrading caffeine in freshwater systems appears to be rare (Ogunseitan, 1996). The environmental fate of caffeine in soils and aquifers is not completely understood (Buerge et al., 2003). The contribution of biodegradation is difficult to quantify because it depends on several parameters such as total microbial activity and temperature (Buerge et al., 2003). In general, the potential for contact between organic

compounds and microorganisms is greater during subsurface transport than during surface transport and caffeine does not behave conservatively during subsurface transport.

Likewise, most pharmaceuticals are attenuated in the subsurface. Investigations of the fate of pharmaceuticals during bank filtration in Berlin reported that most of the tested pharmaceuticals were removed during transportation through the subsurface. In column experiments designed to simulate bank filtration, carbamazepine, diclofenac, and propylphenazone were more resistant to biotransformation than ibuprofen was, but all were degraded eventually (Mersmann et al., 2003). Studies at managed aquifer recharge sites showed similar results of bank filtration, and more adsorption and degradation occurred in the unsaturated zone (vadose zone) than in the saturated zone. Field studies of a managed aquifer recharge system in Sweetwater, AZ, showed that the pharmaceuticals ciprofloxacin, diclofenac, gemfibrozil, ibuprofen, indomethacin, ketoprofen, naproxen, and ofloxacin are readily removed, while carbamazepine, metoprolol, phenazone, propylphenazone, propranolol, silufaethoxazole, and trimethoprim are not completely removed (Drewes et al., 2002b; Drewes et al., 2003; Sedlak et al., 2004). Another study of aquifer recharge systems (Snyder et al., 2004), which classified compounds on the basis of their persistence in groundwater, reported diclofenac, erythromycin–H₂O, and sulfamethoxazole as the most recalcitrant of the compounds.

An alternative to conducting deliberate tracer experiments with wastewater compounds is to measure in situ water quality and compare it with the travel time of groundwater. For a newly developed recharge system, subsequent monitoring of wastewater constituents or indicators (e.g., organics, inorganic chemicals, heavy metals, nutrients, microorganisms, DBPs, and EDCs) after starting recharge can provide information for estimating degradation rates and travel times of those wastewater constituents in the recharge system. Many recharge facilities do not recharge reclaimed water during summer (or dry) months owing to high demand for reclaimed water by customers. Those facilities can also monitor in situ water quality change following the resumption of recharge after an idle period. Water quality data before the recharge restarts can be used as the baseline conditions. Although these approaches can provide a sketch of transport times of wastewater constituents under the initial unsaturated conditions, the results may not represent the transport of the constituents under the partially saturated conditions that occur later in most recharge operations.

2.5 SUMMARY

Water purveyors, municipalities, industries, and agriculture are interested in using reclaimed water to enhance aquifer recharge. About one-third of utilities responding to a national survey are recharging groundwater with reclaimed water (WateReuse Foundation, 2007). Surface spreading (recharge basin), subsurface well recharge into the vadose zone, and subsurface well recharge into an aquifer are three typical methods for recharging reclaimed water. Surface spreading is the most common and widely accepted method. There are significant public health and regulatory concerns associated with the biological and chemical contaminants in the recharged reclaimed water that may degrade groundwater quality. Migration of contaminants in groundwater aquifers is crucial in assessing potential health/environmental impacts and in preventing pollution problems. Tracer testing is one way to direct measurement of the travel times of reclaimed water in the subsurface and the biological and chemical contaminants it may contain. Selection of a tracer compound is important and should include an evaluation of its transport properties at each field site. Ideally, the tracer will behave conservatively and mimic the movement of the water. Aspects of environmental and administrative law also must be considered; in most cases this is a

limiting factor for tracer selection. In most countries, only a few compounds are legal for injection in field experiments.

Deliberate experiments using conservative (nonreactive and nonretarding) tracers are the best methods to estimate the travel time of recharged water in recharge systems. Commonly used tracers for groundwater flow within aquifers include anions, trace gases, fluorescent dyes, and isotopes. Bromide and chloride are considered ideal conservative tracers for water movement and are thus widely used. Bromide may be a more suitable tracer than chloride for artificial recharge systems using reclaimed water because of the relatively high background concentration of the former anion in native groundwater and reclaimed water. Gas tracers, such as SF₆, can be a useful tracer in larger tracer experiments when water volumes in excess of 10⁴ m³ need to be tagged. Dyes, which can be sorbed rather easily on soil materials, may not be suitable for groundwater recharge systems using reclaimed water. The use of isotopes as deliberate tracers in groundwater recharge systems augmented with reclaimed water tends to be limited by public health concerns and complexity in the injection, monitoring, and analysis of isotopes.

The travel time of recharged reclaimed water obtained by the conservative tracer test does not necessarily resemble the movement of biological and chemical constituents of the reclaimed water. Reductions in wastewater constituents can be accomplished by sorption onto geological materials, biogeochemical reactions, and changes in water chemistry (i.e., redox conditions). Nonpathogenic bacteriophages are one of the most representative microbial tracers, and commonly employed bacteriophages have been PRD1 and MS2. IEP, surface charge, and ionic strength are key factors that influence virus adsorption and, thus, their transport.

An alternative method of investigating the transport of constituents present in reclaimed water is to find the best available surrogates for the specific compounds of each investigation. DOC, UVA254, and excitation–emission fluorescence have been used as indicators of organic compounds; chloride, sulfate, conductivity, and TDS have been used as indicators of salts; nitrate, ammonium, and phosphate have been used as indicators of nutrients. Other potential chemical markers to trace movement of wastewater constituents in groundwater are pharmaceuticals and EDCs. Caffeine has received the most interest as an indicator tracer for domestic wastewater contamination in groundwater. Most studies of pharmaceuticals have observed that these species are commonly attenuated in the subsurface. Although most constituents of reclaimed water are not conservative, a comparison of groundwater flows based on the use of conservative tracers and on the shifting times and concentrations of these “indicator” tracers can provide a “snapshot” of contaminant transport in groundwater aquifers near recharge sites.

CHAPTER 3

MATERIALS AND METHODS

This chapter describes the materials and methods used for the evaluation of the tracers at three test sites. The locations of the test sites are not identified, in order to protect public safety, and the three sites are instead described as “Direct Recharge Well,” “Vadose Zone Recharge Well,” and “Recharge Basin” sites. The characteristics of testing sites, experimental methods for laboratory tests and field tracer tests, and analytical methods are described fully below.

3.1 SITE DESCRIPTION

Select tracers were tested in three of the most common aquifer recharge systems: recharge basin, vadose zone recharge well, and direct recharge well (Figure 3-1). Table 3-1 summarizes characteristics of each test site.

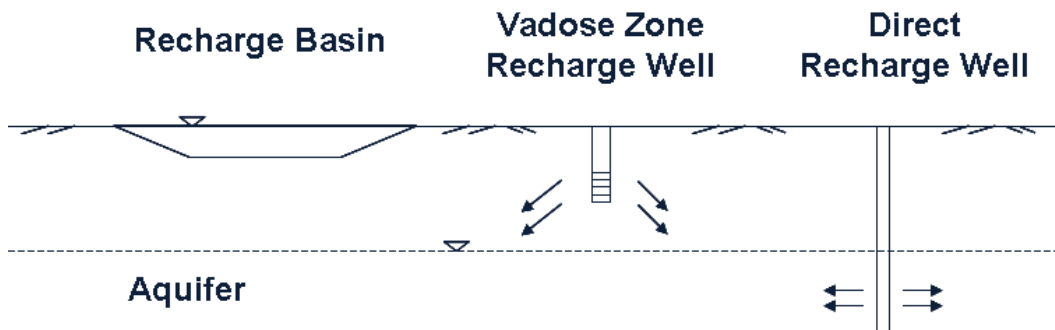


Figure 3-1. Engineered recharge systems for reclaimed water.

3.1.1 Direct Recharge Well Site

Figure 3-2 presents schematics of the Direct Recharge Well Site. The recharge facility rests on typical alluvial sediments. In the vicinity of the recharge well, 45 to 85 ft below land surface (bls) consists of fine sand, sandy clay, and gravel. The next unit consists predominantly of silty clay approximately 400 ft bls. The tertiary conglomerate, predominantly sand and gravel, occurs from approximately 415 ft bls to the bottom of the borehole of the well at 750 ft bls. The fine-grained material in the vadose zone restricts the downward flow of water from precipitation and ephemeral washes to the regional aquifer and causes the confined conditions in the regional aquifer. Groundwater beneath the facility is approximately 240 ft bls.

Table 3-1. Summary of test site characteristics

Aspects other than those of reclaimed water quality	Values for:		
	Direct Recharge Well	Vadose Zone Recharge well	Recharge Basin
Recharge rate (design)	200–250 gpm	75–300 gpm	2800 gpm (max)
Recharge rate tested for this study	200 gpm	200 gpm	1400 gpm
Operation duration	February 2001 to present	November 2005 to present	1999 to present
Aquifer type (mineralogy)	Unconsolidated alluvial sediments	Unconsolidated alluvial sediments	Unconsolidated alluvial sediments
Distance between recharge point and monitoring well (ft)	67	200	750
Water reclamation processes	Biological nitrification/ denitrification, microfiltration, UV, chlorination	Biological nitrification/ denitrification, sand filtration, UV, chlorination	Biological nitrification/ denitrification, sand filtration, chlorination
Aspects of reclaimed water quality			
Conductivity (µS/cm)	1603	1610	1270
pH	7.4	7.4	7.6
DOC (mg/L)	7.6	8.9	8.5
UVA254 (1/cm)	0.094	0.080	0.105
Bromide (mg/L)	0.57	0.99	0.59
Nitrate (mg/L as NO ₃)	10.4	14.3	17.5
Sulfate (mg/L as SO ₄)	308	152	154
SF ₆ (pmol/L)	<0.1	<0.1	<0.1
Caffeine (µg/L)	<0.020	0.042	0.025
Free chlorine residual (mg/L as Cl ₂)	1.0	0.1	0.3
TTHMs (µg/L)	95	100	70
Chloroform (µg/L)	63	70	42
Bromodichloromethane (µg/L)	25	24	22
Dibromochloromethane (µg/L)	7	6	6
Bromoform (µg/L)	<0.21	<0.21	<0.21

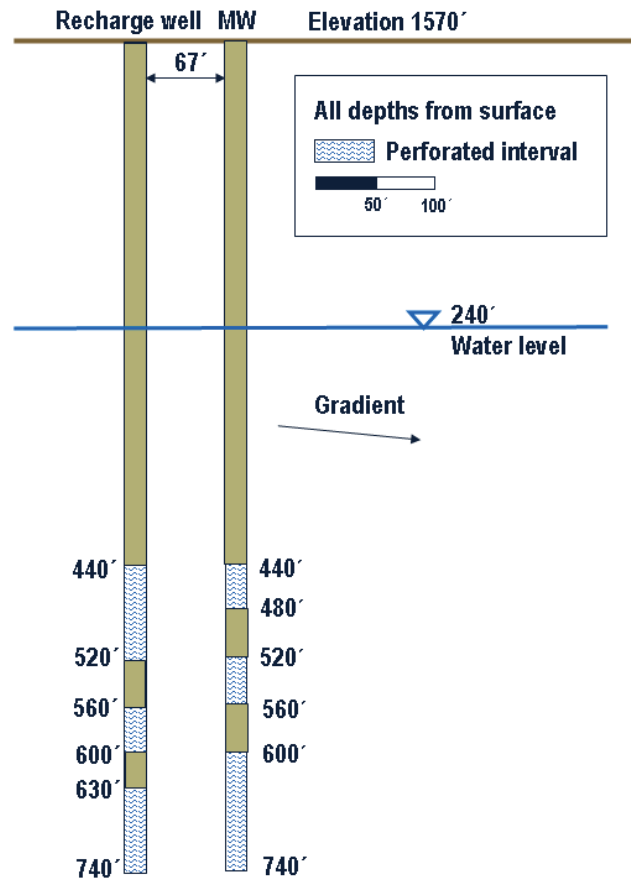


Figure 3-2. Schematic of the injection and monitoring well for the Direct Injection Well Site.

The recharge well consists of a 26-in.-diameter borehole drilled to approximately 750 ft bls. The well was constructed out of 14-in.-diameter stainless steel casing for both the blank and louvered sections. Approximately 230 ft of louvered casing was placed in the well. The 120-slot louvered casing, 230 ft in length, is capable of yielding 2750 gpm, assuming an entrance velocity of 0.01 ft/s. A blank stainless steel cap was welded to the bottom of the casing string to prevent the gravel pack from migrating up the casing during pumping. The outer portion of the boring contains gravel pack on all sides of the casing. Groundwater quality monitoring is conducted from an existing downgradient monitoring well in the same aquifer within the flowpath. The monitoring well is 67 ft from the recharge well, and the wells are screened over the same interval, 440 to 740 ft bls.

The typical recharge rate at the recharge well ranged between 200 to 250 gpm, and the flowrate for this study was set at 200 gpm. The recharge well recharged Class A+ reclaimed water (as defined in Arizona Administrative Code [AAC] R18-11-303) that had undergone secondary treatment, nitrogen removal treatment, filtration (microfiltration), and disinfection

(UV and chlorination). Class A+ reclaimed water needs to meet the following water quality criteria:

- a 24-h average turbidity of filtered effluent of 2 NTU or less
- a turbidity of filtered effluent not exceeding 5 NTU at any time
- No detectable fecal coliform organisms in four of the last seven daily reclaimed water samples taken
- a single sample maximum concentration of fecal coliform organisms in a reclaimed water sample of less than 23/100 mL
- a five-sample geometric mean concentration of total nitrogen in a reclaimed water sample of less than 10 mg/L as nitrogen.

Reclaimed water samples were collected during the tracer injection period; the analytical results are summarized in Table 3-1.

3.1.2 Vadose Zone Recharge Well Site

Figure 3-3 presents schematics of the Vadose Zone Recharge Well Site. The recharge facility rests on typical alluvial materials that overlie bedrock. The upper alluvial unit consists of loose unconsolidated sands and gravels interbedded with clays and silts. The upper alluvial unit is approximately 250 to 350 ft thick. The middle alluvial unit comprises semiconsolidated clay and silt with thin beds of fine to medium sand. The thickness of the middle alluvial unit is reported to be between 50 and 600 ft. The lower alluvial unit is composed of predominantly coarse-grained, unconsolidated, clastic sediments deposited in a high-energy environment. The lower alluvial unit consists of primarily gravels and sands, with some silts and clays. The lower alluvial unit has a reported thickness of 200 to 600 ft. Groundwater beneath the facility is approximately 430 ft bls.

A 48-in. diameter borehole was drilled to 175 ft bls, and 12-in.-diameter PVC casing was installed. The screen interval was located at 80 ft to the bottom of the well (175 ft bls). Coarse-grained gravel was installed in the annulus of the borehole to promote and enhance recharge rates to the surrounding vadose zone. Groundwater quality monitoring was conducted from an existing downgradient monitoring well within the flowpath. The monitoring well was 200 ft from the recharge well.

The maximum injection rate was designed at 300 gpm, and recharge rates at the recharge well varied from 75 to 220 gpm. The flowrate for this study was set at 200 gpm. The recharge well recharged Class A+ reclaimed water that had undergone secondary treatment, nitrogen removal treatment, (sand) filtration, and disinfection (UV and chlorination). Reclaimed water samples were collected during the tracer injection period; the analytical results are summarized in Table 3-1.

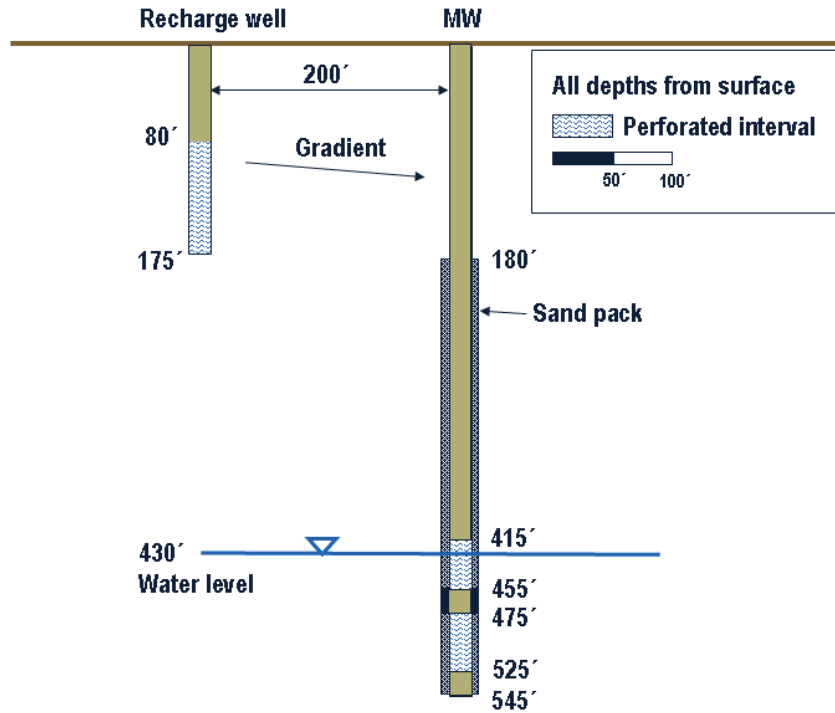


Figure 3-3. Schematic of the injection and monitoring well for the Vadose Zone Recharge Site.

3.1.3 Recharge Basin Site

Figure 3-4 presents schematics of the Recharge Basin Site. The facility is located over typical alluvial deposits. The upper alluvial unit is generally coarser-grained and unconsolidated, the middle alluvial unit is generally finer-grained, and the lower alluvial unit is generally conglomerate. The depth to groundwater beneath the facility is approximately 160 ft bls.

The recharge facility consists of seven surface recharge basins used to recharge to the subsurface and store in the aquifer up to a total of 4 million gallons per day (2800 gpm) of reclaimed water. Each basin is approximately 10 acres and is filled on a rotating basis (i.e., wet/dry cycle) with reclaimed water at a water depth of up to 2 ft. Reclaimed water distributes to the recharge basin through a distribution structure or channels and an inlet located in the “survival” zone designed for aquatic animal protection when the basin is dry. Groundwater quality monitoring is conducted from an existing downgradient monitoring well within the flowpath. The monitoring well is 750 ft from the injection point in the survival zone of the Recharge Basin.

The maximum recharge rate at the Recharge Basin Site is approximately 2800 gpm. The flowrate for this study was set at 1400 gpm for 5 days and turned to dry cycle. The recharge basin recharged Class A+ water that had undergone secondary treatment, nitrogen removal treatment, (sand) filtration, and disinfection (chlorination). Reclaimed water samples were collected during the tracer injection period; the analytical results are summarized in Table 3-1.

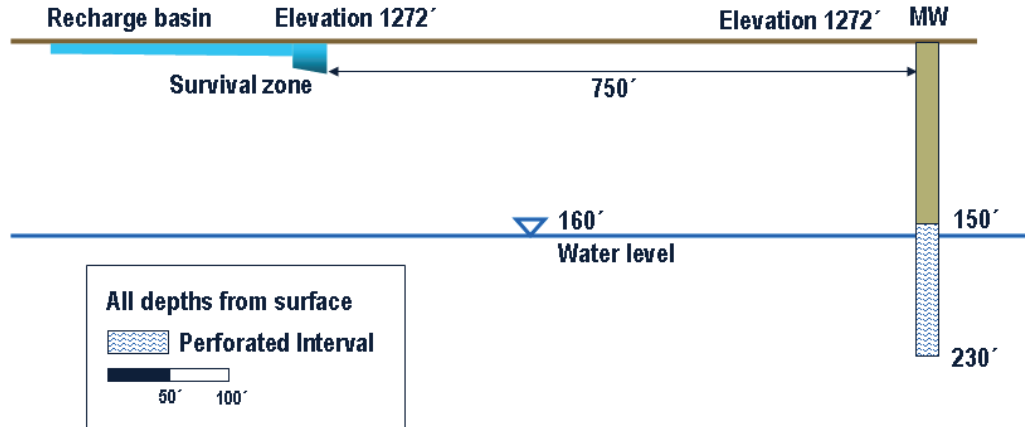


Figure 3-4. Schematic of the Recharge Basin Site.

3.2 MICROBIAL SURVIVAL TEST

To investigate the impact of chlorine residuals in reclaimed water and of groundwater travel time on the detectability of bacteriophages, survival tests of the bacteriophages were conducted in reclaimed water and groundwater from the Direct Recharge Well Site.

A 3-day die-off test was conducted with groundwater collected from the monitoring well at the Direct Recharge Well Site. The free chlorine concentration of the testing water was minimal (0.04 mg/L as Cl_2). A total of eight 15-mL centrifuge tubes were labeled “3-day,” “2-day,” “1-day,” and “initial” in duplicates and were filled with 10 mL of the groundwater. A 100- μL working stock of bacteriophages was spiked into the 3-day sample on the 1st day, 2-day sample on the 2nd day, 1-day sample on the 3rd day, and initial sample on the last day right before sample processing, giving the samples die-off times of 72, 48, 24, and 0 h, respectively. The sample bottles were kept in the dark at room temperature to mimic the groundwater situation. All samples were analyzed for bacteriophages on the last day of the test. The concentrations of bacteriophages were determined at 0, 24, 48, and 72 h. Survival of the bacteriophages in the groundwater over time typically follows pseudo-first order and is expressed as

$$\text{Log}\left(\frac{C}{C_0}\right) = -kt \quad (1)$$

where C_0 is the initial concentration of bacteriophages, C is the concentration of bacteriophages at time t , and k is the decay constant.

Since the reclaimed water contained free chlorine residuals ranging from 0.1 to 1.0 mg/L as Cl_2 , microbial survival tests were conducted with PRD1 and MS2 prior to the field tracer tests to assess the impact of free chlorine residuals on the bacteriophages. A 6-h disinfection test was conducted with 800 mL of reclaimed water from the water reclamation facility of the Direct Recharge Well Site to investigate bacteriophage inactivation rates in chlorinated reclaimed water prior to blending with groundwater. The free chlorine concentration of the

reclaimed water was 1 mg/L as Cl₂. The free chlorine level was maintained at 1 mg/L as Cl₂ by measuring the Cl₂ concentration every 30 min and adding bleach when needed. After spiking of bacteriophages (3 × 10⁵ PFU/mL), samples were collected in duplicates after 1, 3, and 6 h of contact. Samples were immediately dechlorinated after sampling by adding sodium thiosulfate. All samples were processed for bacteriophage analysis at the end of the test.

3.3 TRACER INJECTION AND SAMPLING

3.3.1 Tracer Preparation

Bromide solutions (40% weight; Univar USA Inc.) in 55-gallon containers were delivered to the utilities and transferred to the testing sites on the morning of each tracer injection. Pure SF₆ gas (99.99%) was purchased through Scott Specialty Gases. Concentrated solutions of bacteriophages and caffeine (reagent grade, Sigma-Aldrich) were prepared in the lab and transferred to the testing sites within 1 h.

Bacteriophages PRD1 and MS2 and their respective bacterial hosts *E. coli* and *S. typhimurium* LT2 were obtained from the American Type Culture Collection (ATCC, Rockville, MD). Table 3-2 summarizes characteristics of the two bacteriophages. The two bacteriophages are categorized as Biosafety Level 1, which imposes no health threats, by the U.S. Department of Health and Human Services and National Institutes of Health (1999). Bacteriophage stocks were propagated using the double agar layer method (Adams, 1959). Approximately 10⁷ PFU of bacteriophage, 1 mL of host bacteria, and 5 mL of 0.7% molten tryptic soy agar (TSA) (Difco, Detroit, MI) were combined and poured onto 1.5% TSA plates. After solidifying, the plate contents were incubated at 37 °C overnight. Bacteriophage stocks were collected the following day by adding 10 mL of 1× phosphate-buffered saline (PBS) to the surface of the plate and allowing it to incubate at room temperature for 1 h. The supernatant was collected and centrifuged at 1200 × g for 15 min to remove bacteria. The pellet was discarded, and the supernatant containing the bacteriophages was stored at 4 °C. Typically, stock concentrations are on the order of 10¹⁰ PFU/mL.

Table 3-2. Characteristics of bacteriophages PRD1 and MS2

Bacteriophage	Bacterial Host	Size	IEP	Genetic Structure	Reference
MS2 (ATCC 15597-B1)	<i>E. coli</i> (ATCC 15597)	24–27 nm	3.5–3.9	Single-stranded RNA	Schijven et al., 2002; Gerba et al., 2003; Schulze-Makuch et al., 2003
PRD1 (ATCC BAA-769-B1)	<i>S. typhimurium</i> LT2 (ATCC 19585)	62–65 nm	3.0–4.2	Double-stranded DNA	Sokolova et al., 2001; Schijven et al., 2002; Gerba et al., 2003

3.3.2 Tracer Injection

All the participating utilities wanted to conduct the tracer testing in winter, when they have less demand for reclaimed water from their customers (e.g., golf courses). Tracer injections were conducted at the three test sites on the following dates:

- Recharge Basin Site: November 1–5, 2007
- Direct Recharge Well Site: November 7–9, 2007
- Vadose Zone Recharge Well Site: November 13–15, 2007

Two bacteriophages (PRD1 and MS2), which served as microbial tracers, were injected first over a 24-h period. After the conclusion of bacteriophage injection, bromide, SF₆, and caffeine were simultaneously injected over a 24-h period. The only exception was SF₆ and bromide injection at the Recharge Basin Site over a 3-day and a 12-h period, respectively. Bromide and SF₆ are conservative tracers for evaluating advective water transport, and caffeine is a tracer used as a surrogate for evaluating the transport of pharmaceuticals.

Constant-rate recharge was conducted at the Direct Recharge Well and the Vadose Zone Recharge Well sites, both at 200 gpm throughout the tracer tests. Tracers were injected into well piping and mixed with reclaimed water. The recharge rate at the Recharge Basin Site was set at 1400 gpm for 5 days and turned to normal dry/wet cycle. Tracers were injected through a distribution structure in which reclaimed water was mixed and then flowed into the recharge basin. The injectate solutions of bromide, caffeine, and bacteriophages were mixed with plastic paddles in separate containers and were pumped into each injection point.

For SF₆ injection, different methods were used at the recharge wells (Direct Recharge Well and Vadose Zone Recharge Well sites) and the Recharge Basin Site. At the recharge wells, SF₆ was introduced by bubbling pure SF₆ (99.99%; Scott Specialty Gases) through a diffuser at a rate of approximately 1 cc/min in a flow-through equilibration chamber constructed from a 1-m-long piece of 6-in.-diameter PVC. Water from this chamber was pumped into the recharge well at a rate of about 0.2 L/min using an LMI metering pump. Therefore, during the 24-h injection, approximately 290 L of SF₆-rich water was injected. The target concentration of SF₆ in the recharge water was about 2 nmol/L. Because there was no sampling point between injection ports and well heads, the concentration of SF₆ injected was estimated. At the Recharge Basin Site, SF₆ was introduced by bubbling SF₆ directly into the distribution structure or channel through a diffuser at a rate of approximately 2 cc/min for 3 days.

The target concentrations of the tracers in the recharging water (before mixing with the native groundwater) are summarized in Table 3-3. The target concentration of tracers in recharging water ranged from 1200 to 16,000 times higher than their detection limits, considering dilutions with the native groundwater. All the concentrations except SF₆ at the recharge basin were estimates from the injection amount and flowrate. SF₆ surveys of five samples in the recharge basin were conducted after 3 days of injection, and SF₆ concentrations of the water samples averaged ~100 pmol/L, which is 1000 times the detection limit.

Table 3-3. Target concentrations of tracers in recharging water

Tracer	Concentration	MDL	Concentration/MDL
Bromide	240 mg/L (recharge wells)	0.1 mg/L	2400 (recharge wells)
	120 mg/L (recharge basin)		1200 (recharge basin)
SF ₆	1600 pmol/L (recharge wells)	0.1 pmol/L	16,000 (recharge wells)
	100 pmol/L (recharge basin)		1000 (recharge basin)
Caffeine	200 µg/L	0.020 µg/L	10,000
PRD1	10 ⁴ PFU/mL	1 PFU/mL	10,000
MS2	10 ⁴ PFU/mL	1 PFU/mL	10,000

3.3.3 Sampling

Samples were collected from existing monitoring wells at each site to monitor concentrations of tracers and water quality parameters over time. The configuration of each monitoring well is presented in Figure 3-2, Figure 3-3, and Figure 3-4. The Direct Recharge Well Site had two downgradient monitoring wells, whereas the other two sites had one downgradient monitoring well.

The monitoring wells were purged prior to groundwater sample collection by removing at least three casing volumes of groundwater until specific conductance and pH had stabilized. After purging of the wells, samples for bromide, caffeine, and other general water quality parameters were collected in pre-cleaned and pre-ashed 1-L amber glass bottles, shipped to the laboratory in coolers, and appropriately processed for analysis. SF₆ samples were collected in preweighed 10-mL Vacutainers™. Bacteriophage samples were collected in autoclaved 50-mL plastic vials. Trihalomethane (THM) samples were collected in three 60-mL amber vials with sodium thiosulfate and hydrochloric acid added.

3.4 SAMPLE HANDLING AND ANALYSIS

General sample handling and analysis were in accordance with *Standard Methods* (1998). Table 3-4 summarizes sample handling and analysis. Conductivity and pH were measured at the field site. Bromide levels were estimated at the field site with an ion-selective electrode and more accurately measured in the laboratory using an ion chromatograph. Reported bromide data in this report are from the ion chromatography measurements. Bacteriophage analyses were duplicated for all samples. Selected samples (~10%) were duplicated for other analytes.

3.4.1 Bacteriophages

Water samples were assayed for bacteriophages using the double agar layer technique (Adams, 1959). Bacterial hosts *E. coli* (ATCC 15597) and *S. typhimurium* LT2 (ATCC 19585) were used to detect bacteriophages PRD1 and MS2. Samples (5 mL) were added to molten top agar with the appropriate host and plated on bottom agar in duplicate. The plate contents were incubated at 37 °C overnight, and plaques were counted after 12 h. Positive and negative controls were included in each set of assays and for each bacteriophage.

Table 3-4. Sample handling and analysis

Target analyte	Sample preservation	Analytical method/instrumentation
pH	Measure immediately	pH meter
Conductivity	Measure immediately	Conductivity meter
Bromide (field)	Measure immediately	Ion-selective electrode
PRD1	Keep at 4 °C	Double agar layer technique
MS2	Keep at 4 °C	Double agar layer technique
UVA254	Filter with glass fiber filters (GF/F; Millipore, Billerica, MA); nominal pore size = 0.7 µm), acidify (HCl) at pH of <2, keep at 4 °C	Shimadzu UV/Vis spectrophotometer, MultiSpec-1501 (Shimadzu Corp., Kyoto, Japan)
DOC	Filter (GF/F), acidify (HCl) pH < 2, keep at 4 °C	Shimadzu TOC-V _{CSH} analyzer (Shimadzu Corp.)
Bromide (lab)	Filter (GF/F), keep at 4 °C	Dionex DX-120 Ion Chromatography System (Dionex Corp., Sunnyvale, CA)
NO ₃ ⁻ (IC)	Filter (GF/F), keep at 4 °C	Dionex DX-120 Ion Chromatography System (Dionex Corp.)
SO ₄ ²⁻ (IC)	Filter (GF/F), keep at 4 °C	Dionex DX-120 Ion Chromatography System (Dionex Corp.)
Caffeine	Filter, keep at 4 °C, extract sample within 2 days	GC/MS (Agilent 6890 Gas Chromatograph coupled to an Agilent 5973 inert Mass Selective Detector)
THMs	Acidify (HCl) at pH of <2, dechlorinate with sodium thiosulfate, keep at 4 °C	GC/MS according to USEPA 524 Method
SF ₆	Keep in Vacutainer™	Gas chromatograph/electron capture detector

3.4.2 Caffeine

A sample aliquot, usually 450–500 mL, was used for sample extraction. Initially 900–1000 mL of sample was used; however, later the sample volume was reduced for replicate measurements serving as quality assurance checks. The sample pH was adjusted to 8–9 using potassium hydroxide (KOH). Sodium chloride (40 g/L) was added to facilitate extraction by the “salting out” effect. The sample was then extracted three times against 25 mL of methylene chloride in a separatory funnel. The organic phases were combined, dried over sodium sulfate, and evaporated under a gentle flux of high-purity nitrogen to a final volume of 250 µL. This final extract was stored in the freezer prior to analysis by GC/MS. All samples were analyzed using an Agilent 6890 Gas Chromatograph coupled to an Agilent 5973 inert Mass Selective Detector. An HP5-MS capillary column (30 m × 250 µm × 0.25-µm film) was used for the separation. The temperature program consisted of an initial hold at 65 °C for 10 min followed by a temperature gradient of 10 °C/min up to a final temperature of 300 °C that was held constant for 20 min. The detector was operated in electron impact mode using single-ion monitoring of an *m/z* of 194 for caffeine. Sample injection was performed using an autosampler, and quantification was based on external calibration.

3.4.3 SF₆

SF₆ samples were analyzed using the Wanninkhof head space method (Wanninkhof et al., 1987) modified by Clark et al. (2004). In the field, preweighed 10-mL Vacutainers™ were partially filled (about 5 mL of water sample). These containers were then weighed to determine the sample size and carefully filled with ultra-high-purity nitrogen gas (so that the final pressure was equal to 1 atm). After a brief shaking to equilibrate the nitrogen gas with the water sample, the head space gas was injected through a column of Mg(ClO₄)₂ (to remove water vapor) into a small sample loop of known volume (about 1 mL). Subsequently, the gas in the sample loop was flushed into a gas chromatograph equipped with an electron capture detector with ultra-high-purity nitrogen carrier gas. SF₆ was separated from other gases with a molecular sieve 5a column held at room temperature. The detector response was determined by running gas standards purchased from Scott-Marrin, Inc. Errors on duplicate measurements were typically less than ±10%. Laboratory experiments have shown that SF₆ samples can be stored for at least 6 months without appreciable loss of SF₆ in Vacutainers™.

3.5 Travel Time Determination

For a pulse (or slug-dose) input tracer test, the theoretical mean travel time can generally be determined by examining the tracer breakthrough curve. The travel time to the center of the tracer mass (i.e., centroid) is expressed as

$$t_c = \frac{\sum_{i=1}^n t_i C_i \Delta t_i Q_i}{\sum_{i=1}^n C_i \Delta t_i Q_i} \quad (2)$$

where t_c is the travel time to the center of the tracer mass, t_i is elapsed time since injection during the i^{th} sampling interval, C_i is the tracer concentration during the i^{th} sampling interval, and Q_i is the flowrate during the i^{th} sampling interval. In case the tracer constituent is present in the native groundwater, tracer test breakthrough curves need to be corrected for background tracer concentration to eliminate the impact of the background concentration of a tracer. The travel time to leading edge, peak tracer concentration, and trailing edge can be simply obtained from the tracer breakthrough curve.

For a step input tracer test, in which a tracer compound is continuously introduced at a constant dosage, the theoretical mean travel time (\bar{t}) can generally be determined by the residence time distribution curve,

$$\bar{t} = \sum_{i=1}^n \left(1 - \frac{C_i}{C_o} \right) \Delta t_i \quad (3)$$

where \bar{t} is the mean travel time and C_o is the initial concentration of a tracer.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 BACTERIOPHAGE SURVIVAL

A 3-day die-off experiment of the bacteriophages in groundwater showed that both PRD1 and MS2 inactivation (i.e., decay rate) followed the pseudo-first order kinetic model. Since the test was conducted with groundwater containing free chlorine of <0.05 mg/L as Cl₂ in the dark, this decay was natural inactivation. Table 4-1 summarizes the decay equation expressed as the decay rate constant, *k*. The decay rate of MS2 was higher than that of PRD1. A higher decay rate indicates a more rapid decline in the number of organisms enumerated. As shown in Figure 4-1, concentrations of PRD1 and MS2 decreased by 0.5 and 1.8 log in 72 h, respectively. Assuming consistent decay rates of the bacteriophages, concentrations of PRD1 and MS2 decreased by 1.6 and 5.9 log in 10 days, respectively.

A 6-h disinfection experiment of the bacteriophages in reclaimed water exhibited more than 5.5-log inactivation of both PRD1 and MS2 within 1 h. The free chlorine concentration of the reclaimed water was 1 mg/L as Cl₂. These survival test results indicated that the bacteriophages may not be used as tracers in recharge systems augmented with reclaimed water, which is generally chlorinated. For the tracer test, nonetheless, we injected PRD1 and MS2 with a target concentration of each bacteriophage in injecting water (prior to blending with native groundwater) at 10⁴ PFU/mL to verify inactivation of the bacteriophages in the recharge systems augmented with reclaimed water. Because of the high inactivation of bacteriophages in reclaimed water, this level may not be sufficient for detecting the bacteriophages in groundwater from the monitoring well. However, it was not practical to prepare the bacteriophage injection level above 10⁴ PFU/mL. To obtain bacteriophage concentrations of 10⁴ PFU/mL in injecting water, a total of approximately 10¹³ bacteriophages were prepared for each tracer test, which required 100 10-mL agar plates.

Table 4-1. Pseudo-first order equations for the decay rates of bacteriophages in groundwater from the monitoring well

Bacteriophage	Equation [y = $\text{Log}\left(\frac{C}{C_0}\right) = -kt$]	R ²
PRD1	y = -0.0065 t	0.99
MS2	y = -0.0247 t	0.97

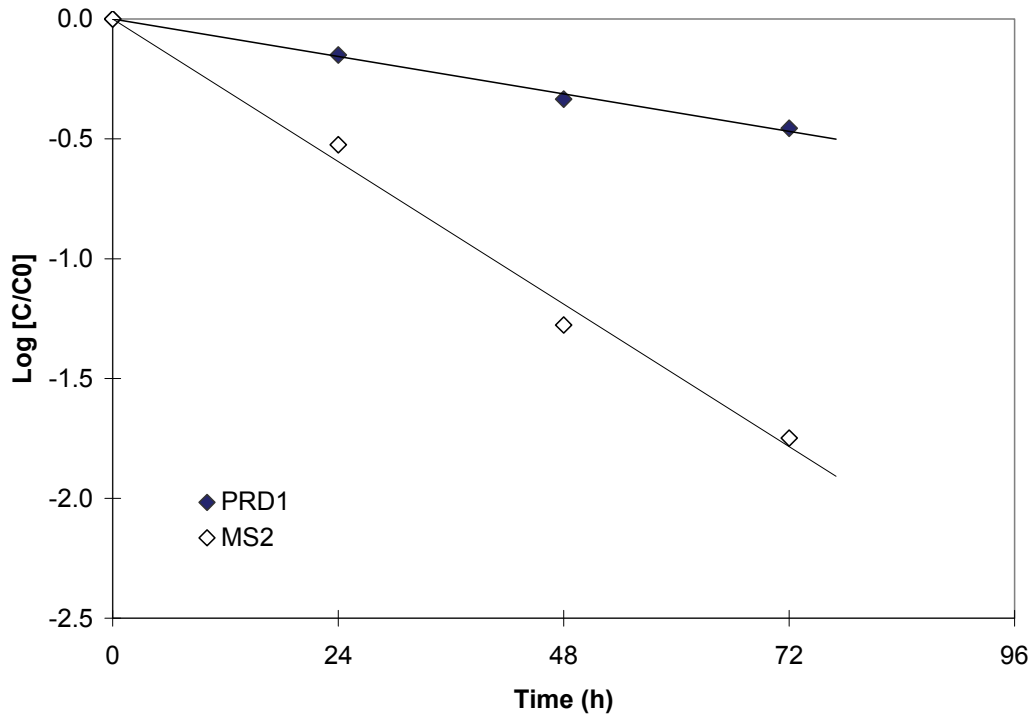


Figure 4-1. Survival of bacteriophages PRD1 and MS2 in groundwater from the monitoring well.

4.2 DIRECT RECHARGE WELL SITE

Figure 4-2 presents breakthrough curve results of tracers at the Direct Recharge Well Site monitoring well, and Table 4-2 summarizes travel times determined by each tracer. Figure 4-3 and Figure 4-4 display water quality data, and Table 4-3 summarizes the water quality of groundwater samples from the monitoring well prior to tracer injection. The average travel time can be determined by the travel time to peak tracer level or the center of mass (centroid). Table 4-2 also lists time for first detection, which can give a sense of the shortest travel times. The following major findings were obtained from the tracer test and water quality monitoring results:

- Based on tracer breakthrough curve results, the travel time to peak tracer levels is 5 to 7 days at a 200-gpm recharge rate. The centroid arrived later, between 31 and 38 days for the conservative tracers, depending on interpretation. Based on bromide breakthrough curves corrected for the background bromide concentration, the mean travel time is 31 days.
- Comparing to those of bromide and caffeine, the travel time for SF₆ peak was 2 days longer, while the centroid arrival times of bromide and SF₆ were very similar. However, the SF₆ breakthrough curve showed much more variability in concentration between successive samples than the bromide did. This variability is most likely due to gas loss during sampling. Although it is difficult to compare the behavior of the

gas tracer and that of the ion tracer because of this variability, the breakthrough curve of the gas tracer overall followed that of the ion tracer.

- Bacteriophages (PRD1 and MS2) were not detected over the monitoring period. Bacteriophages may have been destroyed by the residual chlorine in the recharged reclaimed water as previously addressed in Section 4.1. A microbial survival test in the reclaimed water (1 mg/L as Cl₂) confirmed more than 5-log inactivation of both PRD1 and MS2 within 1 h. Similar results of bacteriophage inactivation during chlorination have been reported from full-scale water reclamation facility monitoring and controlled studies (Rose et al., 1996; Clevenger et al., 2007; Costan-Longares et al., 2008).
- Based upon the normalized concentration of bromide at the peak, the dilution from the native groundwater is at least 24 times.
- SF₆ normalized concentrations were always less than those of bromide, often by more than a factor of 2. This is indicative of 1) gas loss or 2) an overestimate of the initial SF₆ concentration. This shows the importance of measuring the injectate when using a gas tracer.
- As recharge continued (or progressed), levels of wastewater constituents (conductivity, sulfate, nitrate, organics [UVA254], and THMs) gradually increased as shown in Figure 4-3 and Figure 4-4. Because these wastewater constituents were continuously introduced at an almost constant dosage during the recharge, the recharge of reclaimed water can be considered a step input tracer test. The mean travel times of conductivity, sulfate, and nitrate were 23, 29, and 26 days, respectively, based on the step input scenario. These are close to the mean travel time of 31 days from the bromide breakthrough curve. This indicates monitoring of wastewater constituents could be a potential method for estimating the travel time of reclaimed water in recharge systems without conducting tracer tests.
- TTHM levels increased from 23 to 84 µg/L 85 days after the recharge started. Throughout the monitoring period, chloroform was the major THM species (>80% of TTHM) followed by bromodichloromethane. Neither dibromochloromethane nor bromoform was detected.
- Increase in TTHM levels over time correlated with UVA254 levels, indicators of aromatic organic carbon content. UVA254 alone or UVA254 normalized to carbon has been reported as a surrogate for TTHM formation potential. UVA254 measurement is simple and can be performed at the field site, thus giving a quick estimate of TTHM levels in this recharge system.

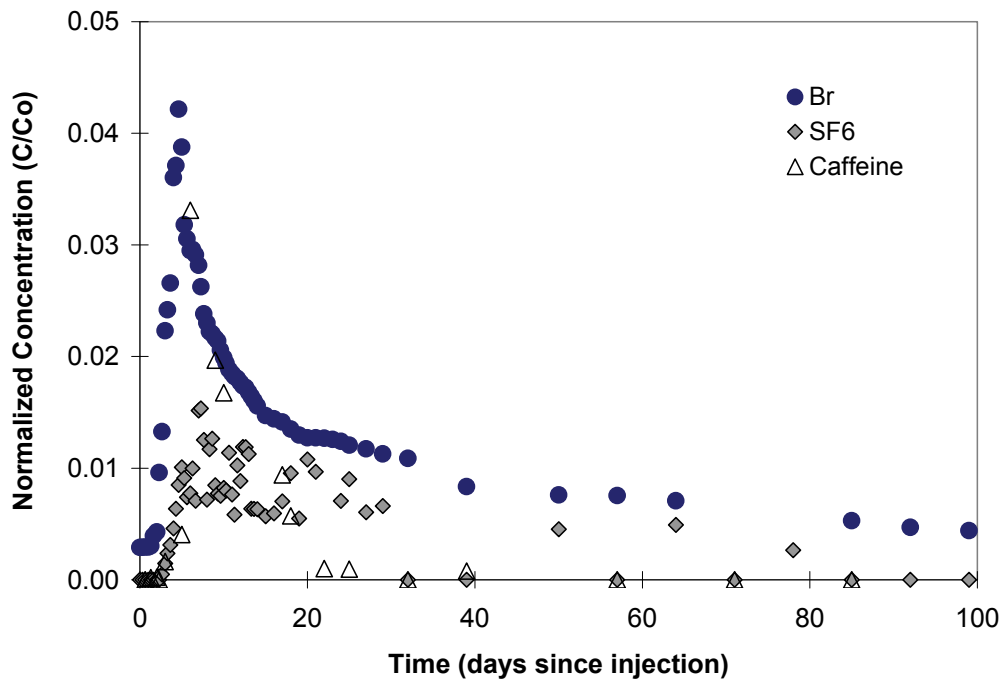


Figure 4-2. Breakthrough curve results of tracers at the Direct Recharge Well Site monitoring well.

Table 4-2. Summary of travel time at the Direct Recharge Well Site

Tracer	Target	Travel Time (Days)			
		Leading Edge	Peak	Centroid ^a	Centroid ^b
Bromide	Reclaimed water	3	5	38	31
SF ₆	Reclaimed water	3	7	31	38
Caffeine	Micropollutant	3	6	13	13

^aRaw data.

^bBreakthrough curves corrected for background bromide concentration and SF₆ nondetects in tail (after day 30).

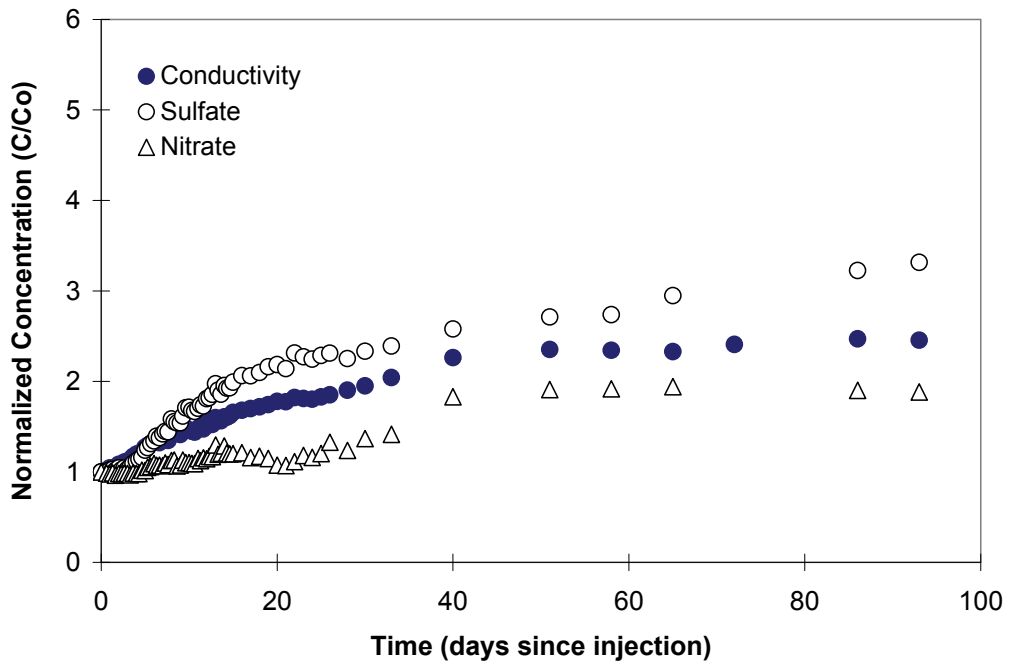


Figure 4-3. Conductivity, sulfate, and nitrate monitoring results at the Direct Recharge Well Site monitoring well.

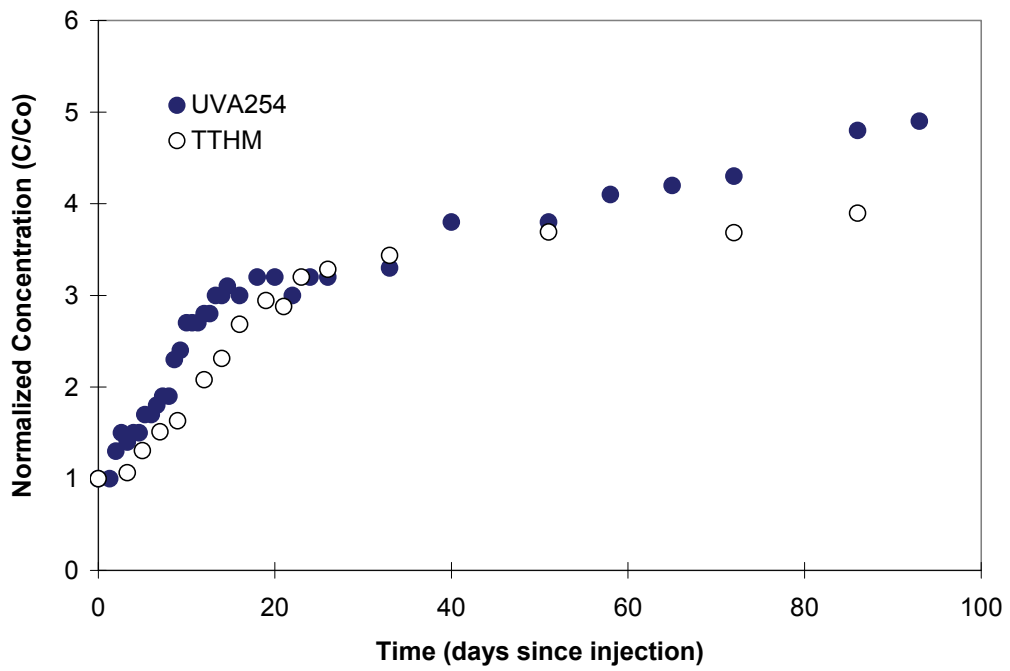


Figure 4-4. UVA254 and TTHM monitoring results at the Direct Recharge Well Site monitoring well.

Table 4-3. Water quality of groundwater samples from the monitoring wells prior to tracer injection

Statistic	Values for:		
	Direct Recharge Well Site	Vadose Zone Recharge Well Site	Recharge Basin Site
Conductivity ($\mu\text{S}/\text{cm}$)	630	1050	1690
pH	7.6	7.6	7.5
DOC (mg/L)	1.5	1.8	1.5
UVA254 (1/cm)	0.009	0.015	0.018
Bromide concn (mg/L)	0.68	0.67	0.74
Nitrate concn (mg/L as NO_3)	7.3	19.5	13.7
Sulfate concn (mg/L as SO_4)	75	145	150
SF_6 (pmol/L)	<0.1	<0.1	<0.1
Caffeine ($\mu\text{g}/\text{L}$)	<0.020	<0.020	<0.020
Free chlorine residual (mg/L as Cl_2)	<0.05	<0.05	<0.05
TTHMs ($\mu\text{g}/\text{L}$)	21.5	55.2	6.2
Chloroform ($\mu\text{g}/\text{L}$)	19	39.9	5.7
Bromodichloromethane ($\mu\text{g}/\text{L}$)	2.5	12.7	0.5
Dibromochloromethane ($\mu\text{g}/\text{L}$)	<0.15	2.6	<0.15
Bromoform ($\mu\text{g}/\text{L}$)	<0.21	<0.21	<0.21

4.3 VADOSE ZONE RECHARGE WELL SITE

Figure 4-5 presents breakthrough curve results of tracers at the Vadose Zone Recharge Site monitoring well, and Table 4-4 summarizes travel times of the first detection, peak, and centroid determined by bromide. Figure 4-6 and Figure 4-7 display water quality data, and Table 4-3 summarizes the water quality of groundwater samples from the monitoring well prior to tracer injection. The following major findings were obtained from the tracer test and water quality monitoring results:

- Based on bromide breakthrough curve results, travel time from the recharge well to the monitoring well is 134 days for the centroid and 108 days for the peak. The centroid value was calculated from breakthrough curves corrected for background bromide concentration.
- The bromide concentrations were low, less than 3.5 mg/L, only slightly above the groundwater concentration of approximately 0.7 mg/L as defined by the initial measurements. Because the maximum concentration was about a factor of 5 higher than the background, the data clearly show that the tagged recharge water passed the well. The curve suggests that there were four active pathways that created four

breakthroughs with two arriving before (at 20 and 38 days) the main peak and one shortly afterward (at 153 days).

- Relative to that of bromide, the detections of caffeine and SF₆ were sporadic. Because the injectate-to-detection-limit concentration ratio is much greater for SF₆ than for bromide, the very low SF₆ concentrations strongly suggest that the gas was lost from the recharged water during percolation through the vadose zone. This behavior was expected based on solubility consideration. It is also likely that the caffeine was lost within the vadose zone, although it is not possible to determine if the loss was caused by sorption or degradation.
- Bacteriophages (PRD1 and MS2) were not detected over the monitoring period. Bacteriophages may have been destroyed by the residual chlorine in the recharged reclaimed water. Similar results of bacteriophage inactivation during chlorination have been reported from full-scale water reclamation facility monitoring and controlled studies (Rose et al., 1996; Clevenger et al., 2007; Costan-Longares et al., 2008).
- Based upon the normalized concentration of bromide at the peak, the dilution from the native groundwater is at least 110:1.
- Other water quality data (conductivity, nitrate, sulfate, UVA254, and TTHM) showed no clear trends, presumably because of the high dilution with the native groundwater and in situ biogeochemical reactions and filtration, which are collectively referred to as SAT. Throughout the monitoring period, chloroform was the major THM species (70–80% of TTHM) followed by bromodichloromethane (17–26%) and dibromochloromethane (2–4%). The concentration of bromoform was below the detection limit.
- Historic data for nitrate levels in the reclaimed water and groundwater from the monitoring well were available for this recharge system since the starting of recharge on November 14, 2005. As shown in Figure 4-8, nitrate concentrations in the groundwater samples were significantly increased during the early period of recharge. Typically long histories of agricultural activity leave aquifers potentially at risk from nitrate. However, this plant was built on native desert. The source of nitrate was possibly derived from nitrogen fluxes and cycling in the Holocene sediments where paleo-root structures retain nitrogen. When the recharged reclaimed water interacts with the nitrogen, it becomes oxidized and soluble in groundwater (Walvoord et al., 2003). The elevated concentrations of naturally occurring nitrates in non-agricultural settings have been observed in many recharge systems throughout the United States. The nitrate peak arrived at the monitoring well approximately after 75 days later since the facility started recharging reclaimed water. This is close to the travel time of the bromide peak (108 days) from the tracer test. For a newly developed recharge system, subsequent monitoring of wastewater constituents and/or groundwater quality after starting recharge can provide information for estimating the travel time of reclaimed water in the recharge system.

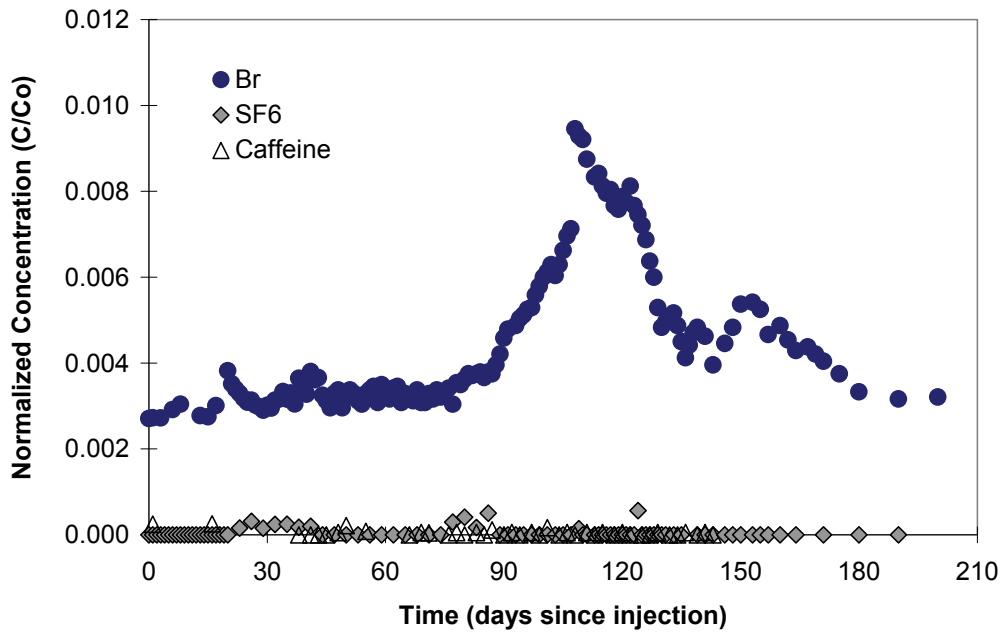


Figure 4-5. Breakthrough curve results of tracers at the Vadose Zone Recharge Well Site monitoring well.

Table 4-4. Summary of travel time at the Vadose Zone Recharge Well Site

Tracer	Target	Travel Time (Days)		
		Leading Edge	Peak	Centroid
Bromide	Reclaimed water	80	108	134

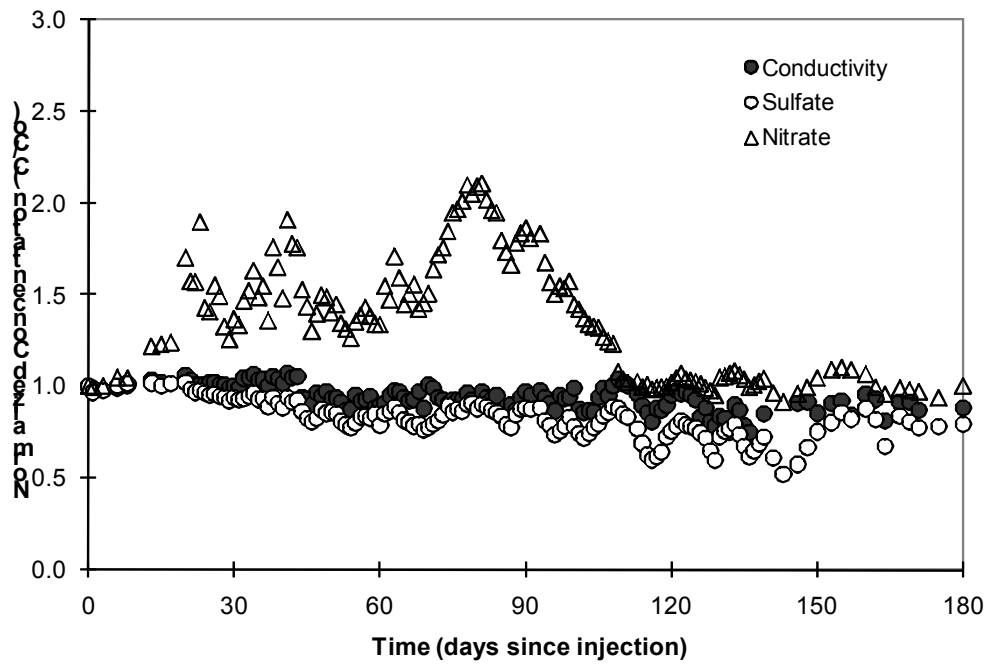


Figure 4-6. Conductivity, sulfate, and nitrate monitoring results at the Vadose Zone Recharge Well Site monitoring well.

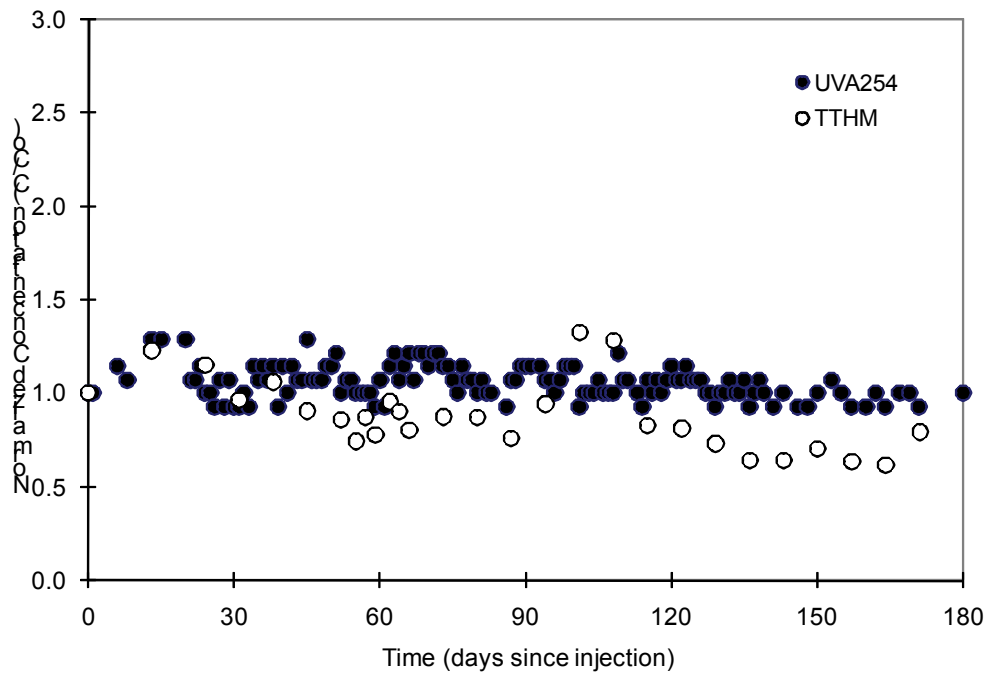


Figure 4-7. UVA254 and TTHM monitoring results at the Vadose Zone Recharge Well Site monitoring well.

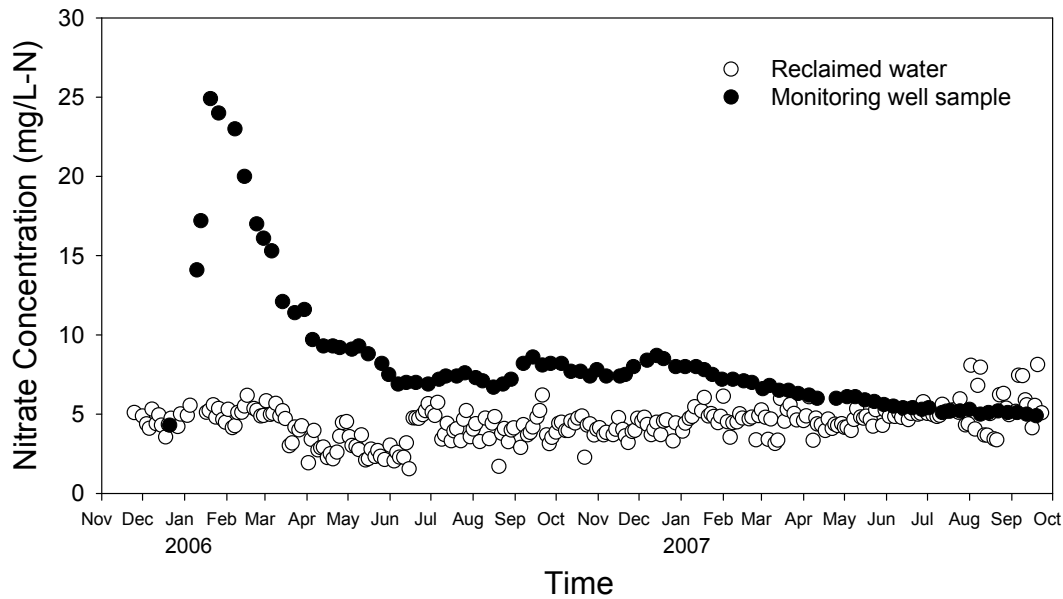


Figure 4-8. Evolution of nitrate levels in reclaimed water and groundwater samples from the Vadose Zone Recharge Well Site monitoring well.

4.4 RECHARGE BASIN SITE

Figure 4-9 presents the bromide breakthrough curve results at the Recharge Basin Site monitoring well, and Table 4-5 summarizes travel times of the first detection, peak, and centroid determined by bromide. Neither SF₆ nor caffeine was detected in the monitoring well. Figure 4-10 and Figure 4-11 display water quality data, and Table 4-3 summarizes the water quality of groundwater samples from the monitoring well prior to tracer injection. The following major findings were obtained from the tracer test and water quality monitoring results:

- Travel time from the recharge basin to the monitoring well is 162 days, based on the arrival of the peak concentration and assuming that the slight change in bromide concentration was due to our deliberate tracer experiment. The centroid arrived on day 183, although this value is a minimum because sampling ended before the tail was fully resolved. The centroid was calculated from breakthrough curves corrected for background bromide concentration.
- The bromide concentrations were low, less than 1.0 mg/L, only slightly above the groundwater concentration in groundwater, approximately 0.7 mg/L, as defined by the initial measurements. Two alternative interpretations of the apparent breakthrough between day 123 and the end of the sampling period are 1) a small temporal change in the native groundwater concentration near the well or 2) a slug of water recharged at a different time, when the bromide concentration of this water was slightly higher. It was difficult to verify the results by flux calculations because the recharge basin had been impacted by neighboring basins.

- Based upon the normalized concentration of bromide at the peak, the dilution from the native groundwater is at least 230:1.
- Neither caffeine nor bacteriophages were detected over the monitoring period. Bacteriophages may have been destroyed by the residual chlorine in the recharged reclaimed water as expected.
- Other water quality data (conductivity, nitrate, sulfate, UVA254, and TTHM) showed no clear trends, presumably because of the high dilution with the native groundwater and in situ biogeochemical reactions and filtration, which are collectively referred to as SAT. Throughout the monitoring period, chloroform was the major THM species (85–100% of TTHM) followed by bromodichloromethane (0–12%). The concentration of dibromochloromethane was minimal, and the concentration of bromoform was below the detection limit.

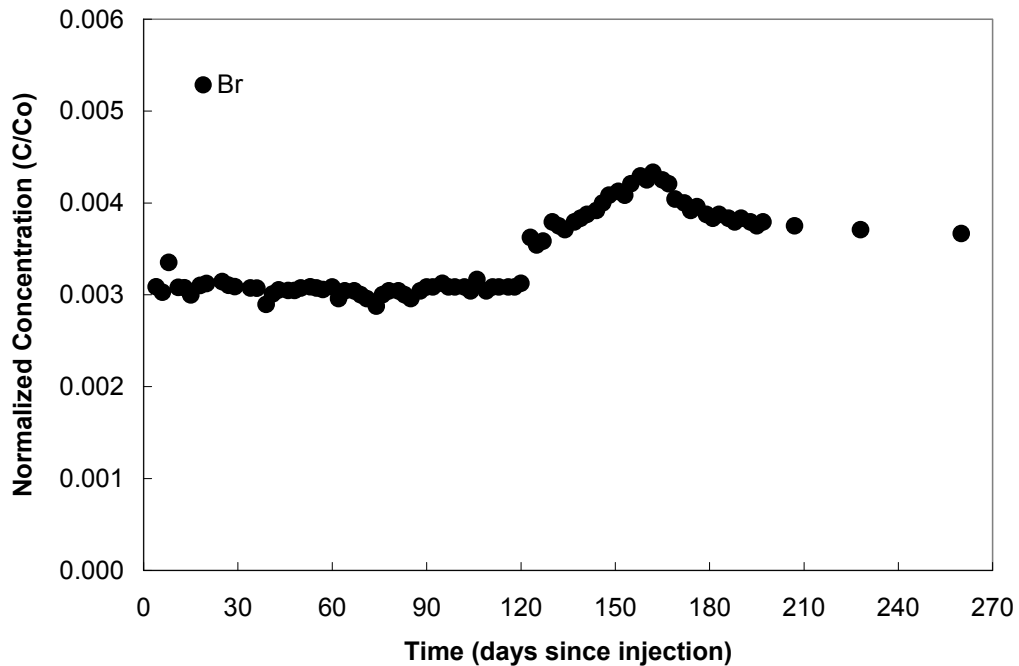


Figure 4-9. Breakthrough curve results of tracers at the Recharge Basin Site monitoring well.

Table 4-5. Summary of travel time at the Recharge Basin Site

Tracer	Target	Travel Time (Days) for:		
		Leading Edge	Peak	Centroid
Bromide	Reclaimed water	123	162	183

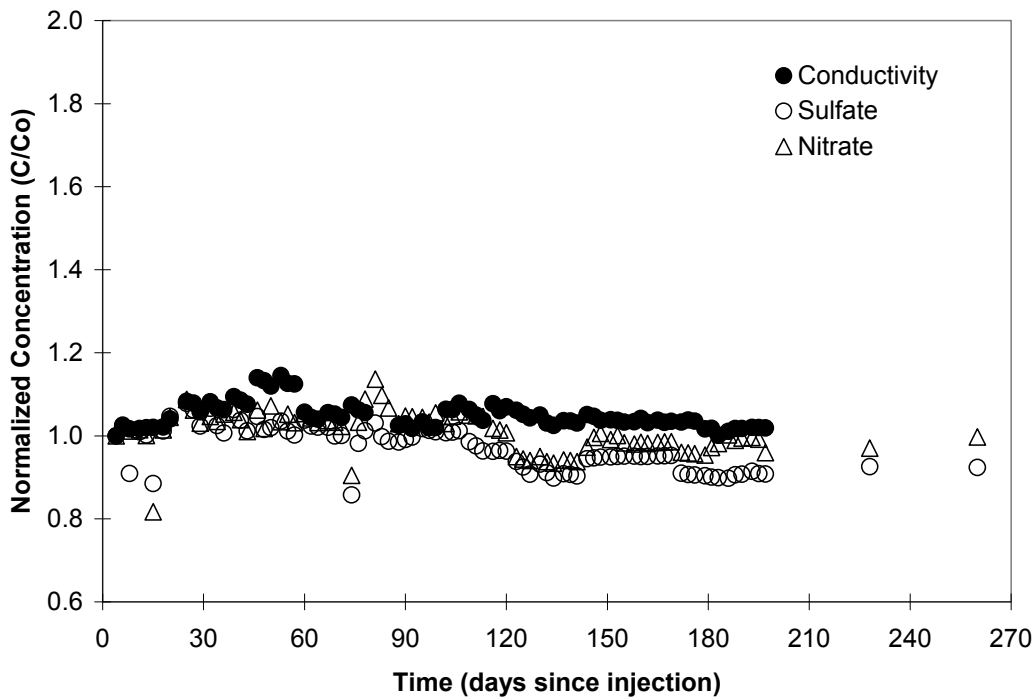


Figure 4-10. Conductivity, sulfate, and nitrate monitoring results at the Recharge Basin Site monitoring well.

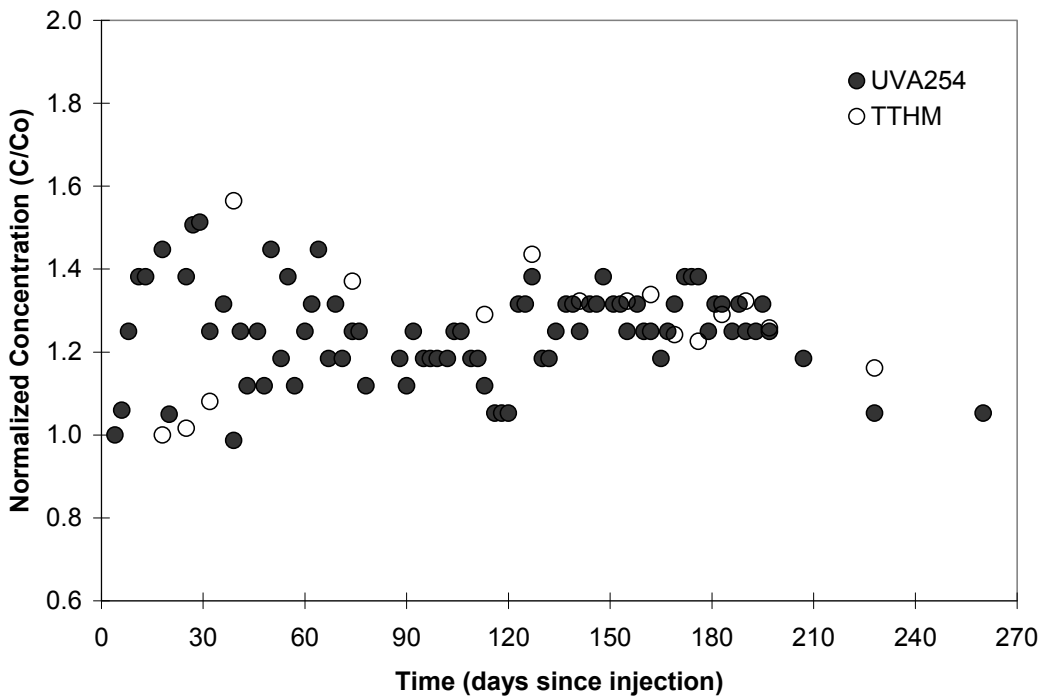


Figure 4-11. UVA254 and TTHM monitoring results at the Recharge Basin Site monitoring well.

4.5 DISCUSSION

During the deliberate tracer experiments, two nonreactive tracers (the dissolved ion, bromide, and the dissolved gas, SF₆), two microbial tracers (PRD1 and MS2), and one reactive organic compound (caffeine) were selected, so that a range of different behaviors could be tested. The three experiments were conducted to test different aspects of each tracer. Two of the tracer tests were conducted at low-volume recharge wells, where the signal-to-noise ratio for bromide could be maximized, and the third at a high-volume recharge basin. The recharge well experiments included both a saturated (Direct Recharge Well) and unsaturated (Vadose Zone Recharge Well) case. It appears that bromide is the preferred tracer under most field conditions.

While neither of the nonreactive tracers is known to adsorb to porous media, their transport behavior differed because one is a gas. The transport of SF₆ was different from that of bromide in the unsaturated zone (Vadose Zone Recharge Well and Recharge Basin sites) whereas the tracers exhibited similar transport behavior in the saturated zone (Direct Recharge Well Site). In porous media, gases will partition between the mobile aqueous and immobile gas phases when present. The amount of partitioning is dependent on the Henry's Law coefficient, the amount of trapped air—small air bubbles contained within the pore space—and the water bubble transfer rate (Fry et al., 1995; Donaldson et al., 1997; Vulava et al., 2002).

Caffeine, a nonconservative tracer, adsorbed and/or degraded in porous media. In neither the Vadose Zone Recharge Well Site nor the Recharge Basin Site monitoring well did we detect the caffeine breakthrough or peak. A caffeine breakthrough was detected at the Direct Recharge Well Site, and the travel time to the peak of the caffeine breakthrough curve was similar to that of the conservative (bromide and SF₆) tracers' breakthrough curves. However, caffeine degraded at the Direct Recharge Well Site 20 days after injection.

Neither PRD1 nor MS2 was detected in any water samples from the monitoring wells. One possible explanation is the significant inactivation of both PRD1 and MS2 in reclaimed water that was chlorinated. Most bacteriophages spiked into reclaimed water were perhaps inactivated at a very early stage by the residual chlorine in the reclaimed water. Laboratory microbial survival testing in the reclaimed water confirmed the inactivation of both PRD1 and MS2. Since most reclamation facilities disinfect their reclaimed water with chlorine, the bacteriophages cannot be used as a tracer for microbial transport.

During the first tracer test at the Direct Recharge Well Site, travel times determined with bromide and SF₆ at the monitoring well were very similar, the bromide breakthrough curve was smooth, and the maximum bromide concentration was an order of magnitude greater than the background concentration defined by a groundwater sample collected during the tracer injection phase of the experiment. The monitoring well is 67 ft from the recharge well, and the wells are screened over the same interval, 440 to 740 ft bls. The detection of SF₆ and caffeine gives additional support to the theory that the bromide breakthrough was due to the passing of the tagged water at the monitoring well. The major differences between the SF₆ and bromide breakthroughs were 1) the normalized SF₆ concentrations were lower and 2) there is much more variability between successive samples in the SF₆ breakthrough. Because hydrodynamic dispersion should have smoothed any concentration variability resulting from the injection or from the transfer of the gas to trapped air, the most likely cause is partial degassing during sampling. This interpretation is supported by the relatively low normalized SF₆ concentrations, although another explanation for the lower normalized concentrations is

that the initial (injection) concentration was overestimated. Clark et al. (2005) estimated the retardation factor for SF₆ with various amounts of trapped air using the model developed by Fry et al. (1995). Their calculations show that SF₆ is one of the most sensitive tracers of trapped air because of its large Henry's Law coefficient. The retardation factor is greater than 1.7 when the trapped air fraction ($V_{\text{air}}/V_{\text{pore}}$) is greater than 0.5%. Therefore, if trapped air was present between the recharge and monitoring wells, the centroid of the SF₆ patch should have lagged bromide. Their nearly simultaneous arrival strongly indicates that trapped air was not contained in the aquifer.

The results of the second tracer test at the Vadose Zone Recharge Well Site showed more variability between tracers. This variability reflects the unsaturated conditions near the recharge well and the more complicated hydrogeology of the field area. To reach the monitoring well, the recharged water traveled about 250 ft vertically to the water table and 200 ft laterally through saturated conditions. This study did not address direct measurements of lateral groundwater movement or hydrological mechanisms for transporting recharged water. The net result of this transport was greater dilution of the tagged water. The breakthrough was defined by concentrations less than a factor of five greater than background. Nevertheless, multiple breakthroughs were clearly detected during the 200-day monitoring period. While SF₆ was occasionally detected, its pattern is hard to interpret independently for the bromide and no travel time information can be estimated from these data. As expected, most of the gas tracer was lost to the immobile gas phase during percolation through the unsaturated zone. Because caffeine shows more complicated biogeochemical behavior, its data are more erratic than those of SF₆.

The final tracer experiment was conducted at the Recharge Basin Site, where the recharge rate (1400 gpm) was about an order of magnitude greater than at either recharge well (200 gpm). Because of the greater volume and its associated tracer cost, the initial bromide concentration in the recharge water was two times less during this experiment than during the other two. Furthermore, the closest monitoring well was 750 ft downgradient. These two features combine to make the signal-to-noise ratio the dominant factor influencing the tracer results. The breakthrough curve shows a <100-day-long increase in bromide concentrations. This increase is very small and therefore ambiguous. At its maximum, 1 mg/L, the bromide increase was only 0.3 mg/L above the 30-day mean concentration observed at the start of the experiment. While the systemic variation in the bromide concentration could be interpreted as the passing of the tagged water, an alternative explanation is a change in the bromide concentration of the source water. The absence of SF₆ detection supports this alternative interpretation. Most of the gas tracer might be lost to the immobile gas phase during percolation through the unsaturated zone. However, it is important that during the vadose zone experiment, in which SF₆ tracer behaved non-ideally, it was detected at times. The testing probably had some misses on the tracers since there was only one monitoring well. Aquifer tracer tests usually include several sets of monitoring wells across the flowpath at different locations. However, most recharge systems augmented with reclaimed water typically have one upstream and one (or a few) downstream monitoring wells. Our study did not install new monitoring wells and used existing monitoring wells only for practical and economic reasons.

Monitoring of reclaimed water constituents or in situ water quality could potentially be a method of estimating the travel time of reclaimed water in recharge systems. For a newly developed recharge system, subsequent monitoring of wastewater constituents or indicators (e.g., conductivity, nitrate, sulfate, organics, and DBPs) after starting recharge can provide information for estimating the travel time of those wastewater constituents in the recharge

system. Many recharge facilities do not recharge reclaimed water during summer (or dry) months owing to high demand for reclaimed water by customers. Those facilities can also monitor in situ water quality change following the resumption of recharge after an idle period. Water quality data before the recharge restarts can be used as the baseline conditions. Although these approaches can provide a sketch of transport times of wastewater constituents under the initial unsaturated conditions, the results may not represent the transport of the constituents under the partially saturated conditions that occur later in most recharge operations.

At the Direct Recharge Well Site, levels of reclaimed water constituents (conductivity, sulfate, nitrate, organics, and THMs) gradually increased as recharge progressed. Because these constituents were continuously introduced at an almost constant dosage during the recharge, the recharge of reclaimed water can be considered a step input tracer test. Mean travel times of the reclaimed water constituents were close to the mean travel time of bromide tracer. This indicated monitoring of reclaimed water constituents or in situ water quality could be a potential method of estimating the travel time of reclaimed water in the Direct Recharge Well Site. However, water quality data showed no clear trends in the Vadose Zone Recharge and Recharge Basin sites. The impact of reclaimed water constituents on the groundwater quality was presumably reduced by the high dilution with the native groundwater and by in situ biogeochemical reactions and filtration, which are collectively referred to as SAT.

CHAPTER 5

PROTOCOLS FOR TRACER TESTS IN RECHARGE SYSTEMS

5.1 BACKGROUND AND PURPOSE

The permitting process for most aquifer recharge projects requires estimating the length of time groundwater will remain in an aquifer before it is used for water supply or discharged to springs, lakes, or rivers. Tracer tests are a well-established method of defining advective flow and residence time. To determine advective flow, a tracer needs to be conservative, meaning that it is not retarded or degraded as it passes through the aquifer materials. Most tracer tests will include a conventional conservative tracer such as bromide or chloride that travels through the aquifer at the same rate of advective flow in the aquifer.

For reclaimed water aquifer recharge projects, an advance level of treatment is used to remove harmful constituents prior to recharge into an aquifer. However, determination of travel times for certain types of constituents present in reclaimed water (e.g., infectious microorganisms, DBPs, endocrine disruptors, pharmaceuticals, etc.) may provide useful information to water reuse communities. That said, tracer tests usually cannot be performed on these types of constituents because injection of these constituents into a potable aquifer is typically not allowed under state permitting requirements. Environmentally acceptable surrogate tracers can be used to evaluate the typical transport time of constituents with similar fate and transport characteristics.

A suite of conservative tracers (bromide and SF₆) and environmentally acceptable surrogate tracers (caffeine and bacteriophages) have been evaluated in common field settings using a variety of recharge methods (recharge basins and wells). This section summarizes some of the procedures that can be used for these tracers using recharge and monitoring wells. Information is provided on some of the general procedures to set up and conduct tracer tests and to determine travel times using recharge and monitoring wells. Details are provided for various aspects of tracer testing, including planning, permitting, tracer injection, sampling and monitoring, and travel time determination.

5.2 AQUIFER RECHARGE USING RECLAIMED WATER

Reclaimed water is usually generated from municipal, industrial, or agricultural processes or wastewater that has been treated. The regulations of most states require that reclaimed water meet potable water quality standards and that its provider subject it to advance treatment. Reclaimed water projects must include a treatment system that can meet the applicable standards. The typical process used for a reclaimed water project to permit and design a reclaimed water collection and treatment system is described elsewhere (*Good, 2005*). Reclaimed water is typically discharged to three types of facilities: recharge basins, vadose zone recharge wells, or direction aquifer recharge wells, shown in Figure 2-1 and Figure 3-1.

5.2.1 Recharge Basins

Recharge to infiltration basins is typically accomplished by creating an impoundment by excavation into earth or by constructing berms to create the impoundment. Reclaimed water is allowed to seep into an aquifer through the bottom of the basin. If the underlying soils are

highly permeable, an infiltration basin is the most economical and easily constructed system for infiltrating water into aquifers. Recharge basins can be used to infiltrate water only into unconfined aquifers with high transmissivity. Effective operation of infiltration basins may require maintenance dredging to remove accumulated sediment. Typical basin configurations usually include sufficient capacity to rotate the operation of the basins to allow for drying and dredging of sediment.

5.2.2 Vadose Zone Recharge Wells

Reclaimed water may be injected through vadose zone recharge wells drilled into highly permeable soils near the surface. Vadose zone wells are used when the distance between the land surface and groundwater is too long for direct recharge wells or when there are water quality benefits from infiltrating water through the vadose zone instead of directly injecting into the aquifer. Vadose zone wells require careful planning and management to avoid a decrease in well performance from clogging, mineralization, and biofouling.

5.2.3 Direct Recharge Wells

Direct recharge wells are used to infiltrate reclaimed water into a confined or unconfined aquifer. Direct recharge wells are also subject to well performance problems, but well performance can often be improved by alternating injection with short pumping cycles. Recharge wells require the highest level of treatment since water is being transferred directly into potable-water aquifers. Recharge wells are the only method that allow for reclaimed water to be stored directly in confined aquifers. ASR wells serve to pump water both into and out of an aquifer (Pyne, 2005). They are often operated as recharge wells when surplus surface water is available and as pumping wells when groundwater supply is needed to offset surface water shortages.

5.3 TYPICAL SETUP AND OPERATION OF A TRACER TEST

Most tracer tests generally use a recharge well and monitoring well. Recharge and monitoring wells are the best method of injecting a known quantity of a reagent into an aquifer and to detect and monitor the concentrations of the tracer as it passes through downgradient monitoring wells (Figure 5-1). The typical tracer test study involves the general procedures summarized below.

- **Plan the Tracer Test:** The tracer test should be designed and planned so that all of the information, data, site investigation, wells, equipment, and personnel needed for the test are prepared prior to the test. Tracer tests may require days, weeks, or months of field time, depending on the tracer test distance, tracer constituents, and hydrogeologic field setting, so advance planning is critical to ensure that staff availability and sampling methodologies match the project requirements. A Sampling and Analysis Plan should be prepared that describes the details of tracer reagent preparation, tracer injection protocols, sampling methods, and field and laboratory analysis procedures.
- **Obtain Permits:** Tracer testing requires obtaining permit approval through state water quality and/or water planning agencies. Permit approval usually requires a 3- to 6-month lead time, so it is advisable to coordinate permitting as soon as possible and in coordination with the overall permitting pathline for the recharge project. Permits requirement for tracer tests in select U.S. states are discussed in Section 5.4 in detail.

- **Characterize Site Hydrogeology:** Basic background information is needed on the hydrogeology of the site so that the recharge and monitoring wells can be designed appropriately for the particular site characteristics. Typical information needed includes aquifer and confining unit thickness, hydraulic conductivity, porosity, storage, type of aquifer (confined or unconfined), groundwater flow direction, recharge and discharge areas, the nature and extent of connections with surface water, and the location of other water supply wells. This information is usually needed for permitting of most facilities. Some of the monitoring wells installed for site characterization can often be used again for tracer testing.
- **Design Tracer Injection and Monitoring Well Layout:** An injection well will be needed upgradient of the area that is to be tested. Monitoring wells should be located downgradient of the injection wells along the groundwater flowpath and near enough to the injection well so that tracers can be detected within the available test time. Injection wells and monitoring wells need to be carefully located along a groundwater flow pathline so that a tracer injected in the aquifer flows downgradient and is detected in the monitoring well. It may be advisable to install several monitoring wells perpendicular to the flowpath to ensure that the tracer is detected during the test, as shown in Figure 5-1. The distance between an injection and monitoring wells needs to be short enough to allow tracers to be detected within the available test time, as shown in Figure 5-2. Travel time can be calculated if the hydraulic gradient, hydraulic conductivity, and effective porosity are known, using equation 3 (Todd, 1980):

$$t = \frac{\alpha L^2}{h K} \quad (4)$$

where t = travel time (day), L = distance between wells (ft), h = difference in water table elevation between wells (ft), α = effective porosity (unitless), and K = hydraulic conductivity (ft/day).

- **Conduct Background Testing:** Sampling and testing of monitoring and injection wells are critical in finding the background levels of constituents prior to conducting a tracer test. Doing so helps one learn whether background water quality needs to be considered in the interpretation of test results.
- **Start Test and Inject Tracer:** Most tracer tests are conducted as “slug-injection” tests, meaning that a specified quantity (slug) of tracer reagent is injected into the well for a specified period at a given injection rate. The mass of tracer reagent needed to be injected into the aquifer will depend on the flowrate, travel time, dispersivity and sampling time, which will vary depending on the site conditions.
- **Sample Monitoring Wells to Detect Tracer:** The reagent will disperse longitudinally and laterally as it travels through the aquifer, depending on the flow velocity and the dispersion characteristics of the aquifer and the injection reagent. The monitoring well sampling program needs to be frequent enough to detect the leading edge of the tracer plume as it reaches the monitoring well and then to detect the increasing concentrations of tracer as the peak concentration reaches the well. It is advisable to include a field monitoring procedure as well as sample collection for laboratory analysis so that the sample collection frequency can be adjusted in the field to ensure that the leading edge of the plume is captured and sample frequency is sufficient to characterize the breakthrough curve.

- Analyze Results:** Calculation of the travel time is accomplished by examining tracer injection and downgradient detection results. This is commonly accomplished using a graphical technique to determine the breakthrough curve. The travel time is computed by differencing the time of maximum tracer detection at the monitoring well from the time that one-half of the mass of tracer was injected into the aquifer (i.e., the center of mass).

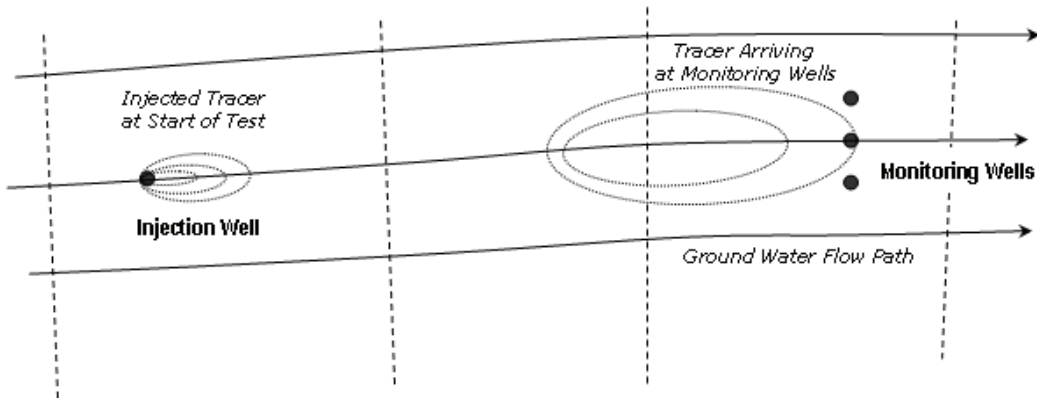


Figure 5-1. Typical setup of injection and monitoring wells for a tracer test.

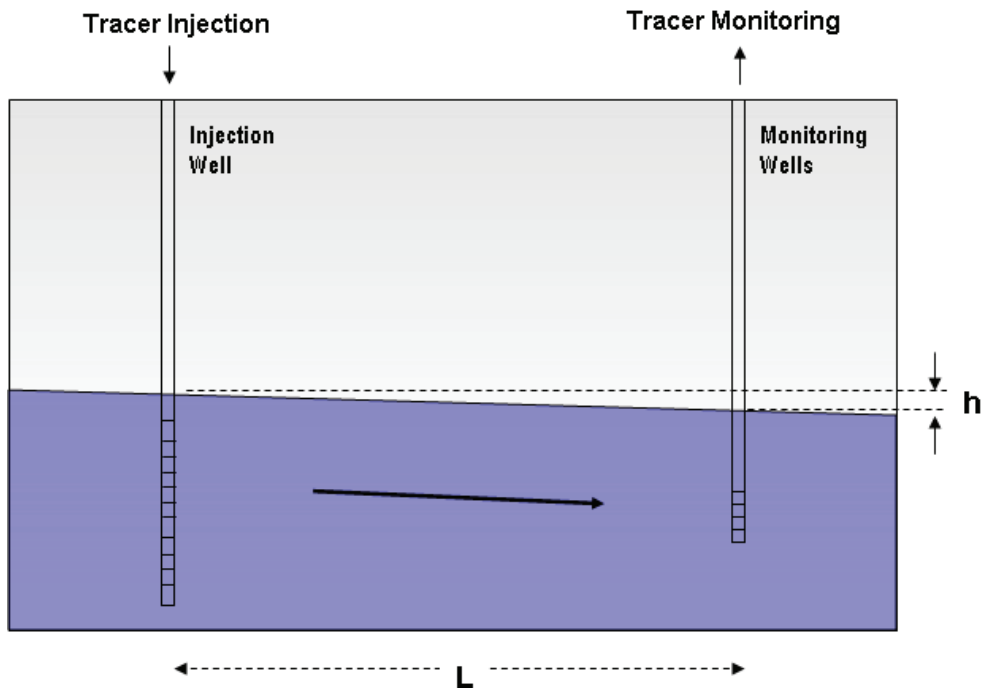


Figure 5-2. Tracer test setup and monitoring in longitudinal cross-section view.

5.4 STATE PERMIT REQUIREMENTS FOR TRACER TESTS

Tracer injection programs require obtaining permit approval through state water quality and/or water planning agencies. Permitting for tracer tests using wells to introduce tracers into an aquifer in most states requires obtaining a Class V well injection permit through the state-administered federal Underground Injection Control (UIC) program. Class V wells are wells generally injecting nonhazardous fluid into or above an underground source of drinking water. Regulations vary between states and may include other permitting requirements, depending on the particular type of recharge project, injection method, and constituent being injected. Table 5-1 summarizes permits required for tracer tests in select U.S. states (Arizona, California, Colorado, Florida, Nevada, Texas, and Washington).

Table 5-1. Permits required for tracer tests in select U.S. states

State	Permit Required	Regulatory Agency	Related Website	Related Regulation/State Code
Arizona	Yes	Arizona Department of Environmental Quality	http://www.azdeq.gov/function/permits/index.html	AAC Title 18 Chapter 9. R18-9-A301(A)(2) or R18-9-A301(B)
California	Yes	California Department of Public Health and Regional Water Quality Control Board	http://www.cdph.ca.gov/HealthInfo/environhealth/water/Pages/Waterrecycling.aspx	California Water Code 13520-13541, California Code of Regulations 60320
Colorado	Yes	Colorado Department of Health	http://www.cdphe.state.co.us/hm/pnc/pbruic.pdf	Colorado Code of Regulations (CCR) 1007-1, 16
Florida	Yes	Florida Department of Environmental Protection	http://www.dep.state.fl.us/water/uic/	Florida Administrative Code (FAC) 62-528
Nevada	Yes	Nevada Division of Environmental Protection	http://ndep.nv.gov/	Nevada Administrative Code (NAC) 445A
Texas	Yes	Texas Commission for Environmental Quality	http://www.tceq.state.tx.us/permitting/waste_permits/uic_permits/UIC_Am_I_Regulated.html	Texas Administrative Code (TAC) 210 & 331, Texas Water Code 27.021, 27.023
Washington	Yes	Washington State Department of Ecology	www.ecy.wa.gov/programs/wq/grndwtr/uic/index.html	Washington Administrative Code (WAC) 173-157(40)

Sufficient lead time should be provided for permitting, and most states require 3 to 6 months to review and process permits. It is advisable to coordinate closely with the state agency staff

doing the permit review to ensure that it has all of the information needed to review the permit at the time the permit application is submitted. A Sampling and Analysis Plan usually needs to be developed and may be required as part of the permit approval process. The plan should describe the type of tracer being injected, preservation requirements, injection equipment and procedures, monitoring equipment and procedures, and staff requirements.

5.4.1 Arizona

General Requirements for Reclaimed Water Aquifer Recharge Projects

Aquifer storage of reclaimed water must adhere to water quality guidelines administered by the Arizona Department of Environmental Quality (ADEQ) in accordance with Arizona Revised Statutes (ARS) 49-203 through 49-252, as well as to technical standards for conveyances of reclaimed water and permit programs for the direct reuse of reclaimed water when applicable. An Aquifer Protection Permit may be required by the ADEQ unless an exemption is granted per ARS 49-250. The Arizona Department of Water Resources requires water storage and underground storage facility permits in accordance with ARS 45-801 through 45-836. In Arizona, the entity that treats wastewater has a right to beneficial use of the water that has been reclaimed.

Requirements for Tracer Testing

Projects for subsurface tracer studies require a Type 2 General Permit from the ADEQ. The application needs to satisfy the requirements in AAC Title 18, Chapter 9, Article 3. Persons must file the appropriate Notice of Intent forms and supplemental information and pay the flat-rate nonrefundable general permit fee (\$300 for the first facility and \$100 for each additional facility). The Type 2 General Permit does not authorize the use of any hazardous substance, radioactive materials, or substance identified in ARS § 49-243(I), which basically restricts any organic substance listed by the secretary of the Department of Health and Human Services pursuant to 42 United States Code section 241 (b)(4) as known to be a carcinogen or reasonably anticipated to be a carcinogen and any organic substance listed in 40 Code of Federal Regulations section 261.33(e), regardless of whether the substance is a waste subject to regulation under the Resource Conservation Recovery Act (P.L. 94-580; 90 Stat. 2795).

Contact Information

Recharge Permit Application Process Department, Arizona Department of Water Resources,
Phone: (602) 771-8585

Maribeth E. Greenslade, P.E., Unit Manager for Water Quality Technical Support, ADEQ,
Phone: (602) 771-4578

5.4.2 California

General Requirements for Reclaimed Water Aquifer Recharge Projects

Reclaimed water aquifer recharge and storage projects are monitored and permitted under the jurisdiction of the California Department of Public Health. Projects must adhere to guidelines as included in California Water Code Section 13520-13541 for water reclamation and waste well standards for treated water effluent, as well as to Title 22, California Code of Regulations Section 60320, for groundwater recharge. The California Department of Public Health is in the process of updating and revising the California Code of Regulations related to groundwater recharge or surface application of reclaimed water and control of regulated

chemicals and other water quality considerations. The status of rule updates can be determined at <http://www.cdph.ca.gov/HealthInfo/environhealth/water/Pages/Waterrecycling.aspx>.

Requirements for Tracer Testing

In the state of California, in comparison, a specific permit is not required for a tracer study. However, one should obtain approval from the California Department of Public Health and Regional Water Quality Control Board for any tracer study. The California Department of Public Health regulates artificial recharge using recycled water under Title 22 of the California Code of Regulations. The Department of Public Health's recommendations to the Regional Water Quality Control Boards for proposed groundwater recharge projects and for expansion of existing projects will be made on an individual case basis where the use of reclaimed water involves a potential risk to public health. The proposed California state criteria for artificial recharge with reclaimed water stipulate that 1) for a surface spreading project, all the recycled water 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 ft of the point of recharge; and 2) for a subsurface recharge project, all the recycled water shall be retained underground for a minimum of 12 months prior to extraction for use as a drinking water supply and shall not be extracted within 2000 ft of the point of recharge.

Contact Information

Jeff Stone, Recycled Water Unit, California Department of Public Health, Phone: (805) 566-9767

5.4.3 Colorado

General Requirements for Reclaimed Water Aquifer Recharge Projects

The Colorado Department of Public Health and Environment regulates water reuse and reclaimed water projects. Most reclaimed water projects in Colorado are associated with land surface irrigation applications that may impact shallow groundwater aquifer systems. Direct recharge of reclaimed water in aquifer systems has been more limited. Regulations 41, 62, and 84 provide guidance for basic groundwater systems, treated effluent standards, and water reuse, respectively. When used for recharge into an aquifer, reclaimed water that meets secondary drinking water quality standards is subject to less regulation than is reclaimed water that does not meet secondary standards and may otherwise require downgradient groundwater monitoring.

Requirements for Tracer Testing

In accordance with 6 Colorado Code of Regulations 1007-1 Parts 16, subsurface tracer studies require a permit issued by the Colorado Department of Public Health and Environment prior to commencement. No licensee shall cause the injection of radioactive material into potable aquifers without prior written authorization from the Colorado Department of Public Health and Environment and any other appropriate state agency.

Contact Information

Liz Lemonds, Colorado Department of Public Health and Environment, Phone: (303) 692-3515

5.4.4 Florida

General Requirements for Reclaimed Water Aquifer Recharge Projects

Florida's Department of Environmental Protection's UIC program enforces rules to protect the state of Florida's underground sources of drinking water (USDWs) while maintaining the lawful option of disposal of appropriately treated fluids via underground injection wells in accordance with Florida Administrative Code Chapter 62-528. A USDW is defined as containing fresh and brackish water supplies, with TDS concentrations less than 10,000 mg/L. ASR wells are typically classified as Class V wells for the storage or disposal of nonhazardous fluid into or above a USDW. The fluid injected must meet appropriate criteria as determined by the classification of the receiving aquifer. For areas where disposal methods may cause contamination or based on hydrogeologic conditions, wells used to recharge reclaimed water below the lowest USDW are classified as Class I wells. The injection wells are required to be constructed, maintained, and operated so that the injected fluid remains in the injection zone, and unapproved interchange of water between aquifers is prohibited. Class I injection wells are monitored and testing is conducted on all Class I injection wells at a minimum of every 5 years to determine that the well structure has integrity. Reclaimed water wells require permits from the Technical Advisory Committee and may require monitoring, proof of mechanical integrity, and other site-specific information.

Requirements for Tracer Testing

If necessary to demonstrate no movement of fluid into or between underground sources of drinking water, tracers may be used to determine the mechanical integrity when settling corrective action. A radioactive tracer survey shall not be required by the department if such testing may pose a threat to an underground source of drinking water.

Prior to conduct of tracer tests in an aquifer, an application to construct, operate, or abandon Class I, III, or V injection well systems must be filed with and approved by the Florida Department of Environment Protection's UIC division, which includes analysis of chemical, physical, and radioactivity characteristics of injection fluids. See <http://www.dep.state.fl.us/water/uic/>.

Contact Information

Rich Deuerling, Underground Injection Control, Florida Department of Environmental Protection, Phone: (850) 245-8653

5.4.5 Nevada

General Requirements for Reclaimed Water Aquifer Recharge Projects

Reuse and reclaimed water aquifer recharge projects require permits from the Nevada Division of Environmental Protection, Bureau of Water Pollution Control. Pursuant to NAC 445A, treated municipal effluent wells are considered Class V wells and prior to issuance of permits must demonstrate no degradation of groundwater quality. An effluent management plan may also be required.

Requirements for Tracer Testing

The Nevada Division of Environmental Protection must approve the use of tracers for groundwater studies pursuant to NAC 445A. The application must include the following information: a summary of the tracer test with the frequency and duration of tracer injection, a topographic map showing extent and potential receptors, the chemical composition of the

tracer, the amount of tracer to be used in the study, the concentration, fate and transport calculations of the tracer, and other information.

Contact Information

Russ Land, Supervisor, Groundwater Protection, Nevada Division of Environmental Protection, Bureau of Water Pollution Control (BWPC), Phone: (702) 687-9428

5.4.6 Texas

General Requirements for Reclaimed Water Aquifer Recharge Projects

The Texas Commission for Environmental Quality (TCEQ) evaluates permit requests related to reclaimed water aquifer recharge projects in accordance with 30 Texas Administrative Code Chapter 210 and 331 and Texas Water Code Chapter 27.021 and 27.023 for Class I injection wells. Injection well classification is based on USDW aquifers located in the proposed project area, defined as water-bearing aquifers with total dissolved solids less than 10,000 mg/L. An injection well is classified as Class I if the well is screened in an aquifer above or below a USDW aquifer. Class V wells are screened in or above a USDW aquifer and must adhere to more stringent nonhazardous water quality criteria. Typically, ASR projects and projects that treat effluent to drinking water standard would qualify as Class V injection wells in accordance with 30 TAC Chapter 331 guidelines. Reclaimed water treated to drinking water quality standards and ASR projects are classified as Class V injection wells. Permits required may include wastewater treatment discharge permits and UIC permits, amongst others. Domestic facilities that discharge treated domestic wastewater by land application are required to obtain a Texas Land Application Permit from the TCEQ.

Requirements for Tracer Testing

Tracer tests for groundwater are regulated in accordance with 30 TAC Chapter 331 and require a permit administered by the Texas Commission for Environmental Quality. See http://www.tceq.state.tx.us/permitting/waste_permits/uic_permits/UIC_Am_I_Regulated.html.

Contact Information

Brian Smith, Underground Injection Control Division, Texas Commission for Environmental Quality, Phone: (512) 239-6075

5.4.7 Washington State

General Requirements for Reclaimed Water Aquifer Recharge Projects

Aquifer recharge projects in Washington State are defined as “controlled subsurface addition of water directly to the aquifer or controlled application of water to the ground surface for the purpose of replenishing the aquifer” (WAC-173-157[40]). Aquifer recharge is regulated by the Washington State Department of Ecology and must conform with WAC 173-157, which requires performing a hydrogeologic study, preparing an operational plan, performing an environmental assessment, and performing pre- and post-project monitoring. Aquifer recharge projects using reclaimed water are regulated by both the departments of ecology and health, and projects must conform to the Water Reclamation and Reuse Standards dated September 1997. The rules require that only Class A water meeting specific treatment requirements may be infiltrated into groundwater and that water must be retained for 12 months prior to use for potable supply with a minimum horizontal separation of 2000 ft

between injection and withdrawal sources. The Department of Ecology is in the process of revising the reclaimed water standards under WAC 173-219. Adoption of the new rules is anticipated in 2010.

Requirements for Tracer Testing

Tracer tests involving the injection of any constituent into groundwater in Washington State are regulated under WAC 173-218 as Class V wells under the UIC program. The website for the Ecology UIC program is www.ecy.wa.gov/programs/wq/grndwtr/uic/index.html. A project proponent is required to register an injection well through the UIC program. The application requires submitting detailed information on the site hydrogeology, sensitive receptors, injection compounds, operational program, monitoring protocols, and other factors. Injected compounds must comply with the Ground Water Quality Standards (WAC 173-200), which regulate the type and nature of compounds that may be injected.

Contact Information

Mary Hansen, Water Quality Program, WA Department of Ecology, Phone: (360) 407-6143

5.5 FIELD TESTING AND ANALYSIS PROCEDURES

Field equipment, supplies, reagents, and instruments needed should be obtained and checked prior to the day of the field test so that everything is in good working order once the testing begins. The following is a checklist to assist in preparing for and conducting the field testing.

5.5.1 Preparation Task Checklist

- Develop a Sampling and Analysis Plan. The plan should include all of the details regarding the type of test, tracers used, other water quality parameters, and tracer injection and sampling procedures.
- Select and purchase tracer reagents. Obtain distilled water for preparation of tracer injection solution.
- Prepare for other analytical water quality parameters needed for testing.
- Check the total volume of samples required for analysis and sample preservation and handling methods.
- Obtain clean sample bottles for collection purposes with the appropriate preservatives.
- Prepare tracer injection and sampling equipment.
- Check if electricity is available (or bring a generator if needed).
- Confirm site accessibility and security.
- Determine a date for tracer injection and an initial schedule for sampling days.
- Prepare field data collection sheets.

5.5.2 Field Testing Checklist

- ❑ Collect background water quality samples at the recharge and the sampling wells.
- ❑ Depending on the type of injection process (either slug or continuous injection), set up tracer injection equipment (pumps) and test the equipment to make sure it is in good working order.
- ❑ Set up sampling equipment in the field. If using a continuous automatic sampler, prepare and test the sampler to ensure that it is in good working order. Make arrangements to collect manual backup samples in the event that the automatic sampler fails.
- ❑ Prepare tracer solutions using distilled water and the appropriate tracer reagents. Preserve the tracer solutions appropriately prior to injection.
- ❑ Start tracer injection as appropriate for the type of test being conducted for the duration needed.

5.5.3 Sampling Procedure

- ❑ Consistent sampling procedures should be followed to ensure that the sample taken from the well is representative of the groundwater at that location and the same method is used for each sample collection event.
- ❑ Sampling procedures will vary depending on the type and length of the test and the parameters that will be analyzed. The Sampling and Analysis Plan should describe the specific samples to be collected for the testing and for quality control/quality assurance purposes.
- ❑ Well purging should be conducted for each sampling event. The large number of samples collected for most tests necessitates the use of a purging pump. Purge at least 3 well volumes from the wells using a bailer or sampling pump. If the equipment is used on other sites, make sure that the bailer and/or pumps are decontaminated using a laboratory-grade detergent wash with distilled water.
- ❑ For a long test, automated sampling equipment (using a peristaltic pump) may be needed, depending on the type of tracer used and the timing of sampling. Field detection equipment (e.g., an ion-selective electrode) greatly assists in optimizing the sampling frequency so that the leading edge of the injection plume is observed and pass-through of the injection plume in the aquifer is sampled with sufficient frequency to record a breakthrough curve.
- ❑ More detailed information on general sampling protocols can be found in *National* (2006) and Nielson and Nielson (2005).
- ❑ The specific sample preservation, handling, and testing will be dependent on the specific tracer reagent used.

5.6 DETERMINATION OF TRAVEL TIME

This section summarizes the method commonly used to determine travel time based on the results of tracer testing. A tracer constituent moving through the aquifer along a groundwater flowpath disperses both longitudinally (along the direction of the groundwater flow pathline) and laterally (across the groundwater flow pathline), as shown in Figure 5-3. Dispersion is caused by the mixing of flowpaths as groundwater flows through the aquifer and, to a lesser extent, by chemical diffusion. Dispersion causes a tracer plume to “spread out” as it moves

through the aquifer. As a result, a tracer will take longer to pass through a monitoring point than the injection time and the concentrations observed at a monitoring well will be much lower than the injection concentrations.

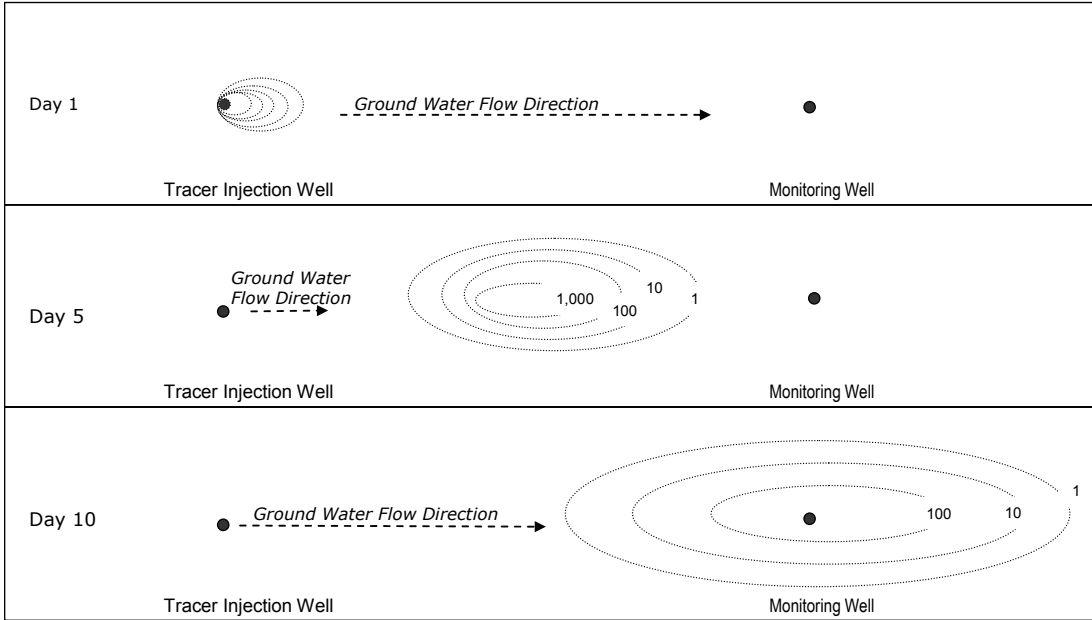


Figure 5-3. Illustration of tracer dispersion along groundwater flowpath.

The travel time for a particular tracer is usually determined by preparing a “breakthrough curve.” An example is presented in Figure 5-4. A breakthrough curve is prepared by plotting the relative concentration of the tracer constituent from monitoring well samples collected during the test. The point of maximum concentration (the peak on the breakthrough curve graph) is subtracted from the midpoint of the tracer injection period to determine the time of travel.

For a pulse (or slug-dose) input tracer test, the theoretical mean travel time can generally be determined by examining the tracer breakthrough curve. The travel time to the center of the tracer mass (i.e., centroid) is expressed as

$$t_c = \frac{\sum_{i=1}^n t_i C_i \Delta t_i Q_i}{\sum_{i=1}^n C_i \Delta t_i Q_i} \quad (2)$$

where t_c is the travel time to the center of the tracer mass, t_i is the elapsed time since injection during the i^{th} sampling interval, C_i is the tracer concentration during the i^{th} sampling interval, and Q_i is the flowrate during the i^{th} sampling interval. In case the tracer constituent is present

in the native groundwater, tracer test breakthrough curves need to be corrected for background tracer concentration to eliminate the impact of the background concentration of a tracer. Assuming the flowrate during the test is the same, the spread of the residence time distribution curve can be calculated as

$$\sigma^2 = \frac{\sum_{i=1}^n t_i^2 C_i \Delta t_i}{\sum_{i=1}^n C_i \Delta t_i} - (t_c)^2 \quad (5)$$

Tracers that move below the advective groundwater velocity are retarded, usually by sorption to the aquifer substrate. The degree of retardation of a tracer constituent moving through an aquifer can be determined by comparing the travel time for that constituent, determined during the tracer test, to the advective flow travel time. The advective flow travel time can be determined using a conservative tracer constituent (one that is not retarded by the aquifer, such as bromide).

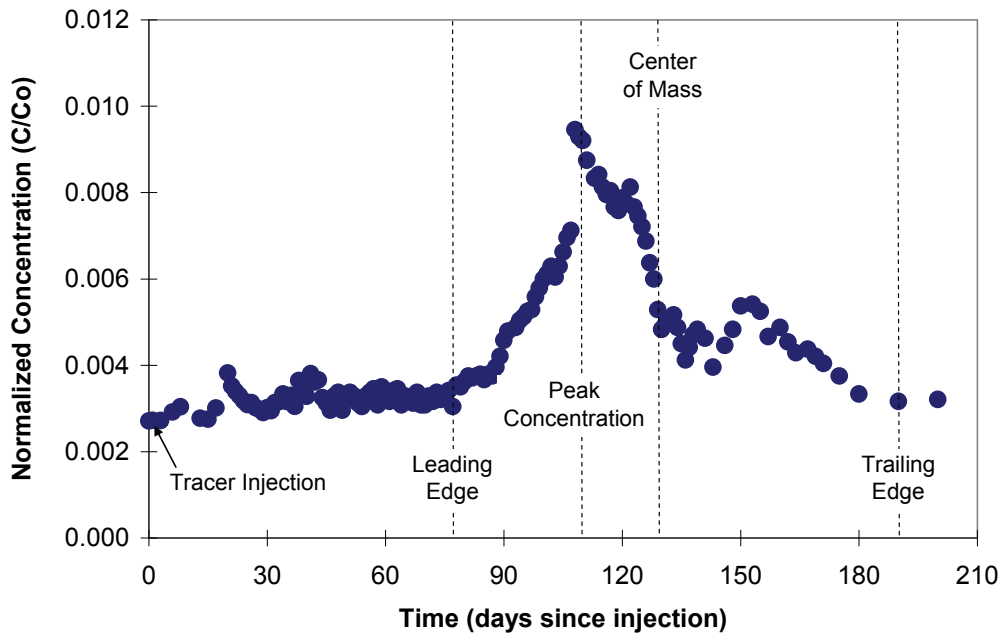


Figure 5-4. An example of a tracer test breakthrough curve (bromide).

5.7 OTHER CONSIDERATIONS AND LIMITATIONS

Planning for a tracer test should be conducted at the initial stages of recharge project development so that the hydrogeologic investigation can be arranged to accommodate a tracer

test. Most recharge projects require submission and approval of hydrogeologic investigation and monitoring plans, so inclusion of details for tracer testing in these plans will make the permitting review and approval process easier. The initial design of the recharge facility, whether using basin or wells, should be arranged so that at least some of the wells needed for tracer testing are constructed as part of the hydrogeologic investigation. However, additional monitoring wells may be needed to ensure that tracer detection and monitoring wells are available in the right locations for the test. Advance planning from the conceptual stages of the project through permitting and into actual testing will help to ensure that the test goes smoothly and that the results are reliable.

An alternative to tracer testing is measuring in situ water quality. For a newly developed recharge system, subsequent monitoring of wastewater constituents or indicators (e.g., organics, inorganic chemicals, heavy metals, nutrients, microorganisms, DBPs, and EDCs) after starting recharge can provide information for estimating the travel time of those wastewater constituents in the recharge system. Many recharge facilities do not recharge reclaimed water during summer (or dry) months owing to high demand for reclaimed water by customers. Those facilities can also monitor in situ water quality change following the resumption of recharge after an idle period. Water quality data before the recharge restarts can be used as the baseline conditions. Although these approaches can provide a sketch of transport times of wastewater constituents under the initial unsaturated conditions, the results may not represent the transport of the constituents under the partially saturated conditions that occur later in most recharge operations.

This document provides generalized guidance on the subject of tracer testing for reclaimed water recharge facilities. This document is not intended to be a comprehensive manual on methodology for conducting hydrogeologic investigations or tracer tests. Specific project methods and procedures will vary and should be based on the actual field setting encountered. Experienced professionals with the appropriate background necessary to plan and conduct hydrogeologic investigations should be consulted for specific projects. No warranty, express or implied, is provided.

REFERENCES

- Abidi, S. L. Detection of diethylnitrosamine in nitrite-rich water following treatment with rhodamine flow tracers. *Water Res.* **1982**, *16*, 199–204.
- Adams, M. H. *Bacteriophages*; Interscience Publishers, Inc.: New York, 1959.
- Amy, G.; Wilson, L. G.; Conroy, A.; Chahbandour, J.; Zhai, W. Y.; Siddiqui, M. Fate of chlorination by-products and nitrogen species during effluent recharge and soil aquifer treatment (SAT). *Water Environ. Res.* **1993**, *65*, 726–734.
- Anders, R.; Chrysikopoulos, C. V. Virus fate and transport during artificial recharge with recycled water. *Water Resour. Res.* **2005**, *41*, W10415.
- Anders, R.; Schroeder, R. A. *Use of Water-Quality Indicators and Environmental Tracers to Determine the Fate and Transport of Recycled Water in Los Angeles County, California*: Water-Resources Investigations Report 03-4279; U.S. Geological Survey: Sacramento, CA, 2003.
- Anderson, P. D.; D'Aco, V. J.; Shanahan, P.; Chapra, S. C.; Buzby, M. E.; Cunningham, V. L.; Duplessie, B. M.; Hayes, E. P.; Mastrocco, F. J.; Parke, N. J.; Rader, J. C.; Samuelian, J. H.; Schwab, B. W. Screening analysis of human pharmaceutical compounds in US surface waters. *Environ. Sci. Technol.* **2004**, *38*, 838–849.
- Arizona Department of Water Resources. *Semi-Annual Status Report: Underground Water Storage, Savings and Replenishment (Recharge) Program*; Arizona Department of Water Resources: Phoenix, AZ, 2006.
- Asano, T.; Cotruvo, J. A. Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations. *Water Res.* **2004**, *38*, 1941–1951.
- Ashton, D.; Hilton, M.; Thomas, K. V. Investigating the environmental transport of human pharmaceuticals to streams in the United Kingdom. *Sci. Total Environ.* **2004**, *333*, 167–184.
- Avisar, D.; Clark, J. F. Evaluating travel times beneath an artificial recharge pond using sulfur hexafluoride. *Environ. Eng. Geosci.* **2005**, *11*, 309–317.
- Babcock, R.; Lin, B.; Spengler, S. Use of boron as a tracer for recycled water in brackish aquifers. *J. Environ. Eng. (N.Y.)* **2006**, *132*, 862–871.
- Bales, R. C.; Gerba, C. P.; Grondin, G. H.; Jensen, S. L. Bacteriophage transport in sandy soil and fractured tuff. *Appl. Environ. Microbiol.* **1989**, *55*, 2061–2067.
- Bales, R. C.; Hinkle, S. R.; Kroeger, T. W.; Stocking, K.; Gerba, C. P. Bacteriophage adsorption during transport through porous media: chemical perturbations and reversibility. *Environ. Sci. Technol.* **1991**, *25*, 2088–2095.
- Bales, R. C.; Li, S. M.; Maguire, K. M.; Yahya, M. T.; Gerba, C. P. MS-2 and poliovirus transport in porous media: hydrophobic effects and chemical perturbations. *Water Resour. Res.* **1993**, *29*, 957–963.
- Bales, R. C.; Li, S.; Maguire, K. M.; Yahya, M. T.; Gerba, C. P.; Harvey, R. W. Virus and bacteria transport in a sandy aquifer at Cape Cod, MA. *Ground Water* **1995**, *33*, 653–661.

- Barber, L. B.; Brown, G. K.; Kennedy, K. R.; Leenheer, J. A.; Noyes, T. I.; Rostad, C. E.; Thorn, K. A. Organic Constituents That Persist during Aquifer Storage and Recovery of Reclaimed Water in Los Angeles County, California. Presented at the AWRA Symposium, Conjunctive Use of Water Resources: Aquifer Storage and Recovery, Herndon, VA, 1997.
- Barton, J. W.; Ford, R. M. Determination of effective transport coefficients for bacterial migration in sand columns. *Appl. Environ. Microbiol.* **1995**, *61*, 3329–3333.
- Bassett, R. L.; Buszka, P. M.; Davidson, G. R.; Chongdiaz, D. Identification of groundwater solute sources using boron isotopic composition. *Environ. Sci. Technol.* **1995**, *29*, 2915–2922.
- Behrens, H.; Beims, U.; Dieter, H.; Dietze, G.; Eikmann, T.; Grummt, T.; Hanisch, H.; Henseling, H.; Kass, W.; Kerndorff, H.; Leibundgut, C.; Muller-Wegener, U.; Ronnefahrt, I.; Scharenberg, B.; Schleyer, R.; Schloz, W.; Tilkes, F. Toxicological and ecotoxicological assessment of water tracers. *Hydrogeol. J.* **2001**, *9*, 321–325.
- Bouma, J.; Jongerius, A.; Boersma, O.; Jager, A.; Schoonderbeek, D. Function of different types of macropores during saturated flow through 4 swelling soil horizons. *Soil Sci. Soc. Am. J.* **1977**, *41*, 945–950.
- Bouwer, H. Groundwater Recharge as a Treatment of Sewage Effluent for Unrestricted Irrigation. In *Treatment and Use of Sewage Effluent for Irrigation*; Pescod, M. B.; Arar, A., Eds.; Butterworth Publishers: Boston, MA, 1988.
- Bowman, R. S. Evaluation of some new tracers for soil water studies. *Soil Sci. Soc. Am. J.* **1984**, *48*, 987–993.
- Buerge, I. J.; Poiger, T.; Muller, M. D.; Buser, H. R. Caffeine, an anthropogenic marker for wastewater contamination of surface waters. *Environ. Sci. Technol.* **2003**, *37*, 691–700.
- Burge, W. D.; Enkiri, N. K. Virus adsorption to five soils. *J. Environ. Qual.* **1978**, *7*, 73–76.
- Busenberg, E.; Plummer, L. N. Dating groundwater with sulfur hexafluoride: natural and anthropogenic sources of sulfur hexafluoride. *Water Resour. Res.* **2000**, *36*, 3011–3030.
- Buser, H. R.; Poiger, T.; Muller, M. D. Occurrence and environmental behavior of the chiral pharmaceutical drug ibuprofen in surface waters and in wastewater. *Environ. Sci. Technol.* **1999**, *33*, 2529–2535.
- California Department of Public Health. Groundwater recharge reuse draft regulation for California Code of Regulations Title 22, Division 4, Section 60320; California Department of Public Health: Sacramento, CA, 2007.
- Chen, Z. L.; Pavelic, P.; Dillon, P.; Naidu, R. Determination of caffeine as a tracer of sewage effluent in natural waters by on-line solid-phase extraction and liquid chromatography with diode-array detection. *Water Res.* **2002**, *36*, 4830–4838.
- Chu, Y.; Jin, Y.; Yates, M. V. Virus transport through saturated sand columns as affected by different buffer solutions. *J. Environ. Qual.* **2000**, *29*, 1103–1110.
- Church, M. *Electrochemical and Fluorometric Tracer Techniques for Streamflow Measurements*; Technical Bulletin 12, British Geomorphological Research Group; University of East Anglia: Norwich, U.K., 1974.
- Clara, M.; Strenn, B.; Kreuzinger, N. Carbamazepine as a possible anthropogenic marker in the aquatic environment: investigations on the behaviour of carbamazepine in wastewater treatment and during groundwater infiltration. *Water Res.* **2004**, *38*, 947–954.

- Clark, J. F.; Hudson, G. B. Excess Air: a New Tracer for Artificially Recharged Surface Water. Presented at the 5th International Symposium on Managed Aquifer Recharge, Berlin, Germany, 2005.
- Clark, J. F.; Hudson, G. B.; Davisson, M. L.; Woodside, G.; Herndon, R. Geochemical imaging of flow near an artificial recharge facility, Orange County, California. *Ground Water* **2004**, *42*, 167–174.
- Clark, J. F.; Hudson, G. B.; Avisar, D. Gas transport below artificial recharge ponds: insights from dissolved noble gases and a dual gas (SF₆ and He-3) tracer experiment. *Environ. Sci. Technol.* **2005**, *39*, 3939–3945.
- Clevenger, T.; Wu, Y.; DeGruson, E.; Brazos, B.; Banerji, S. Comparison of the inactivation of *Bacillus subtilis* spores and MS2 bacteriophage by MIOX, ClorTec and hypochlorite. *J. Appl. Microbiol.* **2007**, *103*, 2285–2290.
- Cook, P. G.; Herczeg, A. L. *Environmental Tracers in Subsurface Hydrology*; Kluwer Academic Press: Boston, MA, 2000.
- Corbett, D. R.; Dillon, K.; Burnett, W.; Schaefer, G. The spatial variability of nitrogen and phosphorus concentration in a sand aquifer influenced by onsite sewage treatment and disposal systems: a case study on St. George Island, Florida. *Environ. Pollut.* **2002**, *117*, 337–345.
- Costan-Longares, A.; Montemayor, M.; Payan, A.; Mendez, J.; Jofre, J.; Mujeriego, R.; Lucena, F. Microbial indicators and pathogens: removal, relationships and predictive capabilities in water reclamation facilities. *Water Res.* **2008**, *42*, 4439–4448.
- Daughton, C. G. Ground water recharge and chemical contaminants: challenges in communicating the connections and collisions of two disparate worlds. *Ground Water Monit. Remed.* **2004**, *24*, 127–138.
- Daughton, C. G.; Ternes, T. A. Pharmaceuticals and personal care products in the environment: agents of subtle change? *Environ. Health Perspect.* **1999**, *107*, 907–938.
- Davis, S. N.; Thompson, G. M.; Bentley, H. W.; Stiles, G. Groundwater tracers: a short review. *Ground Water* **1980**, *18*, 14–23.
- Davis, S. N.; Whittemore, D. O.; Fabryka-Martin, J. Uses of chloride/bromide ratios in studies of potable water. *Ground Water* **1998**, *36*, 338–350.
- DeMarsily, G. *Quantitative Hydrogeology*; Academic Press: New York, 1986.
- Dillon, K. S.; Corbett, D. R.; Chanton, J. P.; Burnett, W. C.; Furbish, D. J. The use of sulfur hexafluoride (SF₆) as a tracer of septic tank effluent in the Florida Keys. *J. Hydrol.* **1999**, *220*, 129–140.
- Dillon, P. Future management of aquifer recharge. *Hydrogeol. J.* **2005**, *13*, 313–316.
- Ding, W. H.; Wu, J.; Semadeni, M.; Reinhard, M. Occurrence and behavior of wastewater indicators in the Santa Ana River and the underlying aquifers. *Chemosphere* **1999**, *39*, 1781–1794.
- Domenico, P.; Schwartz, F. *Physical and Chemical Hydrogeology*; Wiley Publishers: New York, 1990.
- Donaldson, J. H.; Istok, J. D.; O'Reilly, K. T. Development and testing of a kinetic model for oxygen transport in porous media in the presence of trapped gas. *Ground Water* **1997**, *35*, 270–279.

- Dowd, S. E.; Pillai, S. D.; Wang, S. Y.; Corapcioglu, M. Y. Delineating the specific influence of virus isoelectric point and size on virus adsorption and transport through sandy soils. *Appl. Environ. Microbiol.* **1998**, *64*, 405–410.
- Drewes, J.; Amy, G. L.; Reinhard, M. Targeting Bulk and Trace Organics during Advanced Membrane Treatment Leading to Indirect Potable Reuse. Presented at the AWWA Water Sources Conference, Las Vegas, NV, 2002a.
- Drewes, J. E.; Heberer, T.; Reddersen, K. Fate of pharmaceuticals during indirect potable reuse. *Water Sci. Technol.* **2002b**, *46*, 73–80.
- Drewes, J. E.; Heberer, T.; Rauch, T.; Reddersen, K. Fate of pharmaceuticals during ground water recharge. *Ground Water Monit. Remed.* **2003**, *23*, 64–72.
- Duboise, S. M.; Moore, B. E.; Sagik, B. P. Poliovirus survival and movement in a sandy forest soil. *Appl. Environ. Microbiol.* **1976**, *31*, 536–543.
- Dunnivant, F. M.; Newman, M. E.; Bishop, C. W.; Burgess, D.; Giles, J. R.; Higgs, B. D.; Hubbell, J. M.; Neher, E.; Norrell, G. T.; Pfeifer, M. C.; Porro, I.; Starr, R. C.; Wylie, A. H. Water and radioactive tracer flow in a heterogeneous field-scale system. *Ground Water* **1998**, *36*, 949–958.
- Emerick, R. W.; Test, R. M.; Tchobanoglous, G.; Darby, J. Shallow intermittent sand filtration: microorganism removal. *Small Flows J.* **1997**, *3*, 12–22.
- Ferreira, A. P.; De Lourdes, C.; Da Cunha, N. Anthropic pollution in aquatic environment: development of a caffeine indicator. *Int. J. Environ. Health Res.* **2005**, *15*, 303–311.
- Flury, M.; Papritz, A. Bromide in the natural environment: occurrence and toxicity. *J. Environ. Qual.* **1993**, *22*, 747–758.
- Flury, M.; Wai, N. N. Dyes as tracers for vadose zone hydrology. *Rev. Geophys.* **2003**, *41*, 2.1–2.37.
- Fox, P. Advantages of Aquifer Recharge for a Sustainable Water Supply. Presented at the United Nations Environmental Programme/International Environmental Technology Centre International Symposium on Efficient Water Use in Urban Areas, Kobe, Japan, 1999.
- Fox, P. Soil Aquifer Treatment: An Assessment of Sustainability. In *Management of Aquifer Recharge for Sustainability*; Dillon, P. J., Ed.; AA Balkema Publishers: Rotterdam, The Netherlands, 2002; pp 21–26.
- Fox, P.; Narayanaswamy, K.; Genz, A.; Drewes, J. E. Water quality transformations during soil aquifer treatment at the Mesa Northwest Water Reclamation Plant, USA. *Water Sci. Technol.* **2001**, *43*, 343–350.
- Fox, P.; Aboshanp, W.; Alsamadi, B. Analysis of soils to demonstrate sustained organic carbon removal during soil aquifer treatment. *J. Environ. Qual.* **2005**, *34*, 156–163.
- Fry, V. A.; Istok, J. D.; Semprini, L.; O'Reilly, K. T.; Buscheck, T. E. Retardation of dissolved oxygen due to a trapped gas phase in porous media. *Ground Water* **1995**, *33*, 391–398.
- Fujito, B. T.; Lytle, C. D. Elution of viruses by ionic and nonionic surfactants. *Appl. Environ. Microbiol.* **1996**, *62*, 3470–3473.
- Gamlin, J. D.; Clark, J. F.; Woodside, G.; Herndon, R. Large-scale tracing of ground water with sulfur hexafluoride. *J. Environ. Eng. (N.Y.)* **2001**, *127*, 171–174.

- Garabedian, S. P.; LeBlanc, D. R.; Gelhar, L. W.; Celia, M. A. Large-scale natural gradient tracer test in sand and gravel, Cape Cod, Massachusetts. 2. Analysis of spatial moments for a nonreactive tracer. *Water Resour. Res.* **1991**, *27*, 911–924.
- Gardinali, P. R.; Zhao, X. Trace determination of caffeine in surface water samples by liquid chromatography-atmospheric pressure chemical ionization-mass spectrometry. *Environ. Int.* **2002**, *28*, 521–528.
- Gerba, C. P. Microorganisms as Groundwater Tracers. In *Groundwater Pollution Microbiology*; Bitton, G.; and Gerba, C. P., Eds.; John Wiley & Sons: New York, 1984; pp 225–233.
- Gerba, C. P.; Wallis, C.; Melnick, J. L. Viruses in water: the problem, some solutions. *Environ. Sci. Technol.* **1975**, *9*, 1122–1126.
- Gerba, C. P.; Powelson, D. K.; Yahya, M. T.; Wilson, L. G.; Amy, G. L. Fate of viruses in treated sewage effluent during soil aquifer treatment designed for waste-water reclamation and reuse. *Water Sci. Technol.* **1991**, *24*, 95–102.
- Gerba, C. P.; Riley, K. R.; Nwachuku, N.; Ryu, H.; Abbaszadegan, M. Removal of encephalitozoon intestinalis, calicivirus, and coliphages by conventional drinking water treatment. *J. Environ. Sci. Health, Part A* **2003**, *38*, 1259–1268.
- Giger, W.; Alder, A. C.; Golet, E. M.; Kohler, H. P. E.; McArde, C. S.; Molnar, E.; Siegrist, H.; Suter, M. J. F. Occurrence and fate of antibiotics as trace contaminants in wastewaters, sewage sludges, and surface waters. *Chimia* **2003**, *57*, 485–491.
- Glassmeyer, S. T.; Furlong, E. T.; Kolpin, D. W.; Cahill, J. D.; Zaugg, S. D.; Werner, S. L.; Meyer, M. T.; Kryak, D. D. Transport of chemical and microbial compounds from known wastewater discharges: potential for use as indicators of human fecal contamination. *Environ. Sci. Technol.* **2005**, *39*, 5157–5169.
- Good until the Last Drop: A Practitioner's Guide to Water Reuse*; American Public Works Association: Kansas City, MO, 2005.
- Goyal, S. M.; Gerba, C. P. Comparative adsorption of human enteroviruses, simian rotavirus, and selected bacteriophages to soils. *Appl. Environ. Microbiol.* **1979**, *38*, 241–247.
- Guidelines for Water Reuse*; EPA/625/R-04/108; U.S. Environmental Protection Agency, U.S. Government Printing Office: Washington, DC, 2004.
- Halling-Sorensen, B.; Nielsen, S. N.; Lanzky, P. F.; Ingerslev, F.; Lutzhoft, H. C. H.; Jorgensen, S. E. Occurrence, fate and effects of pharmaceutical substances in the environment: a review. *Chemosphere* **1998**, *36*, 357–394.
- Harvey, R. W. Microorganisms as tracers in groundwater injection and recovery experiments: a review. *FEMS Microbiol. Rev.* **1997**, *20*, 461–472.
- Harvey, R. W.; George, L. H.; Smith, R. L.; LeBlanc, D. R. Transport of microspheres and indigenous bacteria through a sandy aquifer: results of natural and forced-gradient tracer experiments. *Environ. Sci. Technol.* **1988**, *23*, 51–56.
- Harvey, R. W.; Garabedian, S. P. Use of colloid filtration theory in modeling movement of bacteria through a contaminated sandy aquifer. *Environ. Sci. Technol.* **1991**, *25*, 178–185.
- Harvey, R. W.; Kinner, N. E.; Bunn, A.; MacDonald, D.; Metge, D. Transport behavior of groundwater protozoa and protozoan-sized microspheres in sandy aquifer sediments. *Appl. Environ. Microbiol.* **1995**, *61*, 209–217.

- Heberer, T.; Mechlinski, A.; Fanck, B.; Knappe, A.; Massmann, G.; Pekdeger, A.; Fritz, B. Field studies on the fate and transport of pharmaceutical residues in bank filtration. *Ground Water Monit. Remed.* **2004**, *24*, 70–77.
- Heilweil, V. M.; Solomon, D. K.; Perkins, K. S.; Ellett, K. M. Gas-partitioning tracer test to quantify trapped air during recharge. *Ground Water* **2004**, *42*, 589–600.
- Higgins, J.; Warnken, J.; Sherman, P. P.; Teasdale, P. R. Survey of users and providers of recycled water: quality concerns and directions for applied research. *Water Res.* **2002**, *36*, 5045–5056.
- Holzbecher, E.; Dizer, H.; Grutzmacher; Lopez-Pila, J.; Nutzmann, G. The influence of redox conditions on phage transport: enclosure experiments and modeling. *Environ. Eng. Sci.* **2006**, *23*, 623–630.
- Karimi, A. A.; Redman, J. A.; Ruiz, R. F. Ground water replenishment with reclaimed water in the City of Los Angeles. *Ground Water Monit. Remed.* **1998**, *18*, 150–158.
- Kolpin, D. W.; Furlong, E. T.; Meyer, M. T.; Thurman, E. M.; Zaugg, S. D.; Barber, L. B.; Buxton, H. T. Pharmaceuticals, hormones, and other organic wastewater contaminants in US streams, 1999–2000: a national reconnaissance. *Environ. Sci. Technol.* **2002**, *36*, 1202–1211.
- Kolpin, D. W.; Skopec, M.; Meyer, M. T.; Furlong, E. T.; Zaugg, S. D. Urban contribution of pharmaceuticals and other organic wastewater contaminants to streams during differing flow conditions. *Sci. Total Environ.* **2004**, *328*, 119–130.
- LeBlanc, D. R. *Overview of Research at the Cape Cod Site: Field and Laboratory Studies of Physical, Chemical, and Microbiological Processes Affecting Transport in a Sewage-Contaminated Aquifer*; Water-Resources Investigations Report 94-4015; U.S. Geological Survey: Reston, VA, 1996.
- Lester, D.; Greenberg, L. A. The toxicity of sulfur hexafluoride. *Arch. Ind. Hyg. Occup. Med.* **1950**, *2*, 348–349.
- Lin, C.; Banin, A. Phosphorous retardation and breakthrough into well water in a soil-aquifer treatment (SAT) system used for large-scale wastewater reclamation. *Water Res.* **2006**, *40*, 1507–1518.
- Litwiller, E. J.; Debroux, J. F.; Reinhard, M. Fate of selected anthropogenic compounds during groundwater recharge. *Abstr. Pap. Am. Chem. Soc.* **2000**, *219*, U621.
- Ma, L.; Spalding, R. F. Stable isotope characterization of the impacts of artificial ground water recharge. *Water Resour. Bull.* **1996**, *32*, 1273–1282.
- Mansell, B.; Drewes, J. Fate of steroidal hormones during soil-aquifer treatment. *Ground Water Monit. Remed.* **2004**, *24*, 94–101.
- Massmann, G.; Knappe, A.; Richter, D.; Pekdeger, A. Investigating the influence of treated sewage on groundwater and surface water using wastewater indicators in Berlin, Germany. *Acta Hydrochim. Hydrobiol.* **2004**, *32*, 336–350.
- Masters, R. W.; Verstraeten, I. M.; Heberer, T. Fate and transport of pharmaceuticals and endocrine disrupting compounds during ground water recharge. *Ground Water Monit. Remed.* **2004**, *24*, 54–57.
- McKay, L. D.; Cherry, J. A.; Bales, R. C.; Yahya, M. T.; Gerba, C. P. A field example of bacteriophage as tracers of fracture flow. *Environ. Sci. Technol.* **1993**, *27*, 1075–1079.

- McLaughlin, M. J. A review of the use of dyes as soil-water tracers. *Water SA* **1982**, *8*, 196–201.
- Mersmann, P.; Scheytt, T.; Heberer, T. Column experiments on the transport behavior of pharmaceutically active compounds in the saturated zone. *Acta Hydrochim. Hydrobiol.* **2003**, *30*, 275–284.
- Miljevic, N. Application of environmental isotopes in evaluation of pollutants. *Crit. Rev. Anal. Chem.* **2003**, *33*, 307–310.
- Mills, A.; Powelson, D. K. Bacterial Interactions with Surfaces in Soils. In *Bacterial Adhesion: Molecular and Ecological Diversity*; Fletcher, M., Ed.; Wiley-Liss: New York, 1996; pp 25–57.
- Muir, K. S.; Coplen, T. B. *Tracing Ground-Water Movement by Using the Stable Isotopes of Oxygen and Hydrogen, Upper Penitencia Creek Alluvial Fan, Santa Clara Valley, California*; U.S. Geological Survey: Reston, VA, 1981.
- National Database of Water Reuse Facilities. <http://www.watereuse.org/info/nwrdb> (accessed April 2009).
- National Field Manual for the Collection of Water-Quality Data*; U.S. Geological Survey: Reston, VA, 2006; Chapter 4.
- National Research Council. *Ground Water Recharge Using Waters of Impaired Quality*; National Academy Press: Washington, DC, 1994.
- National Research Council. *Issues in Potable Reuse: The Viability of Augmenting Drinking Water Supplies with Reclaimed Water*; National Academy Press: Washington DC, 1998.
- National Research Council. *Prospects for Managed Underground Storage of Recoverable Water*; National Academy Press: Washington, DC, 2008.
- Nielsen, J. M.; Pinder, G. F.; Kulp, T. J.; Angel, S. M. Investigation of dispersion in porous media using fiber-optic technology. *Water Resour. Res.* **1991**, *27*, 2743–2749.
- Nielson, D.; Nielson, G. *Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring*; CRC Press: Boca Raton, FL, 2005.
- Ogunseitan, O. A. Removal of caffeine in sewage by *Pseudomonas putida*: implications for water pollution index. *World J. Microbiol. Biotechnol.* **1996**, *12*, 251–256.
- Ogunseitan, O. A. Caffeine-inducible enzyme activity in *Pseudomonas putida* ATCC 700097. *World J. Microbiol. Biotechnol.* **2002**, *18*, 423–428.
- Peeler, K. A.; Opsahl, S. P.; Chanton, J. P. Tracking anthropogenic inputs using caffeine, indicator bacteria, and nutrients in rural freshwater and urban marine systems. *Environ. Sci. Technol.* **2006**, *40*, 7616–7622.
- Penrod, S. L.; Olson, T. M.; Grant, S. B. Deposition kinetics of two viruses in packed beds of quartz granular media. *Langmuir* **1996**, *12*, 5576–5587.
- Pieper, A. P.; Ryan, J. N.; Harvey, R. W.; Amy, G. L.; Illangasekare, T. H.; Metge, D. W. Transport and recovery of bacteriophage PRD1 in an unconfined sand aquifer: effect of anthropogenic organic matter. *Environ. Sci. Technol.* **1997**, *31*, 1163–1170.
- Proposed Guide Lines for Ground Water Recharge with Recycled Municipal Waste Water, and Background Information on Proposed Guidelines for Groundwater Recharge with Recycled Municipal Wastewater*; Interagency Water Reclamation Coordinating Committee and the Groundwater Recharge Committee: Sacramento, CA, 1992.

- Ptak, T.; Piepenbrink, M.; Martac, E. Tracer tests for the investigation of heterogeneous porous media and stochastic modeling of flow and transport: a review of some recent developments. *J. Hydrol.* **2004**, *294*, 122–163.
- Quast, K. W.; Lansey, K.; Arnold, R.; Bassett, R. L.; Rincon, M. Boron isotopes as an artificial tracer. *Ground Water* **2006**, *44*, 453–466.
- Rabiet, M.; Togola, A.; Brissaud, F.; Seidel, J. L.; Budzinski, H.; Elbaz-Poulichet, F. Consequences of treated water recycling as regards pharmaceuticals and drugs in surface and ground waters of a medium-sized Mediterranean catchment. *Environ. Sci. Technol.* **2006**, *40*, 5282–5288.
- Rahe, T. M.; Hagedorn, G.; MacCoy, E. L. A comparison of fluorescein dye and antibiotic resistant *Escherichia coli* as indicators of pollution in groundwater. *Water, Air, Soil Pollut.* **1979**, *11*, 93–104.
- Rettinger, S.; Ronen, D.; Amiel, A. J.; Magaritz, M.; Bischofsberger, W. Tracing the influx of sewage from a leaky sewer into a very thin and fast-flowing aquifer. *Water Res.* **1991**, *25*, 75–82.
- Ronen, D.; Magaritz, M.; Gvirtzman, H.; Garner, W. Microscale chemical heterogeneity in groundwater. *J. Hydrol.* **1987**, *92*, 173–178.
- Rose, J. B.; Dickson, L. J.; Farrah, S. R.; Carnahan, R. P. Removal of pathogenic and indicator microorganisms by a full-scale water reclamation facility. *Water Res.* **1996**, *30*, 2785–2797.
- Schijven, J. F.; Hoogenboezem, W.; Hassanizadeh, S. M.; Peters, J. H. Modeling removal of bacteriophages MS2 and PRD1 by dune recharge at Castricum, the Netherlands. *Water Resour. Res.* **1999**, *35*, 1101–1111.
- Schijven, J. F.; Hassanizadeh, S. M.; de Bruin, H. A. M. Column experiments to study nonlinear removal of bacteriophages by passage through saturated dune sand. *J. Contam. Hydrol.* **2002**, *58*, 243–259.
- Schroeder, R. A.; Anders, R.; Bohlke, J. K.; Michel, R. L.; Metge, D. W. Water Quality at Production Wells near Artificial-Recharge Basins in Montebello Forebay, Los Angeles County. Presented at the AWRA Symposium, Conjunctive Use of Water Resources: Aquifer Storage and Recovery, Herndon, VA, 1997.
- Schulze-Makuch, D.; Guan, H.; Pillai, S. D. Effects of pH and geological medium on bacteriophage MS2 transport in a model aquifer. *Geomicrobiol. J.* **2003**, *20*, 73–84.
- Seaman, J. C.; Bertsch, P. M.; Korom, S. F.; Miller, W. P. Physicochemical controls on nonconservative anion migration on coarse-textured alluvial sediments. *Ground Water* **1996**, *34*, 778–783.
- Sedlak, D. L.; Huang, C.-H.; Pinkston, K. Strategies for Selecting Pharmaceuticals to Assess Attenuation during Indirect Potable Water Reuse. In *Pharmaceuticals in the Environment: Sources, Fate, Effects and Risks*; Kümmerer, K., Ed.; Springer Publishers: Berlin, Germany, 2004, pp 107–120.
- Seiler, R. L.; Zaugg, S. D.; Thomas, J. M.; Howcroft, D. L. Caffeine and pharmaceuticals as indicators of waste water contamination in wells. *Ground Water* **1999**, *37*, 405–410.
- Shields, P. A.; Farrah, S. R. Determination of the Electrostatic and Hydrophobic Character of Enteroviruses and Bacteriophages. Presented at the 87th Annual Meeting of the American Society for Microbiology, Washington, DC, 1987.

- Sidle, W. C. Environmental isotopes for resolution of hydrology problems. *Environ. Monit. Assess.* **1998**, *52*, 389–410.
- Singh, S. N.; Bassous, M.; Gerba, C. P.; Kelley, L. M. Use of dyes and proteins as indicators of virus adsorption to soils. *Water Res.* **1986**, *20*, 267–272.
- Sinton, L. W. Microbial contamination of alluvial gravel aquifers by septic tank effluent. *Water, Air, Soil Pollut.* **1986**, *28*, 407–425.
- Skilton, H.; Wheeler, D. Bacteriophage tracer experiments in groundwater. *J. Appl. Bacteriol.* **1988**, *65*, 387–395.
- Smart, P. L. A review of the toxicity of twelve fluorescent dyes used for water tracing. *NSS Bull.* **1984**, *46*, 21–33.
- Smart, P. L.; Laidlaw, I. M. S. Evaluation of some fluorescent dyes for water tracing. *Water Resour. Res.* **1977**, *13*, 15–33.
- Snyder, S. A.; Westerhoff, P.; Yoon, Y.; Sedlak, D. L. Pharmaceuticals, personal care products, and endocrine disruptors in water: implications for the water industry. *Environ. Eng. Sci.* **2003**, *20*, 449–469.
- Snyder, S. A.; Leising, J.; Westerhoff, P.; Yoon, Y.; Mash, H.; Vanderford, B. Biological and physical attenuation of endocrine disruptors and pharmaceuticals: implications for water reuse. *Ground Water Monit. Remed.* **2004**, *24*, 108–118.
- Society of Dyers and Colourists. *Colour Index International*, 3rd ed.; Society of Dyers and Colourists: Bradford, U.K., 1999.
- Sokolova, A.; Malfois, M.; Caldentey, J.; Svergun, D. I.; Koch, M. H. J.; Bamford, D. H.; Tuma, R. Solution structure of bacteriophage PRD1 vertex complex. *J. Biol. Chem.* **2001**, *276*, 46187–46195.
- Soliman, M. A.; Pedersen, J. A.; Park, H.; Castaneda-Jimenez, A.; Stenstrom, M. K.; Suffet, I. H. Human pharmaceuticals, antioxidants, and plasticizers in wastewater treatment plant and water reclamation plant effluents. *Water Environ. Res.* **2007**, *79*, 156–167.
- Sposito, G. *The Chemistry of Soils*; Oxford University Press: New York, 1989.
- Stan, H. J.; Heberer, T. Pharmaceuticals in the aquatic environment. *Analisis* **1997**, *25*, M20–M23.
- Standard Methods for the Examination of Water and Wastewater*, 20th ed.; American Public Health Association: Washington, DC, 1998.
- Standley, L. J.; Kaplan, L. A.; Smith, D. Molecular tracers of organic matter sources to surface water resources. *Environ. Sci. Technol.* **2000**, *34*, 3124–3130.
- Steenhuis, T. S.; Staubitz, W.; Andreini, M. S.; Surface, J.; Richard, T. L.; Paulsen, R.; Pickering, N. B.; Hagerman, J. R.; Geohring, L. D. Preferential movement of pesticides and tracers in agricultural soils. *J. Irrig. Drain. Eng.* **1990**, *116*, 50–66.
- Steinheimer, T. R.; Johnson, S. M. *The Investigation of the Possible Formation of Diethylnitrosamine Resulting from the Use of Rhodamine WT Dye as a Tracer in River Waters*; Water Supply Paper 2290; U.S. Geological Survey: Reston, VA, 1986; 37–49.
- Ternes, T. A. Occurrence of drugs in German sewage treatment plants and rivers. *Water Res.* **1998**, *32*, 3245–3260.
- Todd, D. K. *Groundwater Hydrology*; John Wiley & Sons: New York, 1980.

- VanDuin, G. Single-Stranded RNA Bacteriophages. In *The Bacteriophages*; Calender, R., Ed.; Plenum Press: New York, 1988, pp 117–169.
- Vengosh, A.; Keren, R. Chemical modifications of groundwater contaminated by recharge of treated sewage effluent. *J. Contam. Hydrol.* **1996**, *23*, 347–360.
- Viriot, M. L.; Andre, J. C. Fluorescent dyes: a search for new tracers for hydrology. *Analisis* **1989**, *17*, 97–111.
- Vulava, V. M.; Perry, E. B.; Romanek, C. S.; Seaman, J. C. Dissolved gases as partitioning tracers for determination of hydrogeological parameters. *Environ. Sci. Technol.* **2002**, *36*, 254–262.
- Walvoord, M. A.; Phillips, F. M.; Stonestrom, D. A.; Evans, R. D.; Hartsough, P. C.; Newman, B. D.; Striegl, R. G. A reservoir of nitrate beneath desert soils. *Science* **2003**, *302*, 1021–1024.
- Wanninkhof, R.; Ledwell, J. R.; Broecker, W. S.; Hamilton, M. Gas exchange on Mono Lake and Crowley Lake, California. *J. Geophys. Res.* **1987**, *92*, 14567–14580.
- Weigel, S.; Berger, U.; Jensen, E.; Kallenborn, R.; Thoresen, H.; Huhnerfuss, H. Determination of selected pharmaceuticals and caffeine in sewage and seawater from Tromsø/Norway with emphasis on ibuprofen and its metabolites. *Chemosphere* **2004**, *56*, 583–592.
- Williams, R. T.; Bridges, J. W. Fluorescence of solutions: review. *J. Clin. Pathol.* **1964**, *17*, 371.
- Wilson, L. G.; Amy, G. L.; Gerba, C. P.; Gordon, H.; Johnson, B.; Miller, J. Water-quality changes during soil aquifer treatment of tertiary effluent. *Water Environ. Res.* **1995**, *67*, 371–376.
- Wilson, R. D.; Mackay, D. M. The use of sulfur hexafluoride as a conservative tracer in saturated sandy media. *Ground Water* **1993**, *31*, 719–724.
- Wilson, R. D.; Mackay, D. M. SF₆ as a conservative tracer in saturated media with high intragranular porosity or high organic carbon content. *Ground Water* **1996**, *34*, 241–249.
- Wilson, R. D.; Mackay, D. M.; Scow, K. M. In situ MTBE biodegradation supported by diffusive oxygen release. *Environ. Sci. Technol.* **2002**, *36*, 190–199.
- Woessner, W. W.; Ball, P. N.; DeBorde, D. C.; Troy, T. L. Viral transport in a sand and gravel aquifer under field pumping conditions. *Ground Water* **2001**, *39*, 886–894.
- Yahya, M. T.; Galsomies, L.; Gerba, C. P.; Bales, R. C. Survival of bacteriophages MS-2 and PRD-1 in ground-water. *Water Sci. Technol.* **1993**, *27*, 409–412.
- Yates, M. V.; Gerba, C. P.; Kelley, L. M. Virus persistence in groundwater. *Appl. Environ. Microbiol.* **1985**, *49*, 778–781.
- Yoo, H. H.; Miller, J. H.; Lansey, K.; Reinhard, M. EDTA, NTA, alkylphenol ethoxylate and DOC attenuation during soil aquifer treatment. *J. Environ. Eng. (N.Y.)* **2006**, *132*, 674–682.

Advancing the Science of Water Reuse and Desalination



1199 North Fairfax Street, Suite 410

Alexandria, VA 22314 USA

(703) 548-0880

Fax (703) 548-5085

E-mail: Foundation@WaterReuse.org

www.WaterReuse.org/Foundation