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100-NR-2 Apatite Treatability Test: Fall 2010 Tracer Infiltration Test

White Paper

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April 2011



Pacific Northwest
NATIONAL LABORATORY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

A tracer infiltration test was run at the Hanford Site near Richland, Washington, to 1) determine whether field-scale hydraulic properties for the compacted roadbed materials and underlying Hanford formation sediments comprising the zone of water table fluctuation beneath the site are consistent with estimates based on laboratory-scale measurements on core samples and 2) characterize wetting front advancement and distribution of soil moisture achieved for the selected application rate. This initial tracer infiltration testing also provided data that would be used to evaluate and refine the geophysical and aqueous sampling methodologies for any future apatite amendment infiltration testing. Results from this field test would feed into the design for a Ca-citrate-PO₄ amendment infiltration test for evaluating the efficacy of using near-surface applications of amendments to form apatite mineral phases in the upper portion of the zone of water table fluctuation. If successful, this technology could be used to supplement the apatite permeable reactive barrier emplaced through saturated zone injections and increase the vertical extent of treatment to include the upper portion of the contaminant profile.

Section 1 provides the background for the testing, including a description of the testing site, the operational and monitoring systems that were used, and the analysis of the infiltration design. Section 2 describes the actual testing of the tracer infiltration system. This includes summaries of Tracer Tests #1 and #2. Section 3 provides the final conclusions.

The primary objectives of the pilot-scale tracer infiltration testing were met. The test successfully demonstrated that 1) the remaining 2 to 3 ft of compacted roadbed material below the infiltration gallery does not limit infiltration rates to levels that would be expected to eliminate near-surface application as a viable amendment delivery approach, and 2) the combined aqueous and geophysical monitoring approaches employed at this site, with some operational adjustments based on lessons learned, provides an effective means of assessing wetting-front advancement and the distribution of soil moisture achieved for a given solution application. Reasonably good agreement between predicted and observed tracer and moisture front advancement rates was observed. Additional work is needed to develop a working relationship between resistivity change and the associated change in moisture content so that 4D images of moisture content change can be generated.

Acronyms

3D	three-dimensional
AC	alternating current
DAS1	Data Acquisition System Model 1
ERT	electrical resistivity tomography
LIDAR	light detection and ranging
MPT	Multi-phase Technologies, Ltd.
NP	neutron probe
OD	outside diameter
PNNL	Pacific Northwest National Laboratory
PRB	permeable reactive barrier
PVC	polyvinyl chloride
RTK	real time kinematic

Contents

Summary	iii
Acronyms	v
1.0 Introduction	1.1
1.1 Site Description	1.2
1.2 Operational and Monitoring Systems	1.4
1.3 Infiltration Design Analysis	1.7
2.0 Tracer Infiltration Testing	2.1
2.1 Tracer Test #1	2.1
2.1.1 Operational Summary	2.1
2.1.2 Geophysical Monitoring	2.3
2.1.3 Aqueous Monitoring	2.7
2.1.3 Well Reconfiguration	2.9
2.2 Tracer Test #2	2.10
2.2.1 Operational Summary	2.10
2.2.2 Geophysical Monitoring	2.11
2.2.3 Aqueous Monitoring	2.18
3.0 Summary and Conclusions	3.1
4.0 References	4.1

Figures

1.1. Aerial Photo of the Treatability Test Site Location (photo taken in 2003).....	1.1
1.2. 100-N Apatite PRB Infiltration Treatability Test Site Location and Gallery/Well Layout	1.2
1.3. Geologic Cross Sections	1.3
1.4. 100-N Apatite PRB Infiltration Site Generalized Stratigraphy and Construction Detail for Wells C7039 Through C7046.....	1.4
1.5. Downstream Section of the Infiltration Gallery Showing the Drip Irrigation Lines and ERT Surface Electrodes	1.5
1.6. Portable Solar Array	1.6
1.7. Simulated Saturations for Elapsed Times (days): 0, 0.5,1,2,7, and 8	1.8
1.8. Simulated Conservative Tracers at Elapsed Times (days) 0.5,1,2,3,5, and 7	1.9
2.1. Tracer Application Rate—Tracer Test #1.....	2.2
2.2. Water-level Measurements During Tracer Test #1.....	2.2
2.3. Percent Difference in Inline Well ERT Measurements During the First Tracer Infiltration Experiment.....	2.4
2.4. Percent Difference in Cross-well ERT Measurements During the First Tracer Infiltration Experiment.....	2.5
2.5. Wetting Front Advancement as Measured With the Neutron Probe During the First Tracer Infiltration Experiment	2.6
2.6. Example of Moisture Drainage Following the End of Tracer Application.....	2.7
2.7. Saturated Zone Tracer Arrival—Wells 2 and 6, Which Are Both Located Within the Infiltration Gallery	2.8
2.8. Saturated Zone Tracer Arrival—Wells 1 and 5	2.8
2.9. Saturated Zone Tracer Arrival—Wells 3 and 4	2.8
2.10. Saturated Zone Tracer Arrival—Wells 7 and 8	2.9
2.11. Well Schematic Illustrating the Reconfiguration of the Two Wells Located Within the Infiltration Gallery	2.9
2.12. Tracer Solution Application Rate During Second Tracer Test.....	2.11
2.13. Water-Level Measurements During Second Tracer Test.....	2.11
2.14. Percent Difference in Cross-well ERT Measurements During the Second Tracer Infiltration Experiment.....	2.13
2.15. Finite-Element ERT Mesh Modeling Surface and Trench Topography.....	2.14
2.16. Time Lapse Cross-Sections of ERT Estimated Changes in Bulk Conductivity Extracted from 3D Inversion Results	2.16
2.17. Results of Saturated Zone Samples Collected During Second Tracer Test.....	2.19
2.18. Results of Vadose Zone Samples Collected During Second Tracer Test	2.19

Tables

2.1. Tracer Application Summary, Tracer Test #1	2.2
2.2. Tracer Application Summary, Tracer Test 2	2.10

1.0 Introduction

The primary objectives of a tracer infiltration test that was run at the Hanford Site near Richland, Washington, were to 1) determine whether field-scale hydraulic properties for the compacted roadbed materials and underlying Hanford formation sediments comprising the zone of water table fluctuation beneath the site are consistent with estimates based on laboratory-scale measurements on core samples and 2) characterize wetting front advancement and distribution of soil moisture achieved for the selected application rate. This initial tracer infiltration testing also provided data that would be used to evaluate and refine the geophysical and aqueous sampling methodologies for any future apatite amendment infiltration testing. Results from this field test would feed into the design for a Ca-citrate-PO₄ amendment infiltration test for evaluating the efficacy of using near-surface applications of amendments to form apatite mineral phases in the upper portion of the zone of water table fluctuation. If successful, this technology could be used to supplement the apatite permeable reactive barrier (PRB) emplaced through saturated zone injections and increase the vertical extent of treatment to include the upper portion of the contaminant profile. Figure 1.1 shows the test site area.



Figure 1.1. Aerial Photo of the Treatability Test Site Location (photo taken in 2003). The 1301-N Crib has been backfilled since this photo was taken.

1.1 Site Description

Eight dual-purpose boreholes were installed at the field test site (Figure 1.2), providing 1) unsaturated zone monitoring through vertical Electrical Resistivity Tomography (ERT) electrode arrays, 2) unsaturated zone monitoring through porous cup samplers, 3) access for borehole moisture logging with a neutron probe, and 4) a short well screen for collecting aqueous samples from near the water table interface. An additional well (C7329, see Figure 1.3) was installed as part of the apatite barrier expansion effort. Infiltration site boreholes were installed by the cable tool method using 8-in. nominal diameter drill casing, providing sufficient room for the 4-in.-diameter well completions and ERT electrodes/porous cups that were strapped to the outside of the polyvinyl chloride (PVC) permanent well casing. Before beginning the tracer tests, the wells were developed by pumping ~2 gpm for several hours from each well. In addition, some wells had to have river water pumped in during development to prevent the well from being pumped dry.

Generalized stratigraphy at the site based on characterization data collected during well installation is shown in Figure 1.3; a generalized well design diagram is shown in Figure 1.4. The stratigraphy of the site includes 5 to 6 ft of roadbed fill material overlying ~10 ft of coarse-grained sediments of the Hanford formation. The contact with the underlying Ringold Formation is at a depth of ~16 ft below ground surface (bgs). The water table at the site is highly variable because of changes in Columbia River stage and can range from as high as 6 or less ft bgs to 17 ft bgs or more during extreme low river stage conditions.

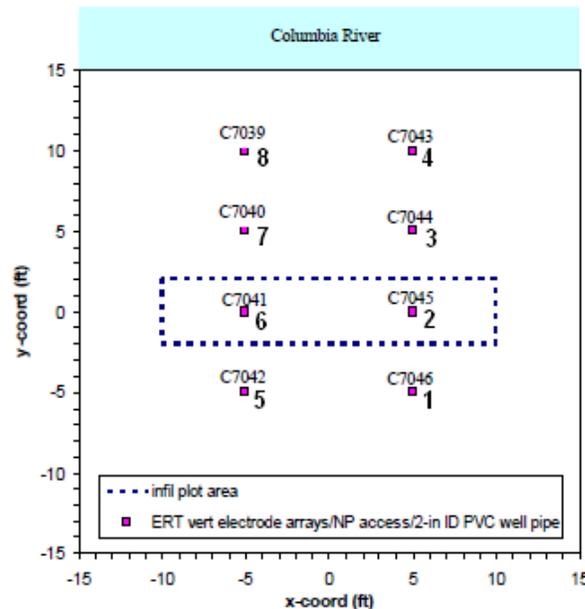


Figure 1.2. 100-N Apatite PRB Infiltration Treatability Test Site Location and Gallery/Well Layout (X-Y)

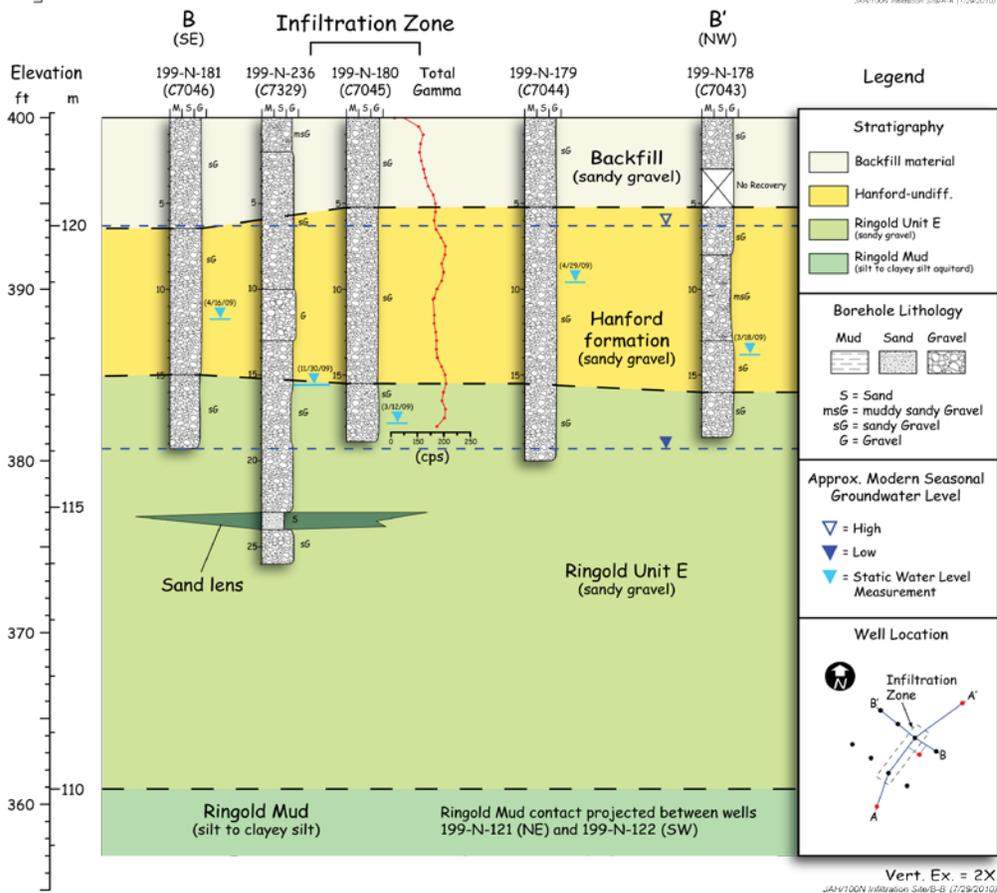
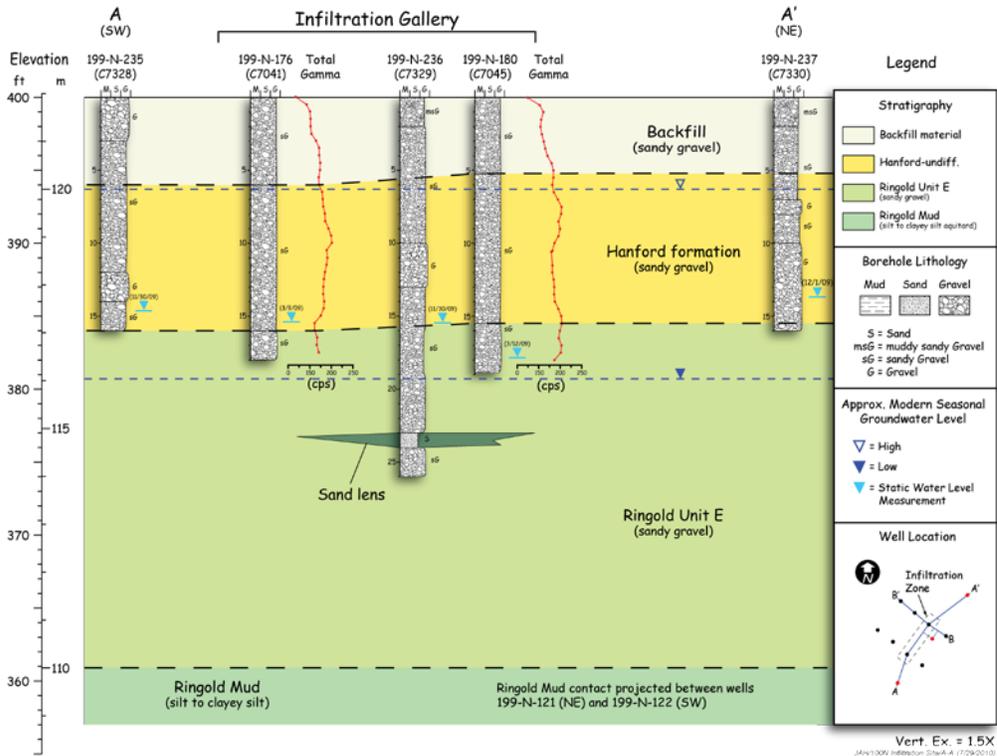


Figure 1.3. Geologic Cross Sections

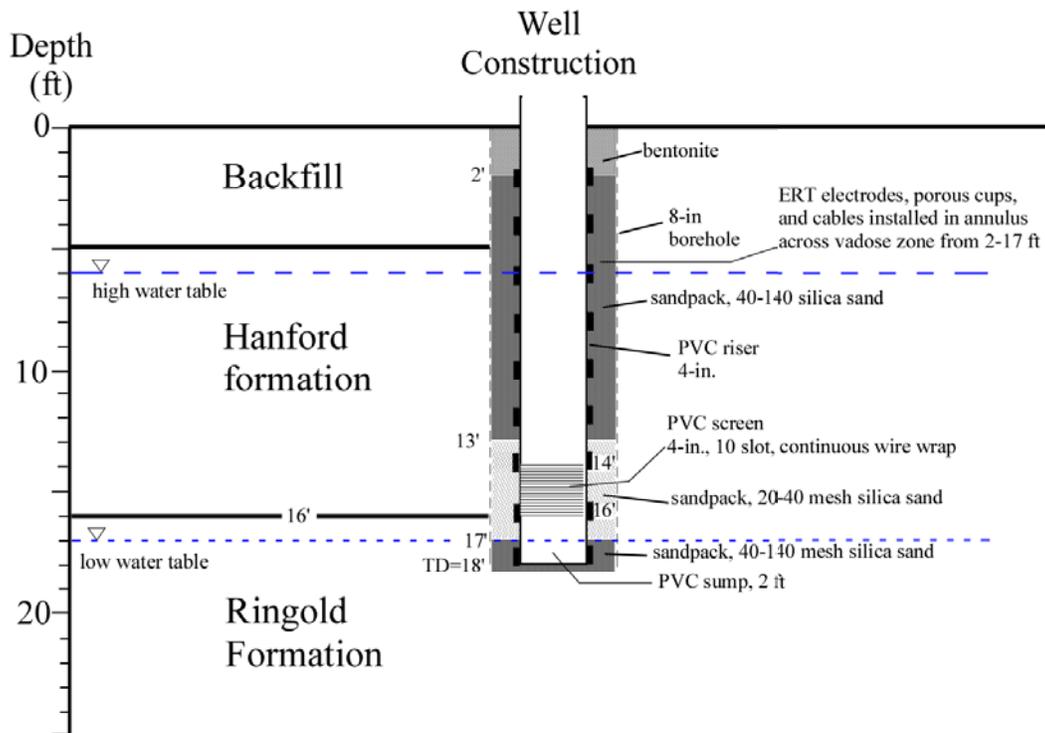


Figure 1.4. 100-N Apatite PRB Infiltration Site Generalized Stratigraphy and Construction Detail for Wells C7039 Through C7046

1.2 Operational and Monitoring Systems

During the tracer infiltration tests, the tracer solution was metered out onto the surface of the gallery through irrigation drip tubing fabricated with emitters spaced 1 foot on center (Figure 1.5). A large (5000 gallon) tank located near the upper 100N access road, which was elevated ~ 50 ft above the treatability test site, was used to store the bulk tracer solution. The tank was filled with filtered river water, and then the appropriate amount of sodium bromide was added to reach the target tracer concentration. During the test, the tracer solution was gravity fed using a pressure regulator to maintain a constant pressure in the drip lines, providing nearly constant solution delivery rates. The delivery rate was monitored continuously with a low-flow, turbine flowmeter and data logger.

Geophysical methods, including both electrical resistivity and neutron probe measurements, were used to characterize advancement of the wetting front during the tracer infiltration testing. Resistivity measurements were collected from both surface and downhole electrode arrays with a Multi-phase Technologies, Ltd. (MPT)-Data Acquisition System Model 1 (DAS1) monitoring system and wire wrap ERT cables procured from MPT in Sparks, NV. Each cable had 15 high-surface-area, wound stainless steel electrodes spaced 1 ft on center and optimized for vadose zone installations. This multi-channel system was designed to run on 120 V AC power. The system draws a dynamic load, which is dependent on both electrode sequencing and soil properties. Because no line power was available at the 100N infiltration test site and extended test times made using generators operationally challenging, a portable solar array along with a bank of 12-V, deep-cycle batteries was used to power the MPT-DAS1 system (Figure 1.6). This array was designed to run the MPT-DAS1 ERT



Figure 1.5. Downstream Section of the Infiltration Gallery Showing the Drip Irrigation Lines and ERT Surface Electrodes

monitoring system and associated logging computer, based on estimates of the power draw from the vendor's specifications. Initial testing during a short window of time that was available before infiltration began suggested that the solar array was providing enough power to run the system.

Once the first tracer infiltration test was initiated, the MPT-DAS1 auto-ranging function required more current than the solar array could provide. A small generator was used for supplemental power, but elevated loads and MPT system software issues led to power-related system malfunctions and loss of data continuity. The vendor was contacted for technical support and was able to provide a software update to improve power handling. In addition, a replacement ERT system was provided by the vendor on loan, though several days of downtime occurred. This loaner system was able to run on the solar battery array using the shorter cross-well raw data sequencing. Three-dimensional (3D) tomography sequencing required too much dynamic power to run with this loaner ERT system and the solar array. During the second infiltration experiment, an updated, vendor-supplied MPT-DAS1 system was capable of collecting both tomography and cross-well sequencing with power supplied by two new power transformers connected to the solar array, with periodic supplemental charging of the storage batteries with a gas powered generator.



Figure 1.6. Portable Solar Array

A sequence of ERT cross borehole resistance measurements was used as a relative indicator of wetting front development and movement. In these measurements, the positive transmitting and negative transmitting electrodes are in two different wells. The receiving electrodes are also positioned in this manner, but one electrode spacing is lower in the vertical plane. The advantage of this method is that power requirements are minimal, and a full sequence completes in less than 10 minutes for the given test site configuration. Also, these data can be directly plotted on a field computer with a charting program. Resistance values are shown as percent change from baseline to allow for comparative plotting. It is important to note that raw cross-well measurements are more sensitive to the near-well region, with the lowest sensitivity occurring halfway between the transmitting and receiving boreholes.

A more complex tomographic image sequence and inversion model is required to account for sensitivity, noise, and time lapse changes in the formation. Full 3D tomography measurements were performed with the 120-electrode downhole array and an additional 27 surface electrodes on 2.5-foot spacings (inline) to provide higher near-surface resolution. The combined 3D ERT array sequences combine both conventional inline dipole-dipole (AB-MN) in the same well and cross-well dipoles (AM-BN), where AM and BN are in different wells. Array definitions and descriptions are covered in Zhou and Greenhalgh (2000). Cross-well dipoles use transmitting electrodes in two different boreholes to increase current penetration within the formation and reduce current channeling effects (Bing and Greenhalgh 2000).

A complete sequence of both AB-MN and AM-BN electrode configurations was generated along with their reciprocals for error and noise filtering. This is a very large number of sequences that would require more than 24 hours to collect at the Apatite Treatability Test Site. For example, a complete data set for N number of electrodes for only a collinear multi-electrode array contains $N(N-1)(N-2)(N-3)/8$ independent nonreciprocal combinations (Xu and Noel 1993). A final more comprehensive data set

results from excluding the redundant configurations, noisy reciprocal sequences, very low-voltage measurements, and low transmitting currents (Stummer et al. 2004). The final optimized borehole sequence has 14,788 measurements, and 4.9 hours are required to complete a survey using a $1/4$ -Hz TDIP wave form produced by the MPT-DAS1 instrument.

Neutron Probe (NP) measurements were collected throughout the test period to characterize near-well changes in moisture content over time. This independent measure of moisture content, when used in conjunction with ERT results, can be used to develop 4D estimates of moisture content change throughout the test domain. NP measurements were obtained using a CPN International model 503DR Hydroprobe. At each well, measurements were collected at discrete depths starting at approximately 1 foot above the water table to 2 feet bgs in 1-foot increments. The sample acquisition time was 30 seconds for each measurement. A complete set of measurements was performed rapidly at the beginning of the infiltration and then approximately daily for the duration of the test. Before each set of measurements, chi (a measure of instrument value repeatability) and standard count values were determined using a depth-control stand, similar to the one described in Evett et. al. (2003), positioned at least 3 m from any neutron moderators, including the operator. A site-specific calibration was not performed; however, each of the neutron probes was calibrated with Hanford sand material following the procedure outlined in Hignett and Evett (2002) in *Methods of Soil Analysis. Part 4. Physical Methods*.

Aqueous samples from the saturated zone were collected before, during, and after tracer solution application by pumping water from the shallow zone wells using a peristaltic pump. Small-diameter ($3/8$ -in. OD) tubing was inserted into the well, with the end located at the approximately midpoint of the well screen. During sampling, wells were purged for several minutes until the field parameters had stabilized, indicating that the well had been adequately purged to provide a representative sample.

Aqueous samples from the vadose zone were collected with porous cup samplers. The porous cup samplers are made of a sintered stainless steel tube attached to a nested pair of polyethylene tubes. During sampling, a vacuum pump is connected to the inner tube, while the outer tube is capped off. This creates a negative pressure inside of the porous cup, which pulls water into the cup from the surrounding sediments. This vacuum is maintained from 10 to 60 minutes, at which point, the outer tube is uncapped, allowing sample water to flow up the inner tube into a sampling vial.

1.3 Infiltration Design Analysis

Scoping-level simulations were conducted to guide the development of a design for tracer infiltration testing. A description of this modeling effort and a summary of simulation results are provided in test-specific documentation (*Field Test Instruction, 100-NR-2 Apatite Permeable Reactive Barrier Treatability Test, September 2010 Tracer Infiltration Test*). Operational parameters that were investigated include application rates and test durations. Simulation results include transient subsurface moisture profiles and tracer concentrations at selected application rates/durations. These simulations used a range of material properties based on laboratory measurements on core samples collected from the site. Simulation results indicate that application rates ranging from 7 mm/hr to 1 cm/hr are favorable for the combined objectives of minimizing phosphate retardation while maintaining unsaturated conditions. Although lower application rates would make certain that unsaturated conditions were maintained, simulation results indicated that the total test duration could be excessive, depending on lateral spreading. Additionally, given the overarching project objective of infiltrating reactive and sorbing species

(e.g., phosphate and citrate-modified calcium amendments), which will require longer travel times than conservative tracers to reach the water table due to amendment retardation, lower application rates were deemed infeasible. Based on a modeling evaluation of these two competing design objectives, an application rate of 7 mm/hr was selected for the tracer infiltration test. Example simulation results are shown in Figure 1.7 and Figure 1.8.

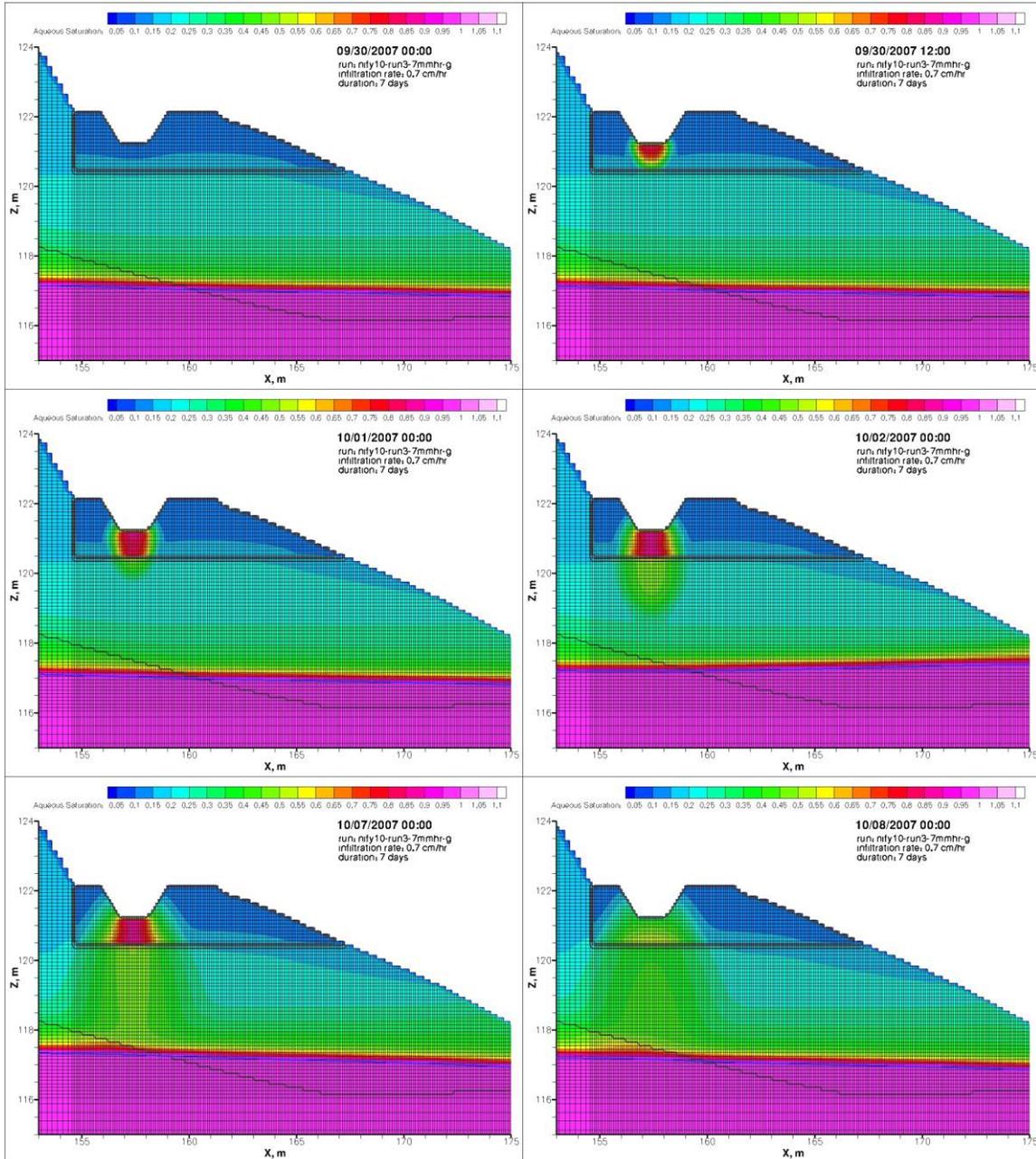


Figure 1.7. Simulated Saturations for Elapsed Times (days): 0, 0.5, 1, 2, 7, and 8

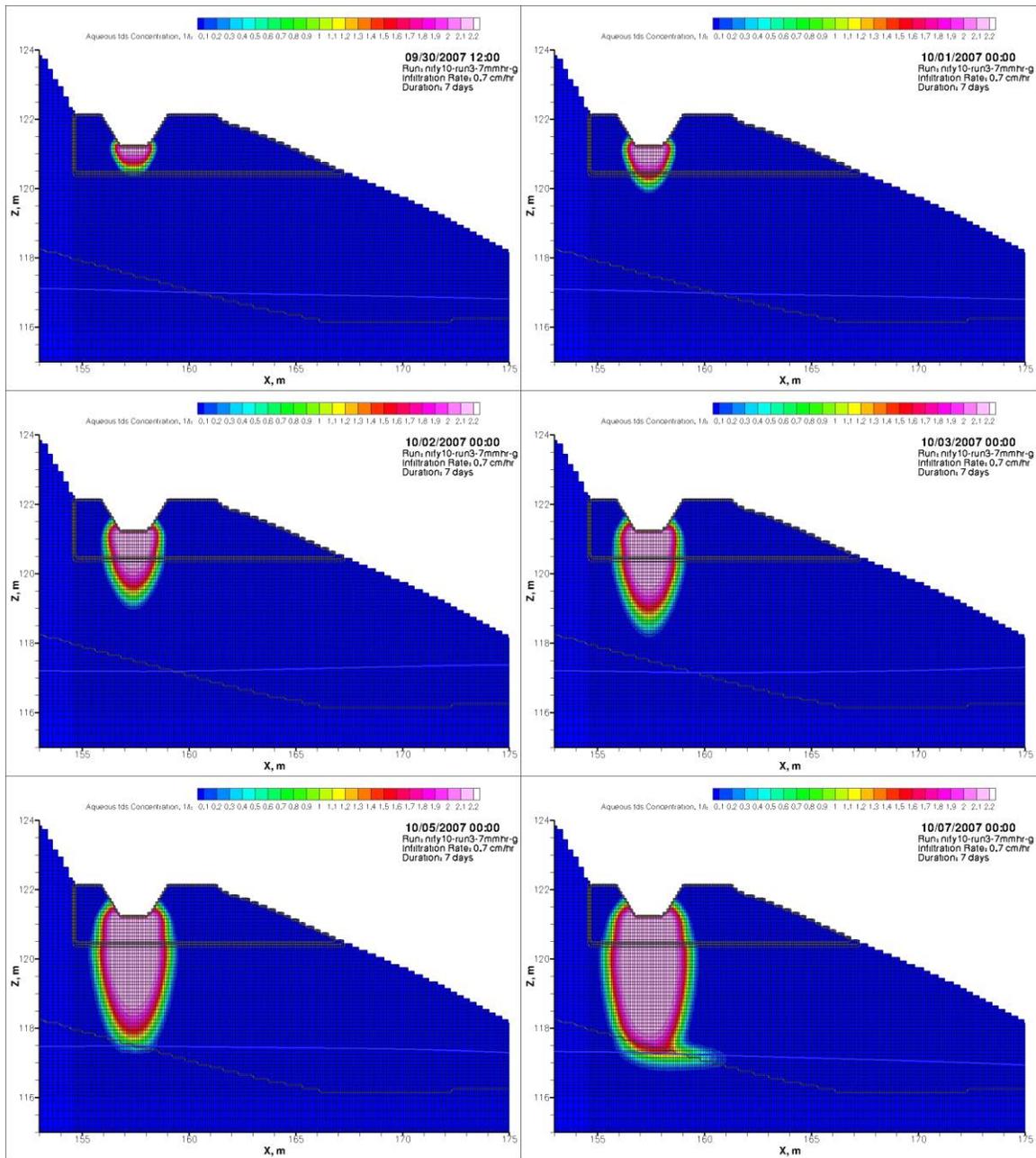


Figure 1.8. Simulated Conservative Tracers at Elapsed Times (days) 0.5,1,2,3,5, and 7

2.0 Tracer Infiltration Testing

The tracer infiltration testing approach that was adopted for the 100-NR-2 Apatite Treatability test can be divided into two general phases: the application phase and the soil column drainage phase. During the application phase, tracer was uniformly applied to the surface of the infiltration gallery using a drip irrigation surface distribution system. Continuous inline monitoring of flow rates and specific conductance as well as periodic collection of aqueous samples from the tracer solution stream were used to control and quantify the application rate, volume, and tracer concentration. The advancement of the wetting front was monitored with neutron probe and surface/subsurface electrical resistivity measurements.

Two separate tracer tests were conducted as part of this field testing campaign. Following the initial tracer test, it became evident that bentonite seals between the porous cup samplers were needed to hydraulically isolate the sampling interval and prevent preferential flow of tracer solution down the annular filter pack material. As discussed in Section 1.3, one of the objectives of the field test design was to utilize an application rate that would maintain unsaturated conditions throughout the sediment profile, thereby eliminating the potential for preferential flow down the annular fill material and/or other naturally occurring high conductivity vertical pathways. Although the test was designed to maintain unsaturated conditions, localized sediment saturation, likely at interfaces between formational heterogeneities, still occurred, and preferential flow down the gallery well filter packs resulted. Following the initial tracer test, well completions for the two sampling locations within the infiltration gallery were reconfigured to include alternating lifts of filter pack sand and bentonite seal material to depths of between 9 and 12 ft bgs. Once this reconfiguration was completed, a second tracer infiltration test was conducted to evaluate seal performance in the reconfigured wells.

2.1 Tracer Test #1

The application phase of the initial tracer test was conducted between September 28, 2010, and October 5, 2010, for a total duration of 7 days. During this test, a comprehensive set of aqueous samples was collected, and routine neutron probe measurements were made to monitor near-well changes in water content. However, due to a malfunction in the ERT acquisition system, full tomographic images of changes in interwell sediment resistivity were not available. A discussion of available resistivity measurements and their implications for assessing the advancement of the wetting front during the tracer test is provided in Section 2.1.2.

2.1.1 Operational Summary

During tracer experiment #1, over 2,400 gallons of tracer solution were applied over a 7-day period at an application rate of 0.7 cm/hr (Table 2.1). While there was some minimal ponding observed on the surface of the infiltration gallery (<0.5 inch), the application rate was sufficiently low that a quasi-steady-state condition was reached within a few hours, and the ponding depth remained constant. The tracer delivery rate showed diurnal variations of between 0.22 and 0.25 gpm (Figure 2.1), which were thought to be a function of changes in ambient temperature and their effect on drip-emitter performance. During tracer application, the water table varied by up to 4 feet in response to changing river stage (Figure 2.2).

This variation in water table elevation made interpretation of changes in water content associated with infiltration processes problematic for profile depths of greater than 12 feet bgs .

Table 2.1. Tracer Application Summary, Tracer Test #1

Test Start	9/28/10, 11:20
Test End	10/5/10, 11:35
Duration	168.3 hour
Volume Applied	2424 gallons
Average Application Rate	0.24 gpm (0.7 cm/hr)
Tracer Concentration	91 mg/L

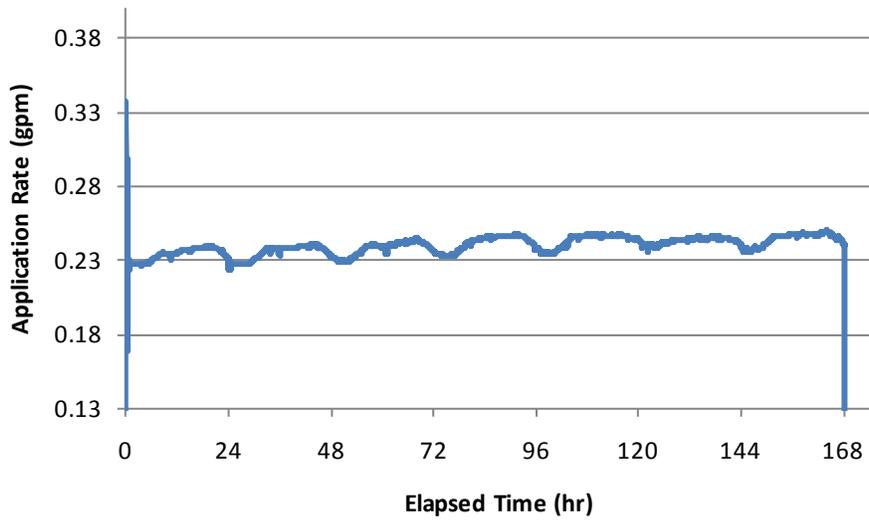


Figure 2.1. Tracer Application Rate—Tracer Test #1

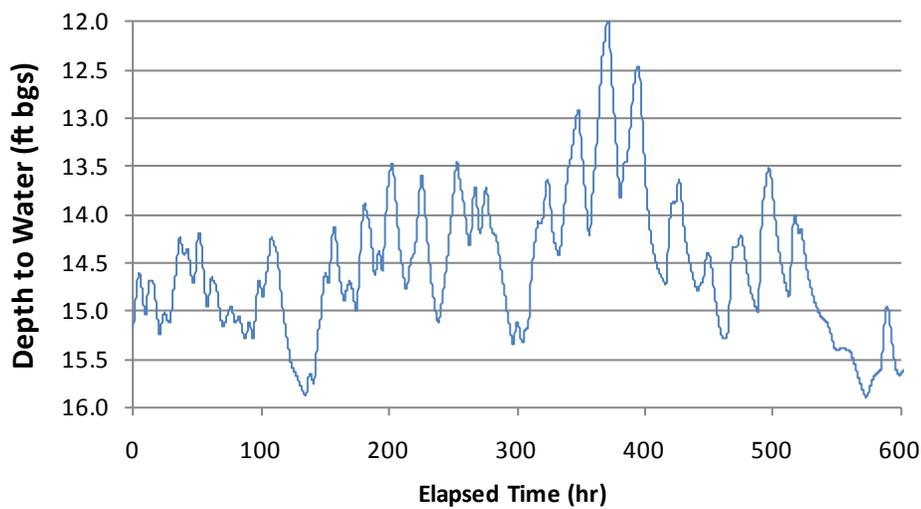


Figure 2.2. Water-level Measurements During Tracer Test #1

2.1.2 Geophysical Monitoring

During the initial tracer infiltration experiment, inline and cross-well measurements were collected with singular down-well electrode pairs and adjacent cross-well pairs. Tomography and larger cross-well spacings were not possible because of power limitations experienced during this test (see discussion in Section 1.2). Inline resistance measurements were collected down each borehole at 1-foot intervals (Figure 2.3). Inline measurements are sensitive to the immediate borehole area in a similar volume as the neutron moisture logs and are not expected to be sensitive to changes more than 1 foot into the formation. Gradual decreases in contact resistance (i.e., increasing moisture) were observed throughout the test period, providing indication of both percent saturation increase and wetting-front advancement.

Cross well pairs 5-6, 2-1, 6-7, and 2-3 all show an immediate lowering of resistance within the first 12 hours down to 15 feet bgs (Figure 2.4). All of these combinations of wells include a central infiltration gallery well. As electrode sensitivity is maximal near the well, a rapid lowering of resistance for wells located within the footprint of the infiltration gallery is an indication of preferential flow down the annular fill material. It should be noted that changes in resistivity for depths greater than 13.5 ft are associated with changes in the Columbia River stage (see Figure 2.2). Cross-well sequences 7-8, 8-4, and 4-3, which are outside the region expected to see significant changes in moisture content within the profile, exhibit minimal or smooth responses during the test period. The resistivity changes observed for cross well pairs 7-8 and 4-3 are likely associated with moisture changes in the wells adjacent to the gallery (Well 7 and 3).

Because the cross-well pair specifications used during the initial tracer infiltration test included a well within the gallery for all near-field measurements, results were strongly influenced by preferential vertical flow in the filter pack and thus were of limited use for assessing the advancement of the wetting front. Lessons learned during this first test were used to develop improved cross-well sequencing during the second field experiment.

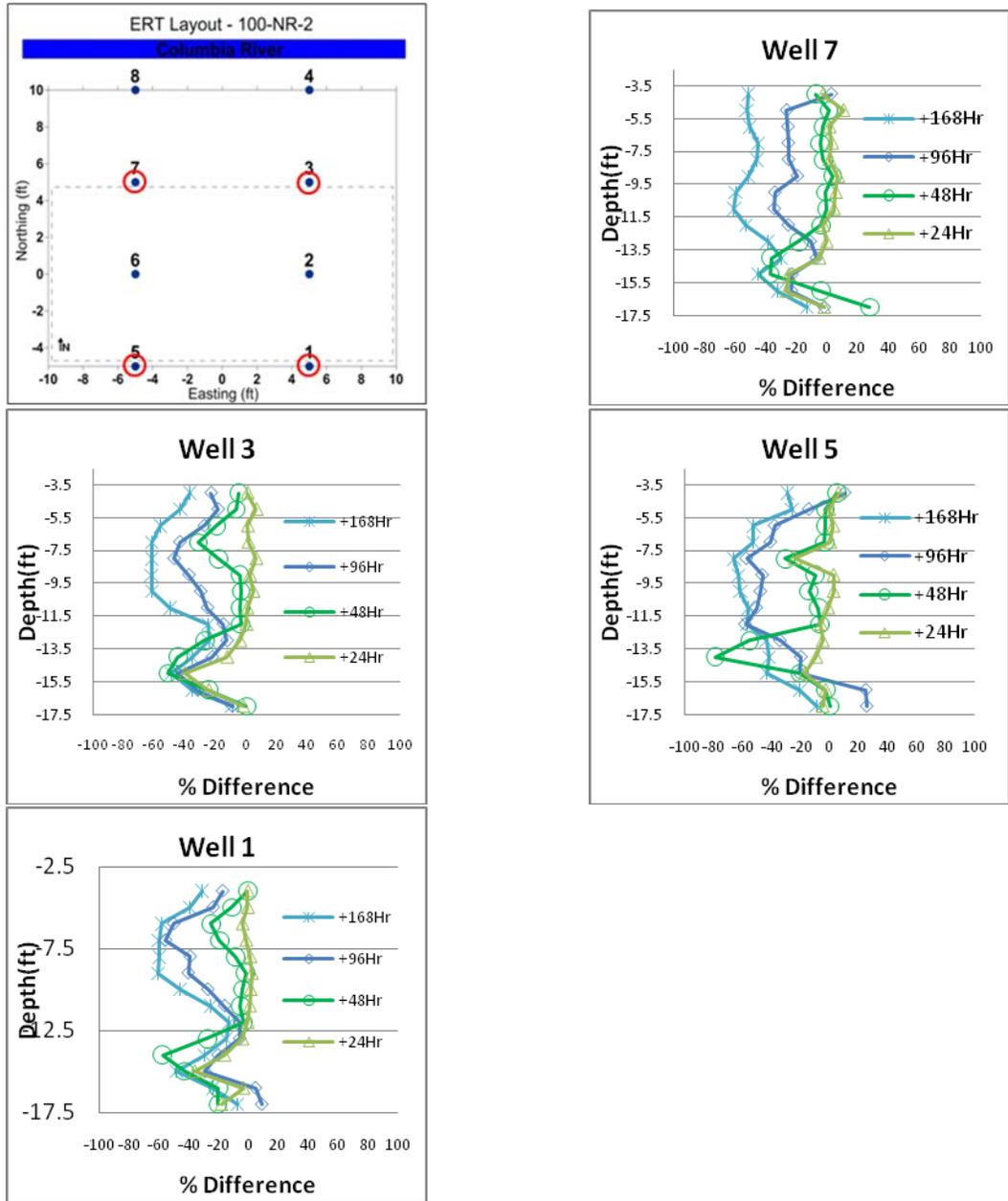


Figure 2.3. Percent Difference in Inline Well ERT Measurements During the First Tracer Infiltration Experiment

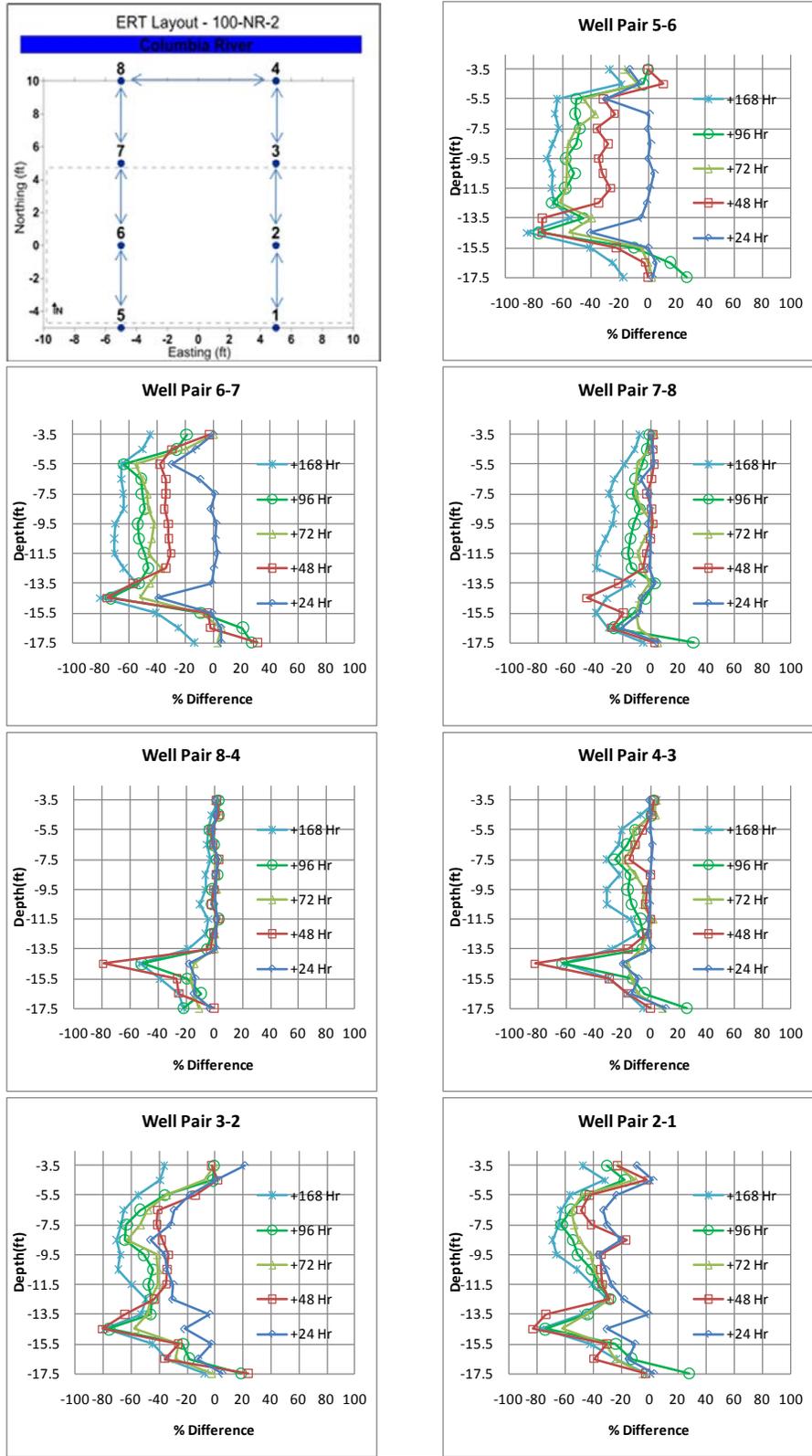


Figure 2.4. Percent Difference in Cross-well ERT Measurements During the First Tracer Infiltration Experiment

Measurements of near-well soil moisture content based on neutron probe measurements (Figure 2.5) were generally consistent with both the inline ERT measurements (see Figure 2.3) and the aqueous monitoring results (Section 2.1.3). In monitoring wells 2 and 6, high saturation levels were observed within the first several hours resulting from preferential vertical flows through the annular fill material. No vadose zone moisture content changes were observed in monitoring wells 4 and 8. In monitoring wells 1, 3, 5, and 7, it appears that moisture began to appear at the 11- to 12-foot depth interval by 100 hours into the tracer application. It is also interesting to note that all four monitoring wells had distinct peak moisture content measurements between 8 and 10 feet, which may be indicative of textural changes within the upper Hanford formation that were not identified in the lithologic description. Neutron probe measurements were also used to characterize the drainage phase of the experiment (Figure 2.6). The drainage was slow, with the moisture content still above baseline levels 220 hours after finishing the application of tracer solution.

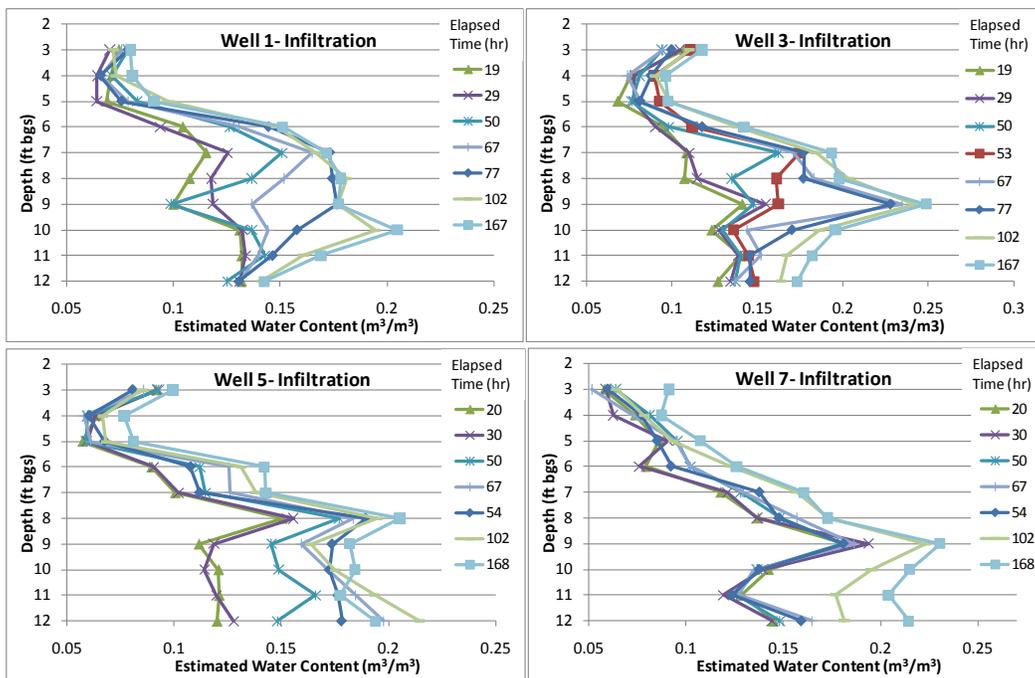


Figure 2.5. Wetting Front Advancement as Measured With the Neutron Probe During the First Tracer Infiltration Experiment

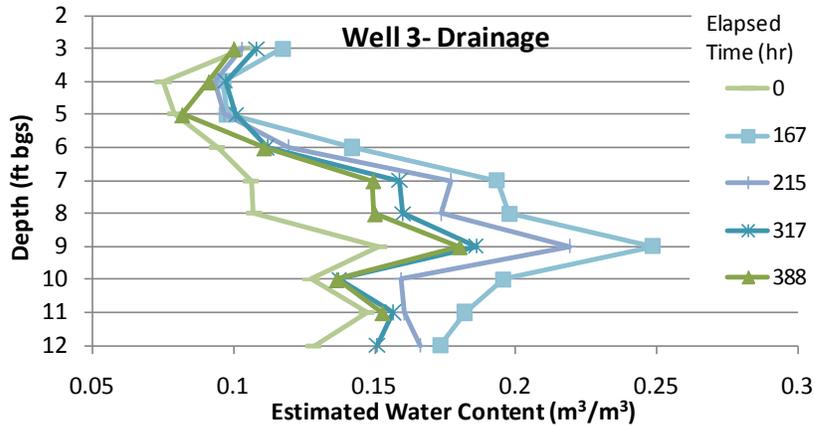


Figure 2.6. Example of Moisture Drainage Following the End of Tracer Application

2.1.3 Aqueous Monitoring

Shortly after the start of the tracer infiltration test, it became apparent that the bentonite seals at the ground surface were ineffective at preventing tracer solution from preferentially migrating down the filter pack and to the water table (Figure 2.7). As a result, vadose zone sampling, which is accessed with porous cup samplers located within the filter pack material, was abandoned. Well 2 in particular showed very quick tracer arrival. However, results from saturated zone aqueous samples collected in wells adjacent to the infiltration gallery indicate that the tracer movement through the vadose zone occurred at a rate consistent with that expected (Figure 2.8 through Figure 2.10).

Wells adjacent to the infiltration gallery (1, 5, and 7) likely are the most representative of the formational arrival, as samples from these wells would not be impacted by tracer solution that moved quickly through the filter pack sand. These three wells indicate that tracer solution was just beginning to reach the water table 120 hours into the tracer application, and maximum arrival occurred approximately 210 hours after the start of the test. These tracer arrival times are generally consistent with the predictive simulation results presented in Section 1.3 (see Figure 1.8). Well 3, and to a lesser extent well 4, were likely impacted by the tracer solution moving through the filter pack at well 2 and being transported downgradient, and this is are not thought to be representative of tracer movement through the vadose zone. It should be noted that wells 7 and 8 both made muddy water during sampling, indicating that the wells were not fully developed. A significant well skin could account for the delayed arrival at these two locations as the well may not have been in good hydraulic communication with the aquifer.

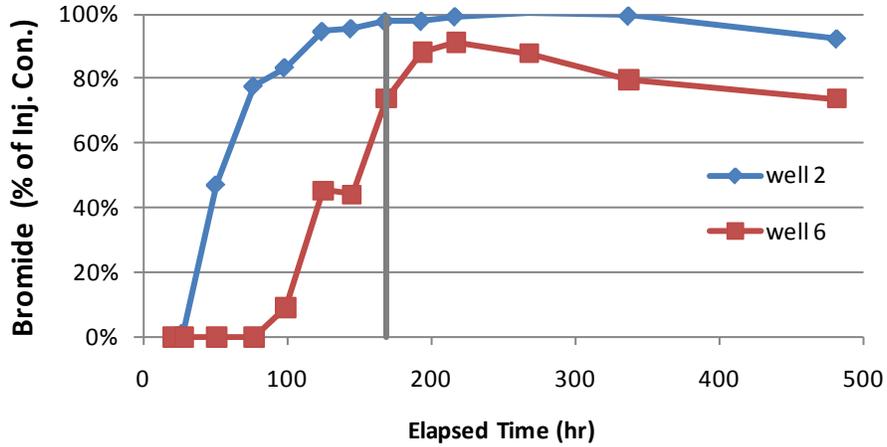


Figure 2.7. Saturated Zone Tracer Arrival—Wells 2 and 6, Which Are Both Located Within the Infiltration Gallery (vertical gray line depicts end of application phase)

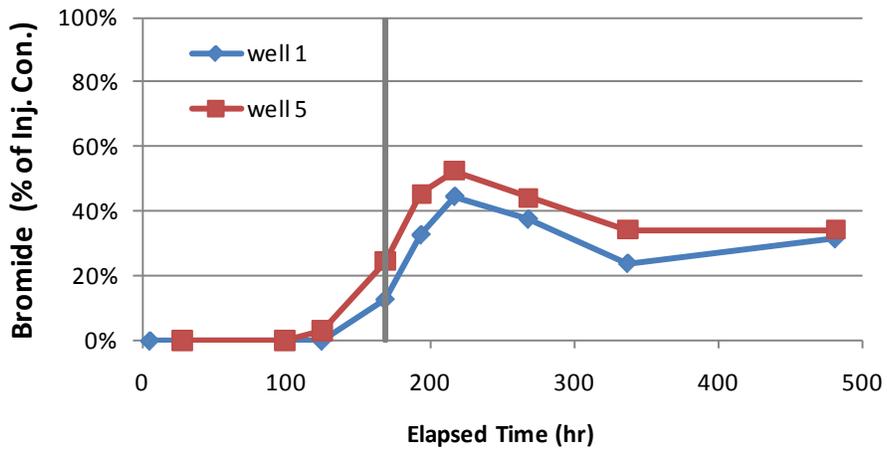


Figure 2.8. Saturated Zone Tracer Arrival—Wells 1 and 5 (vertical gray line depicts end of application phase)

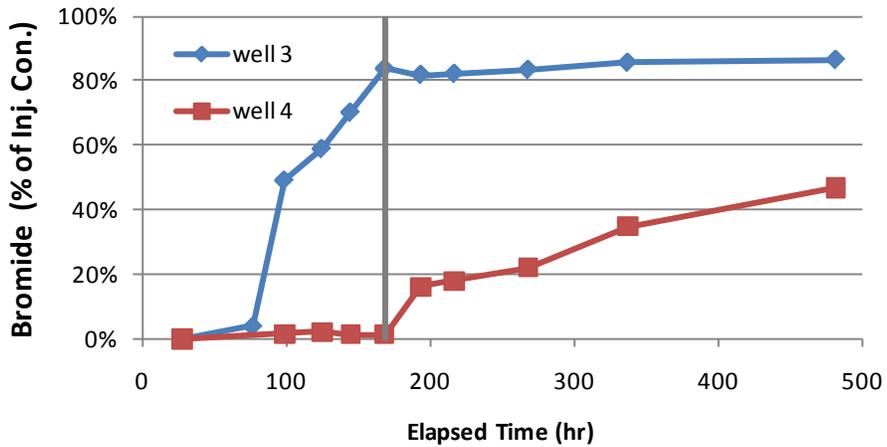


Figure 2.9. Saturated Zone Tracer Arrival—Wells 3 and 4 (vertical gray line depicts end of application phase)

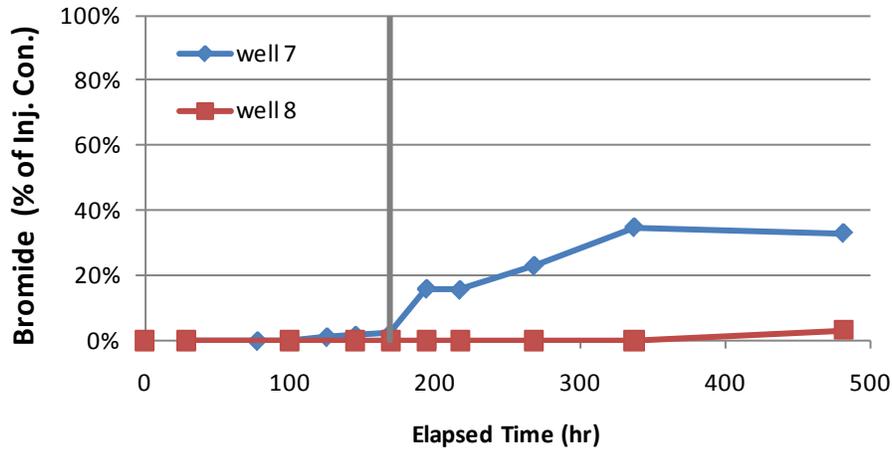


Figure 2.10. Saturated Zone Tracer Arrival—Wells 7 and 8 (vertical gray line depicts end of application phase)

2.1.3 Well Reconfiguration

As discussed previously, results from the initial tracer test provided evidence of the preferential vertical migration of tracer solutions through the annular fill material of the two monitoring wells installed within the infiltration gallery. To address this monitoring system deficiency, the filter pack was reconfigured with alternating layers of sand and bentonite (Figure 2.11). An industrial vacuum outfitted with PVC pipe attachments was used to remove the original filter pack material from the borehole to as deep as possible below the bottom of the infiltration gallery. Porous cup samplers were reinstalled in the middle of 1-foot-thick lifts of 100-mesh sand, with 1-foot-thick bentonite lifts between the sand layers.

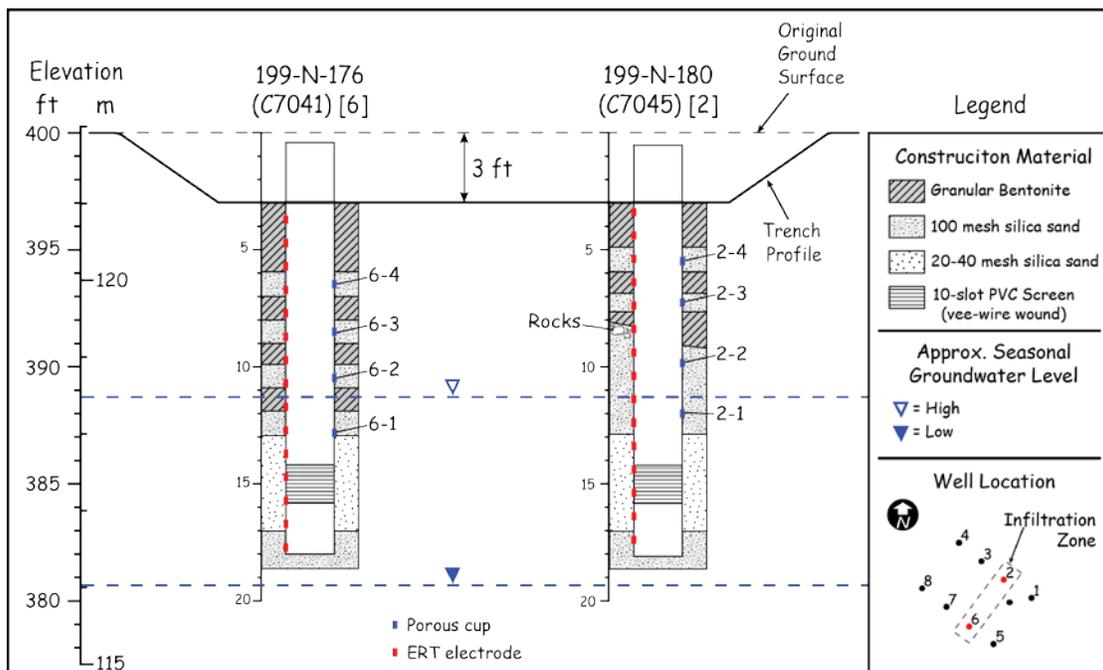


Figure 2.11. Well Schematic Illustrating the Reconfiguration of the Two Wells Located Within the Infiltration Gallery (see Figure 1.4 for original well construction detail)

2.2 Tracer Test #2

The application phase of the second tracer test was conducted between October 26, 2010, and November 2, 2010, for a total duration of 7 days. Due to budgetary constraints associated with conducting this supplemental field experiment, only a limited number of aqueous samples and neutron probe measurements were collected. Aqueous monitoring focused primarily on collecting samples from the porous cups because vadose zone samples were unavailable during the first test. In addition to the well reconfiguration discussed above, this tracer test was conducted with a fully functional ERT system in place, and a primary objective of the experiment was to collect a full electrical resistivity data set that could be used to assess the efficacy of using these geophysical measurements as a primary measure of wetting-front advancement. A discussion of available resistivity measurements, and their implication for assessing advancement of the wetting front during the tracer test, is provided in Section 2.2.2.

2.2.1 Operational Summary

During the second tracer test, over 2,200 gallons of tracer solution were applied over a 7-day period (Table 2.2). For this test, an initial application rate of 0.33 gpm (1 cm/hr) was attempted. At this application rate, significant ponding occurred very quickly, which required the tracer application rate to be reduced. Ultimately, the application had to be suspended temporarily to allow tracer solution to drain from the surface before resuming the test at 0.25 gpm (0.75 cm/hr) (Figure 2.12). After resuming the test, minimal ponding occurred on the surface of the infiltration gallery. During the second tracer test, the water table varied by a little less than 3 feet in response to changing river stages (Figure 2.13). This variation in the top of the water table made interpretation of infiltration results deeper than 13 feet bgs impossible.

Table 2.2. Tracer Application Summary, Tracer Test 2

Test Start	10/26/10, 10:23
Test End	11/2/10, 11:41
Duration	169.3 hour
Volume Applied	2259 gallons
Average Application Rate	0.25 gpm (0.75 cm/hr)
Tracer Concentration	156 mg/L

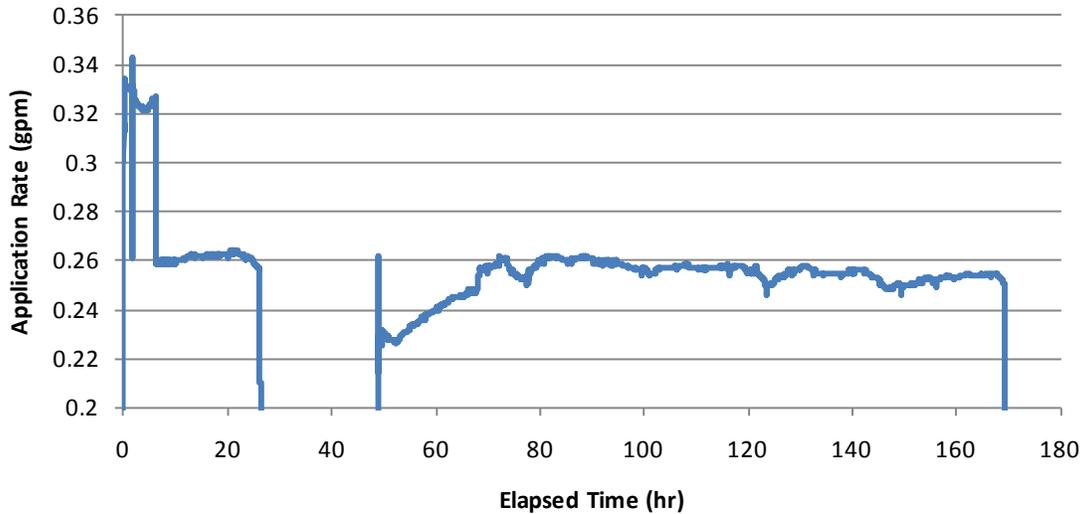


Figure 2.12. Tracer Solution Application Rate During Second Tracer Test

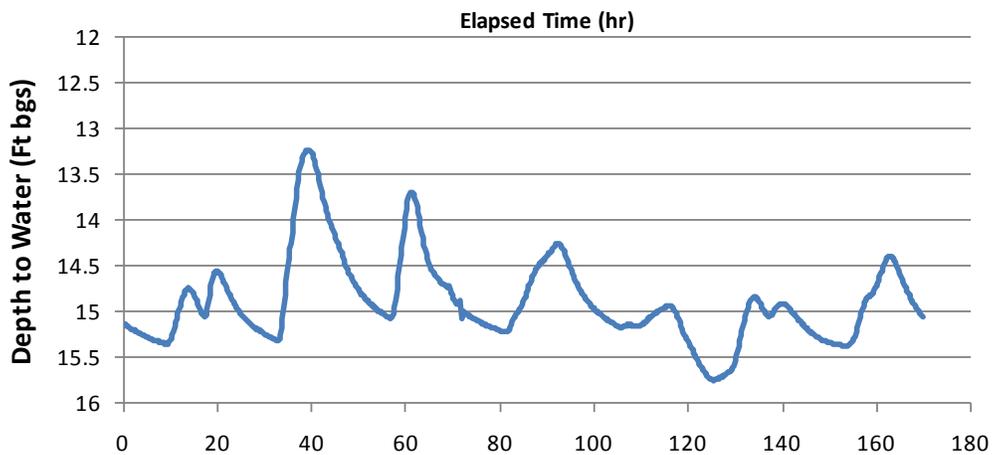


Figure 2.13. Water-Level Measurements During Second Tracer Test

2.2.2 Geophysical Monitoring

During the second tracer infiltration experiment, cross-well measurements were collected using the adjacent well pairs shown in Figure 2.14 (upper left). Although wells within the footprint of the infiltration gallery (see well pair 6-2 in Figure 2.14) were still impacted to some extent by preferential flow and continuing hydration of the recently installed bentonite seal material, other cross-well pairs provided a useful measure of wetting-front advancement. Cross-well sequences for wells located outside the gallery show little change for the first 2 days, followed by decreases in resistivity over time, with the highest changes in resistivity occurring over the 8- to 12-ft depth interval. This resistivity change distribution is consistent with the expected moisture change profile for these well locations (i.e., they are located outside the footprint of tracer application, so shallow depths would be expected to see less increase in moisture).

The sensitivity of these measurements for accurately assessing wetting-front advancement is weighted towards monitoring locations outside of the gallery where changes are more gradual and have the lowest sensitivity to artifacts associated with the gallery wells. The gradual change seen for all of these wells indicates that the moisture content was changing across the full domain delineated by wells 1, 3, 5, and 7. However, some differences within this domain were observed. For example, a comparison of well pairs 7-3 and 5-1 shows that the wetting front arrived sooner at the 9.5-ft depth in the 5-1 well pair. The 5-1 well pair also provides a good example of advancement of the wetting front between the 48- and 96-hour measurements when maximum resistivity change advanced from 9.5 to 11.5 ft bgs.

Full 3D ERT datasets were collected twice daily from the beginning of the test until Nov. 16, 2010, comprising both surface and borehole resistivity measurements. The forward modeling and inversion mesh is shown in Figure 2.15. Surface topography was constructed using local light detection and ranging (LIDAR) and real time kinematic (RTK) measurements near and within the trench.

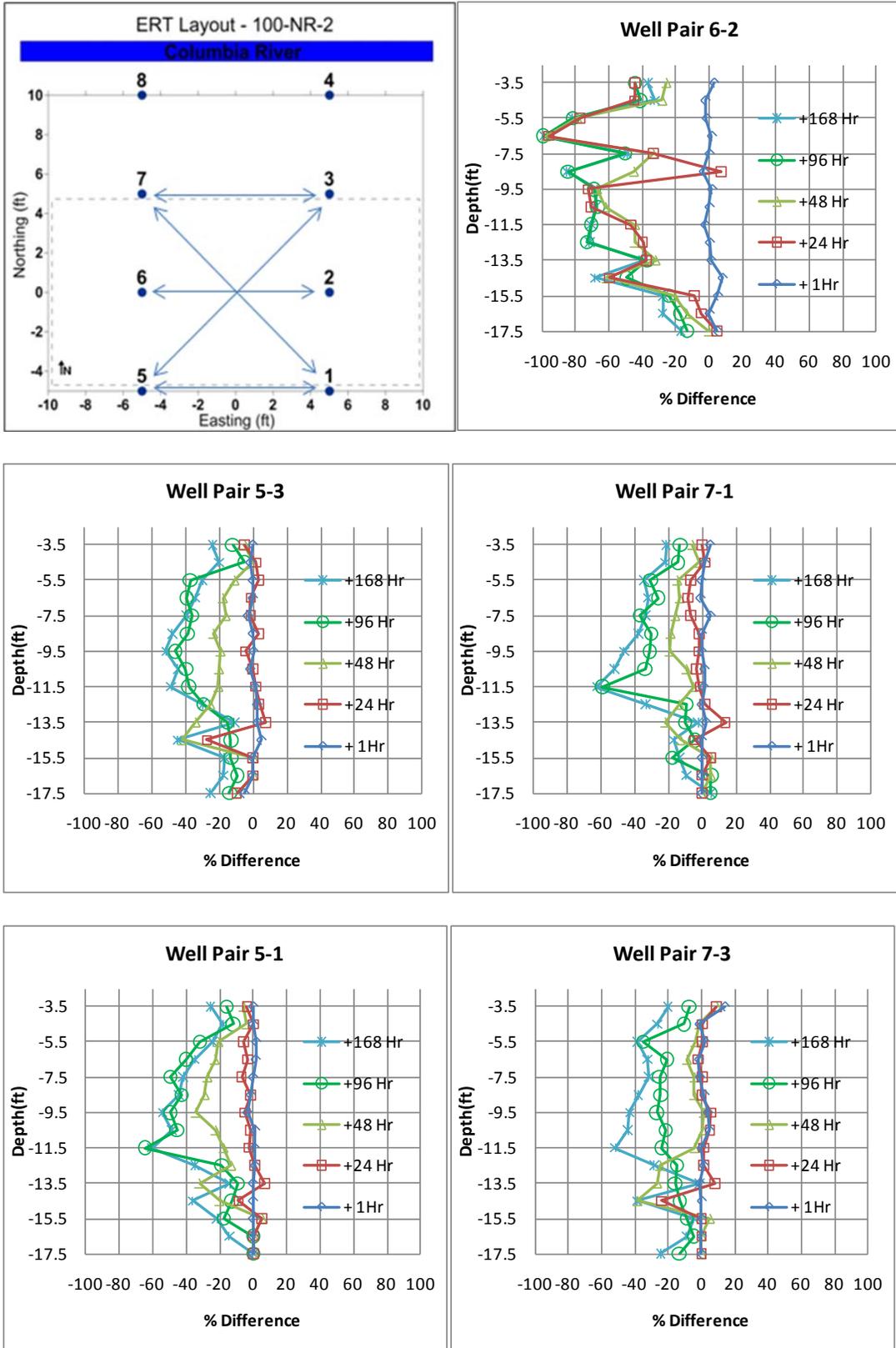


Figure 2.14. Percent Difference in Cross-well ERT Measurements During the Second Tracer Infiltration Experiment.

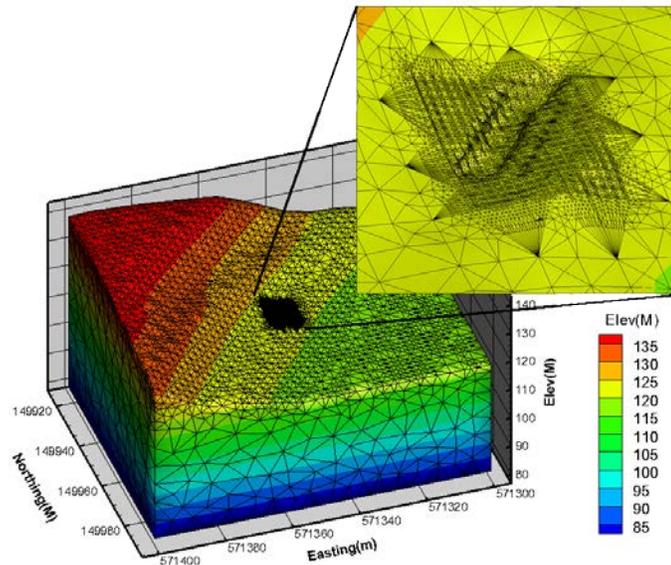


Figure 2.15. Finite-Element ERT Mesh Modeling Surface and Trench Topography

Time-lapse changes in 3D electrical conductivity were estimated by inverting each ERT data-set and subtracting the results from a baseline inversion using the FERM3D code running on the Chinook Supercomputer located at Pacific Northwest National Laboratory (PNNL) (Johnson et al. 2010, Versteeg and Johnson 2008). The difference between the time-lapse inversion and the baseline inversion indicate where conductivity is changing with time. Bulk electrical conductivity increases with both fluid conductivity and with saturation, so increases in electrical conductivity are indicative of the combined effect of these two parameters, both of which change as a direct result of tracer solution infiltration.

Under ideal conditions, the background data set is collected under natural background conditions. For this case, that would have been after the bentonite lifts were installed. It is likely that the bentonite was not completely saturated at the start of the second infiltration test, so it was not possible to collect a background data set under steady-state electrical conditions. Therefore, we used the Nov. 16, 2010, data set (i.e., approximately 2 weeks after infiltration ended) as the background data set. This becomes important when interpreting several features of the time-lapse imaging results. For instance, the bentonite lifts display a negative change in conductivity at the beginning of the test that disappears as the bentonite saturates during infiltration. In addition, the persistent high-conductivity anomaly at the water table near wells 7 and 8 may be caused by a relatively low conductivity in the background, by which time all tracers had migrated out of this downgradient area.

Selected cross-sections of the inversion results are shown in Figure 2.16. The left and right sections show changes in conductivity along the planes intersecting wells 4-3-2-1 and 8-7-6-5, respectively. Note that bentonite lifts were installed within wells 2 and 6 just before the second tracer infiltration test (see Section 2.1.4) to reduce preferential flow within the annulus.

The ERT images are in general agreement with the pre-test modeling. Early in the test, the tracer appears to be moving around the bentonite lifts. However, this is likely an artifact of the background data set and the hydrating bentonite, as discussed previously. The 60-hour image shows the pulse of tracer from the initial high infiltration rate reaching the water table. Taking into account changes in application

rate, the ERT monitoring suggests a relatively uniform distribution of tracer below the trench by the end of infiltration in each section shown.

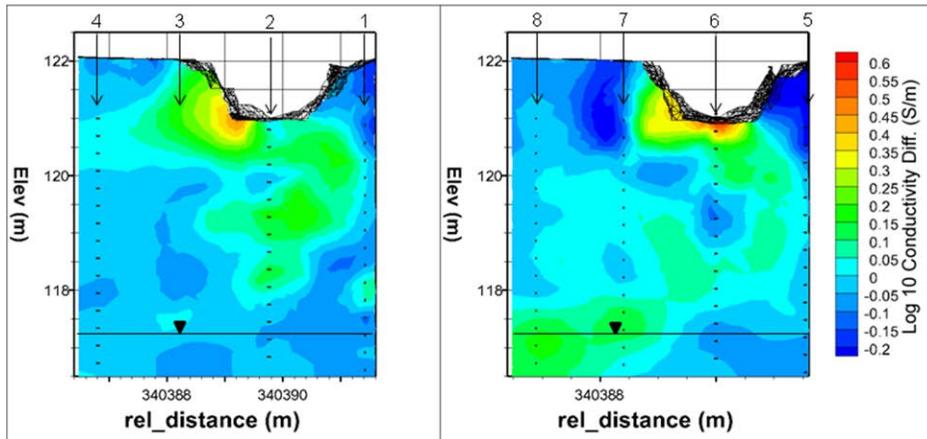
The ERT images are also generally consistent with the aqueous monitoring results discussed in Section 2.2.3, which suggest preferential flow in well 2 and a corresponding fast breakthrough in well 3 (and 4). The 8-7-6-5 transect suggests a breakthrough in well 7 sooner than indicated by the aqueous monitoring results. This discrepancy can be explained by the apparent poor hydraulic communication between wells 7 (and 8) and the surrounding aquifer sediments (see Section 2.1.3). In addition, the persistent elevated conductivity in this region may be caused by a corresponding decreased conductivity in the background image as discussed previously.

As mentioned previously, given the conditions of this test, changes in bulk conductivity are governed by changes in fluid conductivity and changes in saturation. If we assume uniform hydrogeologic properties and a constant change in fluid conductivity (e.g., from background conductivity to tracer conductivity), then changes in bulk conductivity are highly correlated to changes in saturation, which can be measured with borehole neutron logging. If the constant fluid conductivity change assumption is valid (where changes actually occur), then the relationship between changes in bulk conductivity and saturation can be calibrated with neutron logging data and co-located ERT inversion results. This would allow 4D estimates of changes in saturation based on the ERT results. Neutron logging was conducted during the second tracer test to support this effort. However, due to budget constraints and the extensive monitoring conducted during the first test, only a handful of measurements were made. Additional work is needed to develop this relationship for potential future applications at the site.

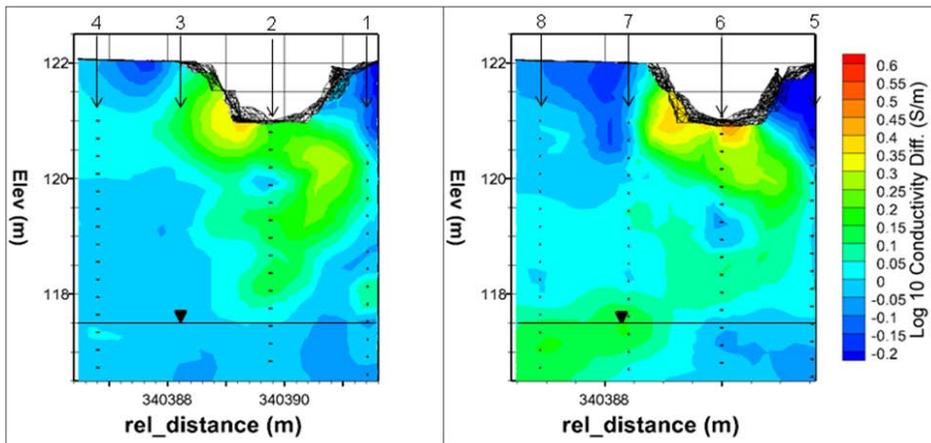
The following lessons learned during this field campaign will be considered during any future applications of the technology:

1. ERT imaging resolution is directly related to data quality, or to the level of “noise” in the transfer resistance measurements. Noise levels are significantly reduced when electrodes are well coupled with the subsurface. When the solid phase is resistive, electrical coupling relies primarily on the contact area between electrodes and pore fluids and is therefore often compromised in unsaturated zone environments. Such is the case for the infiltration test, resulting in a significant loss of data (approximately 30%). This condition was partially mitigated during the second tracer test through the well reconfiguration activities that were performed on wells 2 and 6. The data quality can be improved by encasing electrodes in a small amount of bentonite or by grouting electrodes in place with a resistive grout. If bentonite is used, as was the case at this site, it should be installed in small lifts around each electrode separated by resistive fill material. Bentonite is conductive, and larger (or continuous) lifts can cause short-circuit pathways between electrodes, which can violate the point source assumption necessary in modeling and inversion codes. During future field experiments, it is expected that the bentonite lifts that were installed and that have been well hydrated during the second tracer test will result in a significant improvement in data quality.

Elapsed Time (hrs): 12



Elapsed Time (hrs): 24



Elapsed Time (hrs): 60

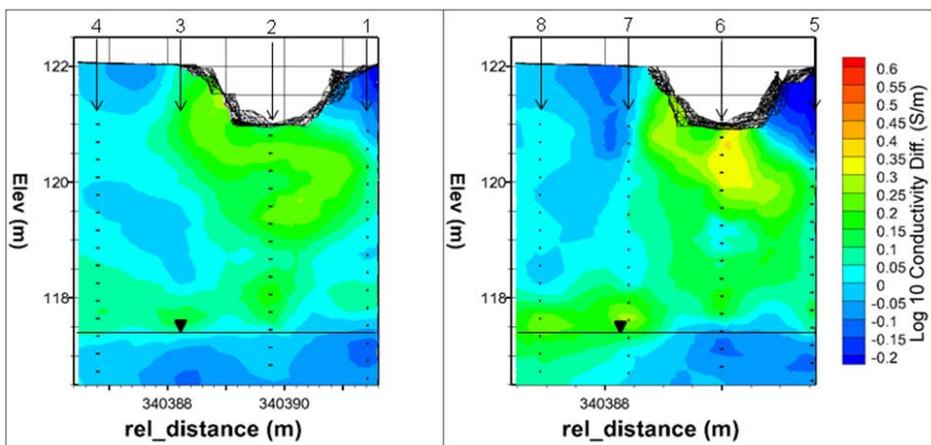
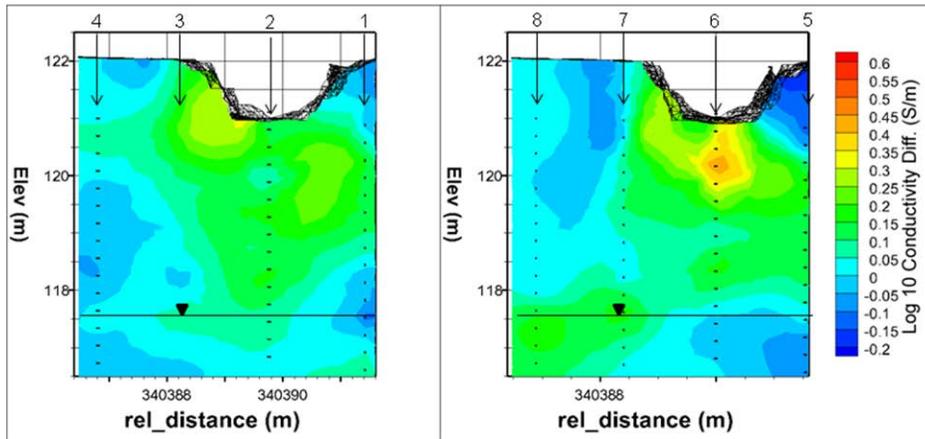
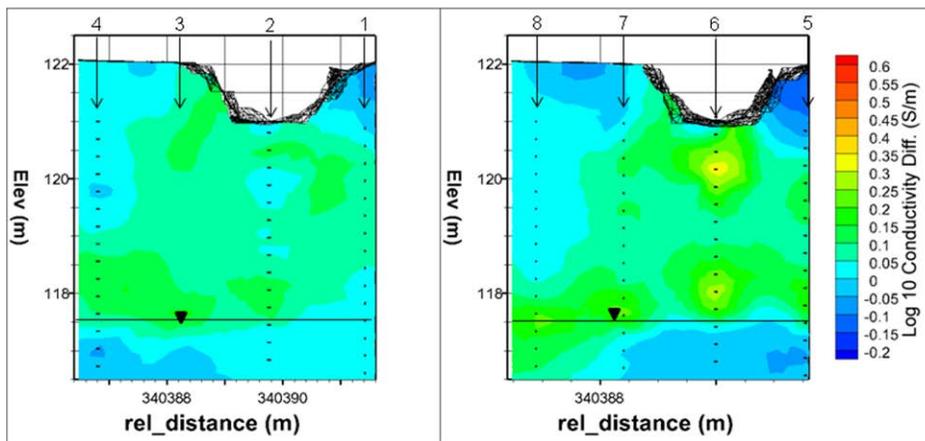


Figure 2.16. Time Lapse Cross-Sections of ERT Estimated Changes in Bulk Conductivity Extracted from 3D Inversion Results

Elapsed Time (hrs): 96



Elapsed Time (hrs): 168



Elapsed Time (hrs): 192

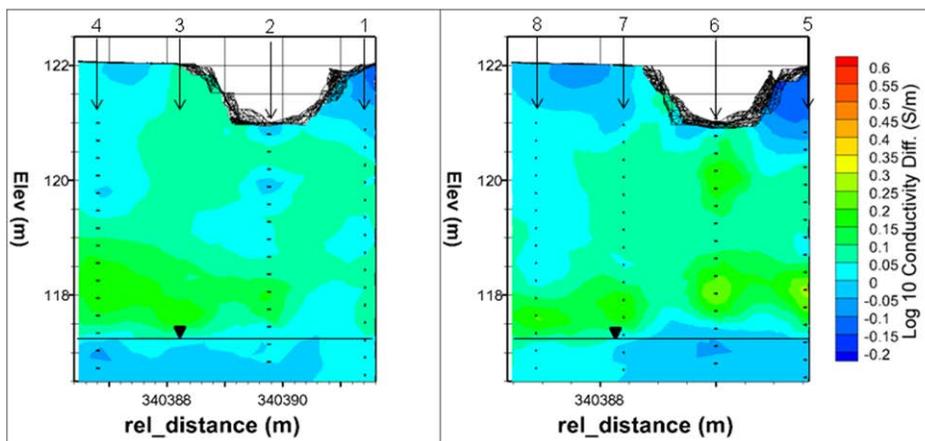


Figure 2.16 (contd)

2. Current ERT data systems are capable of collecting large amounts of data in short periods of time. This enables time-lapse ERT to image with high temporal resolution. This capability was not leveraged fully during the infiltration test because of power limitation. During future field experiments, the power supply (i.e., larger solar array and/or more batteries) will be upgraded to allow for greater temporal resolution in ERT imaging. An adequate power supply should allow for more full 3D surveys per day. Only two surveys per day were collected during this test.

2.2.3 Aqueous Monitoring

Only a limited number of saturated zone aqueous samples were collected during the second tracer test. This was because the initial tracer test provided adequate characterization of the tracer solution arrival in the saturated zone, and a second full dataset could not be collected within budget. The samples collected in the saturated zone indicate that the reconfiguration of well 2 was not sufficient to prevent tracer from moving vertically through the filter pack (Figure 2.17). This is demonstrated by the early arrival time and high bromide concentrations observed in well 2; these concentrations were not a result of residual tracer remaining from the first test because the solution used for the second tracer test had a higher bromide concentration than the initial test.

The increase in bromide concentration observed in wells 3 and 4 (downgradient of 2) indicate significant tracer arrival, which is likely associated with the preferential vertical flow at well 2. However, it also appears that partway through the test, the bentonite seals in well 2 may have hydrated sufficiently to provide an effective seal. After 120 hours, the upper two porous cup samplers no longer produced samples, providing indication that moisture content of the filter pack material over this interval had been reduced. This drying likely occurred because the bentonite seals installed during the reconfiguration were not fully wetted during installation and had not had sufficient time to expand fully when the test began. This resulted in the tracer solution bypassing the seals during the early portion of the test, but also provided excess water that resulted in full hydration and better sealing of the plugs. The additional ponding that occurred early during the second tracer test likely also contributed to the leakage through the filter pack of well 2.

While there appeared to be leakage through the filter pack of well 2, the reconfiguration of well 6 appeared to prevent leakage during the second tracer test. The vadose zone samples indicated an early arrival at the shallowest location, with a delayed arrival at deeper sampling points. And the deepest vadose zone sampling location where samples were collected had an arrival curve very similar to samples collected from the saturated zone (Figure 2.18).

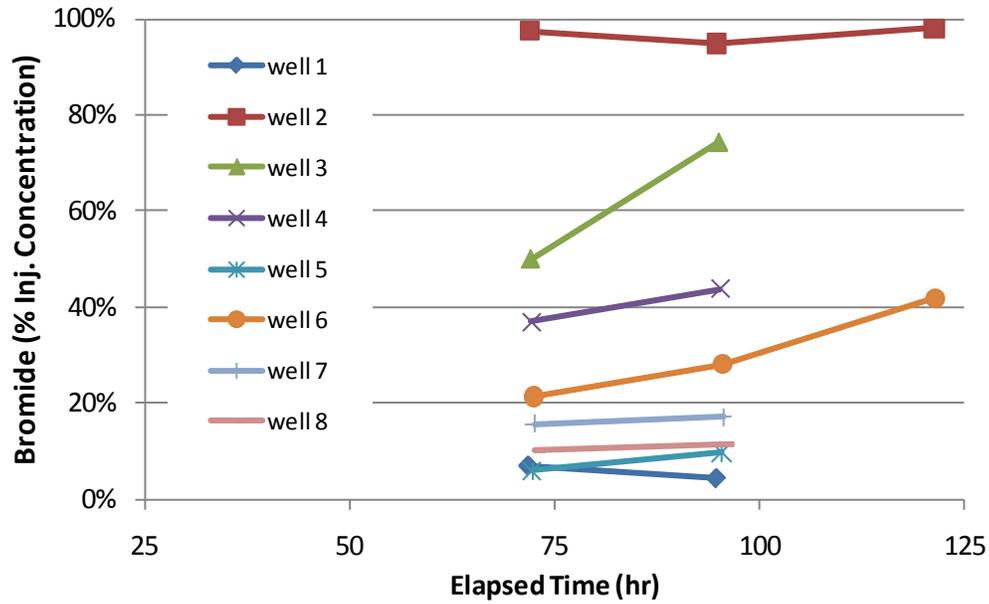


Figure 2.17. Results of Saturated Zone Samples Collected During Second Tracer Test

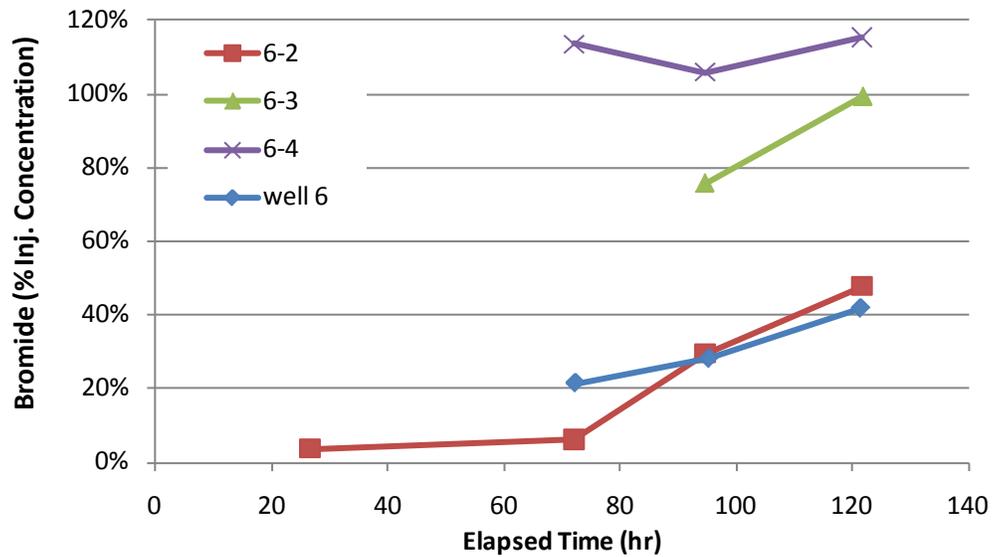


Figure 2.18. Results of Vadose Zone Samples Collected During Second Tracer Test (three porous cup depths and the underlying saturated zone screen in well 6)

3.0 Summary and Conclusions

The primary objectives of the pilot-scale tracer infiltration testing were met. The test successfully demonstrated that 1) the remaining 2 to 3 ft of compacted roadbed material below the infiltration gallery does not limit infiltration rates to levels that would be expected to eliminate near-surface application as a viable amendment delivery approach, and 2) the combined aqueous and geophysical monitoring approaches employed at this site, with some operational adjustments based on lessons learned, provides an effective means of assessing wetting-front advancement and the distribution of soil moisture achieved for a given solution application.

Reasonably good agreement between predicted and observed tracer and moisture front advancement rates was observed. During the first tracer infiltration test, which used a solution application rate of 0.7 cm/hr, tracer arrivals were observed at the water table (10 to 12 ft below the bottom of the infiltration gallery) after approximately 5 days, for an advancement rate of approximately 2 ft/day. This advancement rate is generally consistent with pre-test modeling results that predicted tracer arrival at the water table after approximately 5 days (see Figure 1.8, bottom left panel). This agreement indicates that hydraulic property values specified in the model for the compacted roadbed materials and underlying Hanford formation sediments, which were based on laboratory-scale measurements, are reasonable estimates of actual field-scale conditions.

Additional work is needed to develop a working relationship between resistivity change and the associated change in moisture content so that 4D images of moisture content change can be generated. Results from this field test will be available for any future Ca-citrate-PO₄ amendment infiltration tests, which would be designed to evaluate the efficacy of using a near-surface application of amendments to form apatite mineral phases in the upper portion of the zone of water table fluctuation.

4.0 References

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