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Evaluating Travel Times Beneath an Artificial Recharge Pond Using Sulfur Hexafluoride

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Key Terms: ***Geochemistry, Groundwater Hydrology, Artificial Recharge, Tracer Experiment, Site Investigation, Sulfur Hexafluoride***

ABSTRACT

Draft rules for artificial recharge operations, which use recycled waste water as a source water, require minimum travel times to production wells in California. Deliberate tracer experiments are the accepted method for determining travel times. An example of a tracer experiment using sulfur hexafluoride is discussed at an artificial recharge site located within a regional water table depression. The study shows the complexity in interpreting travel times because of the influence of recharge rates and water production. It also demonstrates the effectiveness of recovering recharged water at spreading basins surrounded by production wells.

INTRODUCTION

Artificial recharge is an important management strategy for potable water supplies in both developed and developing countries around the world (Dillion, 2003). It is also used for combating seawater intrusion in some coastal areas. The practice consists of recharging surplus runoff, imported surface water, or recycled wastewater into aquifers. This is achieved using injection wells or enhancing recharge rates at specially designed facilities such as spreading ponds. The latter are typically small basins that are periodically drained and cleaned of clogging material to maintain high infiltration rates. After residing in the subsurface for a period of time, which can be as short as a few days, the recharged water becomes part of the basin's water supply and can be extracted at municipal, irrigation, or domestic wells.

A common design used in artificial recharge places production wells next to spreading ponds. This design works well when the main goal, usually for water quality reasons, is to exploit the recently recharged water without significant dilution with native groundwater. The water balance near this type of facility is controlled by the relative amounts of recharge and production. In cases where long-term well production is greater than recharge, a regional cone of depression forms and traps the recharged water near the spreading ponds. A mound will develop when long-term recharge exceeds production. Because both recharge and production are often seasonal and out of phase, groundwater levels usually fluctuate dramatically near this type of facility with local mounding occurring during parts of the year and cones of depressions occurring at other times. By surrounding spreading ponds with production wells, the travel distance and, consequently, the residence time of the recharged water in the subsurface are often very short. Because of these features, this type of artificial recharge facility has many similarities with river-bank filtration, a common practice used in Western Europe (e.g., Tufenkji et al., 2002).

For an artificial recharge operation to be successful, a few challenges must be overcome. First, a source of surface water must be found. Second, because the available water for the recharge operation is often of lesser quality than generally used in potable supplies, there is a potential to degrade the existing groundwater supply. The introduction of infective micro-organisms, disinfection by-products, or organic compounds with unknown health risks is a concern, especially when recycled wastewater is a large component of the source water (NRC, 1998). In California, to ensure the quality of the potable supply, draft rules created by the Department of Health Services regulate artificial recharge sites when a component of the source water is recycled. In addition to various source regulations, these rules require that production wells be more than 150 m (500 ft) from the recharge facility and that the travel time to production wells be greater than 6 months (DHS, 2004). The rules do allow for an exemption of the travel distance requirement if the water agency can document with a deliberate tracer experiment that the travel time is greater than 6 months (DHS, 2004). The subsurface requirements recognize that water quality typically improves during transit through the aquifer downgradient from recharge operations (Fox et al., 2001; Fox, 2002; and Drewes et al., 2002). Numerous field studies at river-bank filtration sites have shown that water quality improvements often occur even when the flow

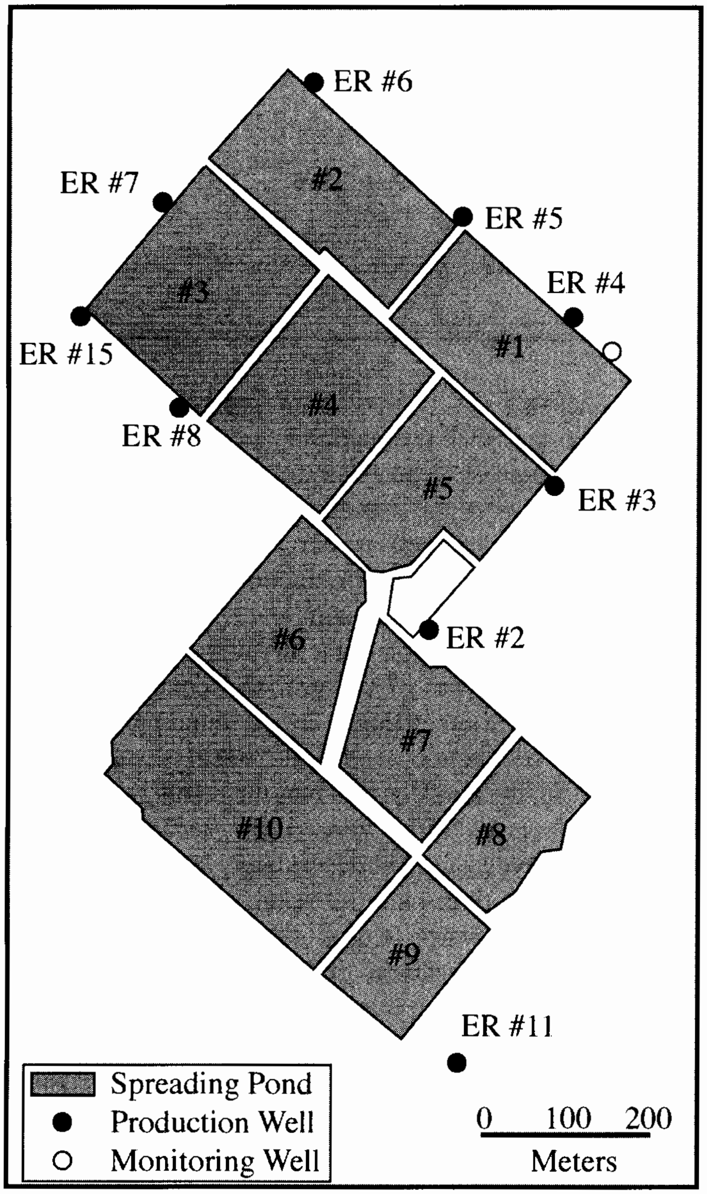

Figure 1. Map of the El Rio Spreading Grounds. The deliberate tracer experiment using SF_6 was conducted from Pond 2 while recharge was occurring from Pond 2 and 3.

distance is less than 150 m (Schwarzenbach et al., 1983; Alain and Bertin, 1993; Hiscock and Grischeck, 2002; and Tufenkji et al., 2002).

Recently, Gamlin and others (2001) and Clark and others (2004) developed methods using dissolved gas tracers for the direct determination of travel times between recharge areas and wells that can be used to satisfy the draft rules in California. To follow the movement of recharge water for periods greater than 6 months, non-reactive tracers that could be economically introduced into a large volume of recharge water ($>10^6$ m^3) at a sufficient concentration to allow quantification after at least a 1,000:1 dilution needed to be found. Sulfur hexafluoride (SF_6) and isotopes of noble gases were found to satisfy these conditions (Gamlin et al., 2001; Clark et al., 2004).

Here, we present results from a SF_6 tracer experiment at the El Rio Spreading Grounds, Ventura County, CA. This site is significantly different in terms of water balance, well location, and local groundwater flow than at the Orange County, CA, sites described by Gamlin and others (2001) and Clark and others (2004). Whereas the Orange County artificial recharge facilities were at the up-gradient end of the groundwater system, the El Rio Spreading Grounds lie in a regional cone of depression, which acts to prevent artificially recharged water from flowing away from the site. The seasonality of recharge and groundwater production cause large variations in the water table beneath the spreading grounds, which add additional complications to the local groundwater flow direction and rates. The case study we present here adds to the methodological development of deliberate dissolved gas tracer experiments, which may be used during permitting in California and elsewhere.

STUDY LOCATION

The El Rio Spreading Grounds are located near Oxnard, CA, and are managed by the United Water Conservation District (UWCD). This public agency supplies high-quality water for both agriculture and municipal uses. The district encompasses about 87,000 ha of central Ventura County, CA, and manages the water supply contained in the Santa Clara–Calleguas Basin. Included in this basin is the Santa Clara River watershed. To maintain a high-quality groundwater supply, UWCD has implemented a number of management practices, including artificial recharge, which began in the 1920s.

The hydrology of the Santa Clara–Calleguas Basin was recently examined in detail by Hanson and others (2003) as a part of the U.S. Geological Survey Regional Aquifer-System Analysis (RASA) program. This study determined that natural groundwater recharge occurs primarily through infiltration of stream flow within the major rivers and numerous arroyos that drain the mountain fronts of the basin. Direct recharge of precipitation on bedrock outcrops and the valley floor contributes a lesser amount. For the period 1984–1993, natural recharge averaged about 140×10^6 m^3/year. Artificial recharge at the three spreading grounds (El Rio, Saticoy, and Piru) and irrigation return flow contribute together about the same amount of water to the groundwater system. During 1984–1993, artificial recharge averaged 70×10^6 m^3/year, whereas irrigation return flow averaged 63×10^6 m^3/year.

The gas tracer experiment was performed in the El Rio Spreading Grounds (Figure 1), which are located toward the downgradient end of the Santa Clara River watershed where the groundwater basin expands to form the permeable alluvial deposits of the Oxnard Plain. The upper aquifer (late Pleistocene and Holocene age) is composed

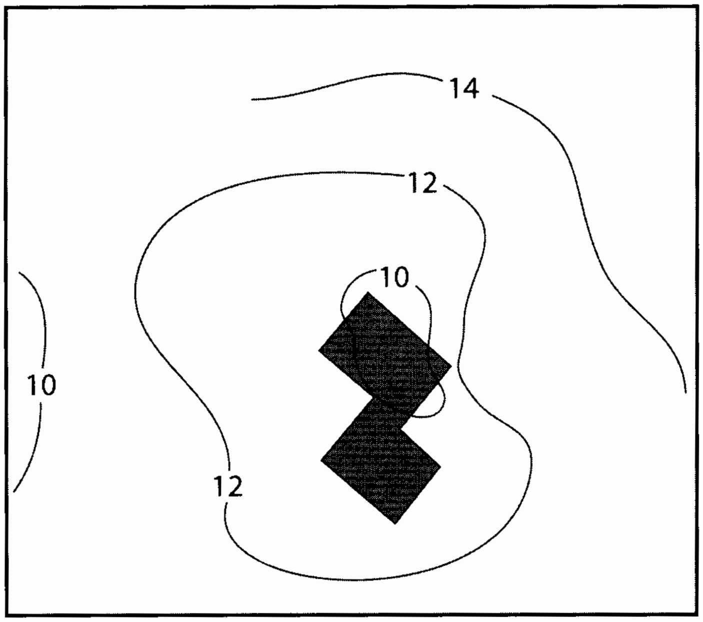

Figure 2. The water table elevation (m above sea level) near the El Rio Spreading Grounds in November 2002. Near the spreading grounds, the ground surface elevation is ~30 m above sea level.

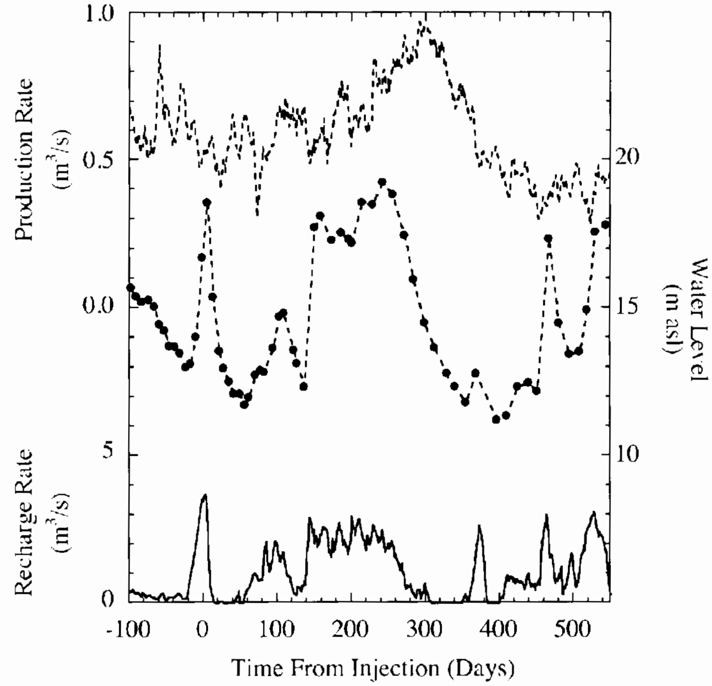

Figure 3. The rate of artificial recharge from all the basins (solid line), water table elevation measured at the monitoring well (filled circles with dashed line), and total groundwater production rate (dashed line) at the El Rio Spreading Grounds. The bottom of Pond 2 is about 30 m above sea level. Time zero is September 27, 2002.

of discontinuous layers of gravel, sands, and silts (Hanson et al., 2003). Ten ponds with a maximum wetted surface area of 40 ha (UWCD, 2001) make up the spreading grounds. Pond 1 is used as a desilting basin and, thus, has a very low percolation rate. Pond 9 is closed and will be used in the potable supply system as a storage reservoir of chlorinated water. The other eight ponds are used to recharge the upper aquifer artificially. The daily percolation rate from these ponds varies by more than an order of magnitude. It is at a maximum in recently cleaned ponds and decreases with usage as the pond bottom becomes clogged. During the 1990s, about 40 × 10^6 m^3 (32,000 acre-ft; AF) was recharged annually from the El Rio Spreading Grounds (UWCD, 2001). The source of the recharge water was primarily diverted seasonal run-off from the Santa Clara River and released stored water from Lake Piru, a reservoir located northeast of the spreading grounds.

The spreading basins are surrounded by nine production wells (Figure 1). Because long-term groundwater production at these wells exceeds recharge from the ponds, a regional groundwater depression surrounds the spreading grounds (Figure 2). As a result, groundwater flow is toward the spreading grounds. Within the spreading area, much steeper local cones of depressions form around each well during periods of intense pumping and local mounding within the regional depression occur beneath the ponds during recharge events. On average, groundwater production is higher during the summer and artificial recharge is higher during the winter and spring. The seasonality in the recharge and production create a very complex pattern of flow beneath the El Rio Spreading Grounds.

METHODS

In September 2002, about 24 × 10^6 m^3 (19,500 AF) of water was released from Lake Piru, down Piru Creek, and into the Santa Clara River. A portion of this water was diverted into the El Rio Spreading Grounds (~6 × 10^6 m^3 or ~4,800 AF), flooding Ponds 2 (surface area ~3.8 ha) and 3 (surface area ~4.2 ha) for almost 5 weeks between September 7, 2002, and October 8, 2002 (Figure 3). Except for 2 weeks in August when deep groundwater was released into Pond 2, the spreading area had been essentially dry for more than 6 months before the release.

During the September recharge event, the water depth in both Ponds 2 and 3 was initially less than 0.3 m, despite the very high influx of surface water, 1.3 m^3/s, which demonstrates the very high percolation rates of these ponds. After about 2 weeks, the water level in Pond 2 rose in response to the increasing flow into the spreading area and a water depth of ~1.2 m was maintained for the tracer experiment.

For a period of 8 days (September 27, 2002, to October 4, 2002), a gas mixture containing SF_6 (~0.9 m^3) and ^3He (~0.001 m^3) was injected into Pond 2 by bubbling through a diffusion stone that was placed in a water depth of ~1 m. During this time, the average percolation rate of surface water into the ground was 1.8 m^3/s or 4 m/day. The mean residence time of water in the pond, which had a volume of ~4.5 × 10^5 m^3, was

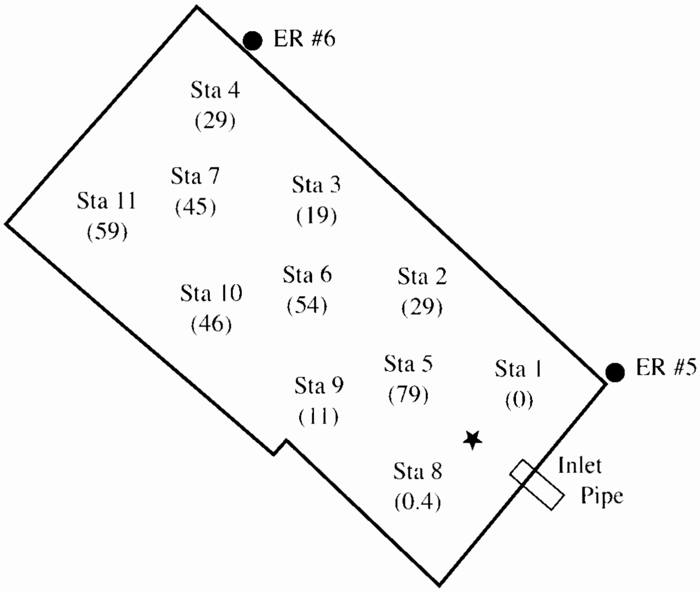

Figure 4. Location of the sampling stations within Pond 2 during the injection period. Below each station number is the mean SF_6 concentration (pmol/L). The gas tracers were injected at the star ~10 m offshore of the inlet pipe.

0.3 day. While the tracer injection was in progress, an additional 1.7 m^3/s was percolating from Pond 3.

The release point of SF_6 in Pond 2 was close to the inlet pipe (~10 m offshore) but away from the "white water" (to minimize the gas lost), which was observed immediately downstream from the pipe (Figure 4). The injection rate was maintained using a battery-operated switcher valve (an eight-port, two-way valve) set to release about 1.5 mL at standard temperature and pressure (STP) of the gas mixture per minute. Approximately 17 L (0.72 mol) of SF_6 was injected into the pond during this experiment. Pond samples for SF_6 analysis were collected every 2 days, ~10 cm below the surface in 15 mL Vacutainers at 11 designated locations (Figure 4). These samples were collected to determine the tracer concentration and spatial distribution in the pond so that the tracer input function to the groundwater could be determined.

Groundwater samples were also collected in 15-mL Vacutainers before, during, and after the tracer injection from eight production wells located in the spreading grounds (Figure 1). The production wells have relatively long screened intervals (40 and 70 m in length) and, with the exception of El Rio 11, they are located within 600 m of Pond 2 (Table 1). During the first 3 months, groundwater samples were collected every 3 to 7 days. Monthly samples were collected during the next 9 months. Thereafter, samples were collected every 2 months.

All the SF_6 samples were analyzed on a gas chromatograph (GC) equipped with an electron-capture detector using the head-space method described by Clark and others (2004). SF_6 was separated from other gases with

Table 1. *The arrival times of SF_6 and the physical properties of the wells sampled during the El Rio tracer experiment.*

Well	Distance From Pond 2 (m)[1]	Top of Perforation (m bgs[2])	Bottom of Perforation (m bgs)	First Arrival (days)	Peak Arrival (days)	Duration (days)[3]
2	610	33	100	125	125	48 ± 10
3	480	33	92	103	125	49 ± 10
5	10[4]	45	92	17	82	>407
6	10[4]	50	92	5	20	>421
7	180	33	73	26	68	56 ± 6; 152
8	260	46	97	82	196	43 ± 10; 23 ± 10; >183
11	1,130	48	112	none	none	none
15	260	47	103	82	82	1 ± 10; 112

[1]Unless noted, the distance is between the center of Pond 2 and the well.
[2]bgs = below ground surface.
[3]In El Rio 7, 8, and 15, the tracer passed multiple times.
[4]Distance is from the edge of pond, not the center.

a Molecular Sieve 5a column held at room temperatures. The GC detector response was calibrated about every 10 samples with standards (~148 parts per trillion by volume [pptv], ~524 pptv, and ~1947 pptv) prepared by Scott-Marrin Inc. (Riverside, CA). The precision and detection limits of this method were ±5 percent and 0.04 pmol/L (1 pmol/L = 10^{-12} mol/L), respectively.

RESULTS AND DISCUSSION

SF_6 Input Function

During the injection period, SF_6 concentrations within Pond 2 ranged from the limit of detection to 286 pmol/L. Although the pond was never well mixed, the distribution of SF_6 did exhibit a consistent pattern defined by the pond's circulation, location of the diffusion stone (injection point), and gas lost across the air–water interface (Figure 4). The highest concentrations were found toward the northwestern end of the pond at stations 3, 4, 6, 7, 10, and 11. Station 5, which was the closest to the injection point, showed the highest variability. At stations 2, 8, and 9, SF_6 concentrations were generally below 5 pmol/L, and the tracer was never detected at station 1. These four stations were located at the southeastern end of the pond to both sides of the injection point and apparently received mostly water that was not tagged with the gas tracers.

The mean concentration of SF_6 in the pond, ~32 pmol/L, remained relatively constant during the 8-day injection period. Similarly, the mean concentration at the northwestern end, ~41 pmol/L, was also relatively constant. Based on the mean concentration, the mean percolation rate, and the length of time of the injection period, approximately 0.033 moles of SF_6 were transported to the subsurface by the recharging water. This is <5 percent of the total amount released. Thus, most of the tracer was lost to the atmosphere, demonstrating the inefficiency of bubbling SF_6 into shallow water bodies. Gamlin and others (2001) reported similar losses during the Orange County tracer experiment. A day after the injection was stopped, the concentration of SF_6 decreased to <0.1 pmol/L. This decrease is consistent with the very short residence time of water within the pond and losses by gas transfer across the air–water interface.

Water Balance

During the 18-month study, $\sim 47 \times 10^6$ m^3 of water was recharged during four distinct periods at the El Rio Spreading Grounds (Figure 3). During the first period, which resulted from the managed release of surface water from Lake Piru, only Ponds 2 and 3 were wet, and the tracer experiment was started. The second period of recharge coincided with the start of seasonal precipitation. Sufficient runoff was produced by the middle of November 2002 (day 55) to divert significant volumes of water into El Rio. During the next seven months, approximately 33×10^6 m^3 of surplus runoff was artificially recharged from six of the ponds. The wetting history for each pond differed. After a dry summer, recharge began once again on day 351, following a second release from Lake Piru. The final period of recharge was initiated by the return of seasonal precipitation on day 402.

During the first 250 days of the study, El Rio 2, 3, 5, 6, and 11 were usually operated at least 15 hours per day, whereas El Rio 7, 8, and 15 were rarely on, and El Rio 4 was closed because of equipment problems. Total groundwater production averaged 0.60 m^3/s, and 13×10^6 m^3 of water was produced. After day 250 (June 4, 2003), El Rio 7, 8 and 15 were operated 20–24 hours per day, and production at well 3 decreased significantly for the next 100 days (Table 2). El Rio 2, 5, 6, and 11 were still pumped heavily. During this 100-day period, the average production rate was slightly higher, 0.84 m^3/s, and 7.3×10^6 m^3 was produced. After day 350, groundwater production decreased to rates equal or below that observed during the first 250 days of the experiment. The average production rate for the final 200 days of the experiment was 0.45 m^3/s, and 7.8×10^6 m^3 was produced.

The water balance below the El Rio Spreading Grounds depends on two major components: rate of artificial recharge and groundwater production. At the monitoring well located next to Pond 1 (Figure 1), static groundwater levels show a rapid response to artificial recharge (Figure 3) and indicate fast recharge velocities. In the absence of artificial recharge, water levels slowly dropped due to groundwater production and the dissipation of the recharge mound. Although not shown at the monitoring well, large local cones of depression form near actively pumped production wells. The size and duration of these cones are highly variable and depend on the rate of production and local hydrogeology.

Groundwater Velocities and Tracer Arrival Times

After infiltrating, the tracer was transported more than 10 m through the unsaturated zone to the water table. The unsaturated zone contains three principal phases: sediment, water, and soil air. During transport, gas exchange between the water and soil air will occur. Thus, there is the potential of losing gas tracers from the tagged recharge water to the soil air during percolation. The amount of loss is dependent on the volume ratio of water and soil air, the percolation rate, Henry's law coefficient, the thickness of the unsaturated zone, and the duration of the tracer experiment. Because the transfer direction reverses once the dissolved tracer becomes undersaturated with respect to the soil air, the net effect of gas transfer within the unsaturated zone is retardation—the slower movement of gas tracers relative to the water (Fry et al., 1995).

Clark and others (2005) discussed the effects of trapped air on the transport of the gas tracers beneath the El Rio Spreading Grounds in a companion article. Using dissolved noble gas data and a second dissolved gas tracer (^3He), these authors demonstrate that the transport time during infiltration through the unsaturated zone is not significantly slowed by trapped air, nor is a significant percentage of the gases lost to the soil air. The rapid infiltration rate, moderately shallow water table, and non-equilibrium gas transfer between the percolating water and trapped air limit the magnitude of retardation (Clark et al., 2005). This result is not universal (e.g., Heilweil et al., 2004).

Once in the saturated zone, non-reactive gas tracers, like SF_6, ^3He, and other noble gas isotopes, are not retarded (Wilson and Mackay, 1996; Gupta et al., 1994, Fry et al., 1995; and Clark et al., 2004). By monitoring tracer concentration at wells, travel times of the initial detection, peak, and center of mass can be determined from the breakthrough curves (Table 1 and Figure 5). The initial arrival time represents the fastest flow paths between the well and where the tracer was introduced (Pond 2) and is the most relevant timescale for the draft regulations in California. At monitoring wells with narrow screened intervals, the arrival time of the center of mass represents the mean travel time of the tracer patch and can be used to calculate groundwater velocities. However, during this experiment only production wells were available. Because these wells draw water in from the entire length of screen, multiple flow lines with, presumably, different travel times are sampled. Therefore, these wells typically mix groundwater that contains

Table 2. *Monthly water and SF_6 mass balance. During the 18-month period, 6.09 × 10^6 m^3 of water was produced at El Rio 11.*

Month	Water Recharged (× 10^6 m^3)	El Rio 2 Water Prod. (× 10^6 m^3)	El Rio 2 SF_6 Prod. (%)	El Rio 3 Water Prod. (× 10^6 m^3)	El Rio 3 SF_6 Prod. (%)	El Rio 5 Water Prod. (× 10^6 m^3)	El Rio 5 SF_6 Prod. (%)	El Rio 6 Water Prod. (× 10^6 m^3)	El Rio 6 SF_6 Prod. (%)	El Rio 7 Water Prod. (× 10^6 m^3)	El Rio 7 SF_6 Prod. (%)	El Rio 8 Water Prod. (× 10^6 m^3)	El Rio 8 SF_6 Prod. (%)	El Rio 15 Water Prod. (× 10^6 m^3)	El Rio 15 SF_6 Prod. (%)
Oct-02	1.15	0.35	0	0.29	0	0.43	0.8	0.09	0.66	0.01	<0.01	<0.01	0	<0.01	0
Nov-02	0.41	0.36	0	0.38	0	0.41	4.51	0.02	0.42	0.05	0.18	<0.01	0	<0.01	0
Dec-02	2.93	0.06	0	0.33	0.02	0.40	7.81	0.28	4.73	<0.01	0.04	0.02	0.04	<0.01	<0.01
Feb-03	3.69	0.35	0.14	0.36	0.2	<0.01	0.03	0.32	2.56	0.03	0	0.09	0.07	0.01	0
Mar-03	5.95	0.42	0.17	0.40	0.05	0.11	1.09	0.28	1.78	0.03	0	0.08	0.01	<0.01	0
Apr-03	5.39	0.39	<0.01	0.34	0	0.32	1.97	0.22	0.74	0.01	0	0.11	0.36	<0.01	0
May-03	5.75	0.40	0	0.38	0	0.18	0.28	0.34	1.4	0.01	0	0.13	0.01	0.02	0
Jun-03	3.70	0.41	0	0.16	0	0.23	0.56	0.13	0.48	0.09	0.06	0.47	1.78	0.17	0
July-03	0.47	0.39	0	0.23	0	0.26	0.56	0.19	0.68	0.10	0.13	0.44	1.72	0.33	0.14
Aug-03	0	0.36	0	0.19	0	0.21	0.39	0.14	0.47	0.01	0.14	0.43	1.37	0.27	0.38
Sept-03	0.83	0.14	0	0.08	0	0.27	0.36	0.06	0.14	0.04	0.03	0.40	1.14	0.16	0.22
Oct-03	2.21	0.10	0	0.01	0	0.17	0.21	0.03	0.07	<0.01	0.03	0.18	0.42	0.25	0.26
Nov-03	1.66	0.18	0	<0.01	0	0.10	0.35	<0.01	0.07	<0.01	0	0.22	1.03	0.01	0
Dec-03	2.15	0.10	0	<0.01	0	<0.01	<0.01	<0.01	<0.01	<0.01	0	0.02	0.02	0.47	1.96
Jan-04	3.22	0.11	0	<0.01	0	0.03	0.01	<0.01	<0.01	<0.01	0	0.05	0	0.23	0.56
Feb-04	3.72	0.07	0	<0.01	0	<0.01	<0.01	0.01	<0.01	<0.01	0	0.03	0	0.44	0.16
Mar-04	5.52	0.31	0	0.01	0	0.02	0	0.11	<0.01	<0.01	0	0.02	<0.01	0.45	<0.01
Total	51.9	4.13	0.4	3.54	0.5	3.27	22.2	2.45	18.1	0.53	0.6	2.66	7.8	1.24	3.7

SF_6 = sulfur hexafluoride; prod. = produced.

tracer with unknown amounts of water that has not been tagged. Because the fraction of water tagged with tracer can change with time, velocity determined with either the peak concentration or the center of mass does not necessarily represent the mean groundwater velocity.

Within the first few weeks of the experiment, SF_6 was detected at two nearby wells, El Rio 5 and 6. These two wells lie within 10 m of the edge of the pond at opposite corners along the northeastern side (Figure 1). The arrival histories differ for a number of reasons including the distribution of tracer within the pond during the injection, flow distance, and production rates.

Tracer first arrived at El Rio 6 after 5 days, and the concentration reached a maximum at 20 days (Table 1 and Figure 5). This well is located near the northwestern corner of the pond (the high SF_6 concentration end) and is screened between 50 m and 92 m below the ground surface. Hence, flow to this well was predominantly vertical. The groundwater velocity calculated from the first arrival was 10 m/day. The maximum SF_6 concentration (10.6 pmol/L) was 26 percent of the mean concentration in the northwestern end of Pond 2, nearby this well (41 pmol/L), and 33 percent of the mean concentration of the entire pond (32 pmol/L). This decrease in concentration could be caused by hydrodynamic dispersion, gas loss within the unsaturated zone, or dilution with untagged water within the well (because of the relatively long screened interval). Assuming no dispersion or gas loss, recently recharged water tagged with SF_6 contributed at least 26 percent of the water pumped at the time of the maximum.

At El Rio 5, SF_6 was first detected on day 17 and the concentration reached a maximum after 82 days (Table 1; Figure 5). This well is located approximately the same distance from the edge of Pond 2 and is screened over approximately the same depth interval as El Rio 6. The relatively late tracer arrivals at El Rio 5 can be explained by poor mixing in Pond 2 during the injection period. Whereas El Rio 6 is located near the northeastern (high concentration) end, El Rio 5 is located at the southwestern (low concentration) end. During the injection period, SF_6 was never detected at Station 1, the closest station to El Rio 5. Therefore, tagged water had to flow both vertically and laterally to reach this well. Intensive groundwater production at El Rio 5, which averaged 1.3×10^5 m^3/day before the first arrival, created a local cone of depression, which probably contributed to this lateral flow.

Following the initial detections, tracer was observed in all samples collected from El Rio 6 and 5. Tracer concentration in both wells decreased nearly exponentially after peaking (Figure 5). This gradual decrease can be explained by the local water balance. Untagged water that was recharged after the tracer injection (especially from Pond 2) acted to flush the tagged water away from these two wells and to greater depths in the aquifer. Counteracting this was groundwater production that would draw the tagged water toward these wells.

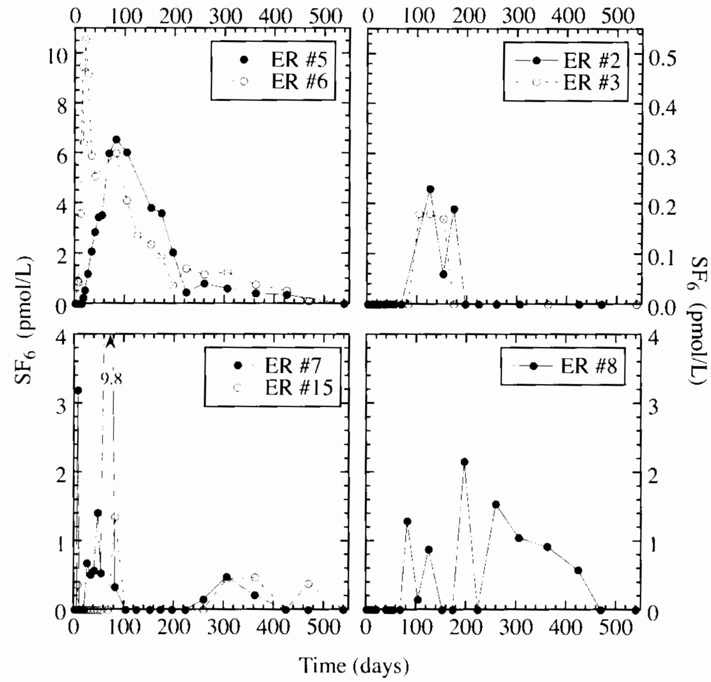

Figure 5. Tracer breakthrough curves at El Rio production wells.

The mass of SF_6 recovered at each well can be calculated from the daily production rates and concentrations, interpolated between measurement days. At El Rio 6, ~18 percent of the total mass of SF_6 that entered the ground was recovered (Table 2). Slightly more (~22 percent) was recovered at El Rio 5 (Table 2). Thus, 40 percent of the tracer contained in the recharge water was produced beneath essentially the same location where it infiltrated.

The very long period of detection and the very high recovery rates indicate that the tagged groundwater remained near these wells during the study period despite the large amount of artificial recharge that occurred during the winter and spring following the September 2002 recharge event. The regional cone of depression that surrounds the El Rio Spreading Grounds and groundwater extraction at the eight production wells prevented the tracer from being transported away from the spreading grounds.

At the more distant wells (2, 3, 7, 8, and 15), the tracer appeared at different times and concentrations. It was never detected at El Rio 11, the well farthest from Pond 2. Recharge rates, location, and production rates seem to be the principal factors governing detection of SF_6. At El Rio 2 and 3, SF_6 was detected after about 100 days for a relatively short period (Figure 5). The arrival occurred about 60 days after the start of the second recharge period. These two wells lie to the south of Pond 2 on the far side of Pond 1, the desilting basin, and Pond 5. The brief detection (~50 days) may be related to the second recharge event. For 50 days after the end of the injection period, the patch was free to spread radially from the injection point. However, after the initiation of the second recharge period, mounding occurred below the spreading basins (Figure 3), creating flow barriers and, presumably in some places, reversing the direction of flow. We speculate that the patch split, and a portion moved toward the southern wells. The rest of the patch flowed to the north and east and remained near the northern wells.

SF_6 was detected at El Rio 7, 8 and 15 multiple times during the study (Table 1). These wells lie to the west of Pond 2, on the far side of Pond 3, and they produced very little groundwater until day 250 (summer 2003). At 7 and 15, tracer was detected during the first 80 days of the experiment, before the second recharge episode (Figure 5). It was also detected during the summer of 2003, after the rate of recharge slowed and pumping at these wells increased significantly (Figure 5, Table 2). At El Rio 8, tracer was periodically observed after day 80 (Figure 5). It was only consistently detected after day 250, when intensive pumping began at this well (Table 2).

The history of SF_6 at El Rio 7 (Figure 5) clearly illustrates the effects of intensive local production on groundwater flow and on the tracer's detection at wells. SF_6 was first detected here after 26 days (October 24, 2002). This well is ~50 m from the northwestern corner (high-concentration end) of Pond 2. The concentration remained steady (0.5–0.7 pmol/L) for about two weeks while little water was produced from this well. On day 41 (November 7, 2002), intensive pumping was switched from El Rio 6 to 7 for 3 weeks. At El Rio 6, the 3-week average production rate decreased from 1.6×10^4 m^3/day to 0, whereas at El Rio 7, production increased from 0.6×10^4 m^3/day to 1.7×10^4 m^3/day. During this time, SF_6 concentrations increased significantly at El Rio 7, reaching a peak (9.8 pmol/L) a month later (day 68). Moreover, immediately after the intensive pumping stopped at El Rio 7, SF_6 concentrations decreased rapidly to less than 0.3 pmol/L. This decrease also coincided with the initiation of the second recharge period.

The concentration and duration of detection at the five distant wells were lower than at El Rio 5 and 6. Thus, the amount of SF_6 recovered by these wells was lower (Table 2). Nevertheless, 7.8 percent and 3.7 percent of the total mass of SF_6 that infiltrated were produced by El Rio 8 and 15, respectively. El Rio 2, 3, and 7 each produced less than 0.6 percent. The total recovery fraction at the seven wells where tracer was detected was 53.3 percent. This very high recovery fraction resulted from the very high groundwater production and the trapping of the patch near the ponds by the regional cone of depression.

SUMMARY

The very short residence time of water in the pond (~0.3 day) combined with the location of the diffusion stone created a complicated spatial input function of the tracer to the groundwater system. Therefore, direct measurements were required to define this function. These measurements showed SF_6 was successfully introduced into the recharge water, but significant variations in concentrations existed within the pond. Most important, the surface water monitoring revealed that parts of the pond received very little or no tracer. This spatial variability contributed to the late arrival of tracer to El Rio 5 relative to El Rio 6, both located ~10 m from Pond 2. Placing the diffusion stone closer to the inlet pipe would decrease this variation, although more of the SF_6 would be lost via the air–water gas transfer in the white water immediately downstream of the inlet. This loss could be offset by increasing the injection rate of the tracer.

Analysis of the tracer data from all the production wells during the 18-month study indicates that the tracer plume remained close to its point of entry and more than half of the recharged SF_6 was recovered. The location of the spreading grounds within a regional cone of depression trapped the recharge water near the ponds where it could be produced. This type of design could be used for storing high-quality surface water in aquifers that contain low quality or saline groundwater. Maintaining the regional cone of depression by extracting the low-quality or saline water would be necessary.

The movement of the tracer within the spreading area was influenced by two major factors. First, pumping at production wells located within the spreading grounds caused frequent changes in the water level by creating steep cones of depression, thus influencing the direction of the flow. Second, additional recharge events (lacking tracer) that occurred during the winter of 2002–2003 diluted and moved the tracer patch. In some cases, additional recharge created barriers (mounds) that prevented the patch from reaching wells. These effects were demonstrated during summer 2003, when a significant decrease in the amount of recharge water at the ponds, accompanied by increases in the pumping rate, allowed the tracer patch to be drawn toward El Rio 7, 8, and 15.

The deliberate tracer experiment was able to provide travel time information required by the California draft regulations. This information could also be used to provide a timescale for *in situ* water quality changes that may occur during transit. However, any interpretation of the travel time must recognize the complex flow pattern below the spreading grounds and the limited geographical area that was tagged by the tracer. Because the movement of the tracer was influenced by production and additional recharge periods, care must be taken when generalizing to all time periods.

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