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IN SITU PERMEABLE FLOW SENSORS AT THE SAVANNAH RIVER INTEGRATED DEMONSTRATION: PHASE II RESULTS

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Abstract

A suite of In Situ Permeable Flow Sensors was deployed at the site of the Savannah River Integrated Demonstration to monitor the interaction between the groundwater flow regime and air injected into the saturated subsurface through a horizontal well. One of the goals of the experiment was to determine if a groundwater circulation system was induced by the air injection process. The data suggest that no such circulation system was established, perhaps due to the heterogeneous nature of the sediments through which the injected gas had to travel. The steady state and transient groundwater flow patterns observed suggest that the injected air followed high permeability pathways from the injection well to the water table. The preferential pathways through the essentially horizontal impermeable layers appear to have been created by drilling activities at the site.

Acknowledgments

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Introduction

In order to clean up the numerous environmentally contaminated sites around the U. S. in an efficient and cost effective manner, new remediation technologies will be required. In addition, new monitoring technologies are needed to track the progress and measure the effectiveness of the remediation technologies that are deployed. As part of this effort, the Cleanup of VOCs in Non-Arid Soils Integrated Demonstration was conducted at the Savannah River Site in South Carolina, with the goal of demonstrating the utility of using horizontal wells for in situ air stripping, in situ bioremediation and in situ heating to remove/destroy volatile organic compounds (VOCs) in saturated and unsaturated soils. In addition to the field scale implementation of innovative remediation technologies, numerous innovative supporting technologies were deployed to characterize the site, monitor the remediation process and treat the off-gas that resulted from the in situ air stripping

The In Situ Permeable Flow Sensor is one of the monitoring technologies which was developed and demonstrated as part of the Savannah River Integrated Demonstration. This instrument uses a thermal perturbation technique to directly measure the magnitude and direction of the full 3-dimensional groundwater flow velocity in an approximately 1 cubic meter volume of unconsolidated, saturated sediments. The purpose of deploying this technology during the Integrated Demonstration was to measure the effect of air injection into the saturated sediments on the groundwater flow patterns at the site and thereby contribute to an understanding of the zone of influence of the remediation process. Beyond serving the local needs of the Integrated Demonstration, and additional goal was to develop an instrument that could be used throughout the environmental characterization, monitoring and remediation industry. To that end, a calibration experiment was conducted at another location on the Savannah River Site where a direct comparison could be made between measurements obtained with the flow sensors and results obtained with standard hydrologic techniques. A complete description of the In Situ Permeable Flow Sensor technology, as well as the results of the calibration experiment described above, can be found in Ballard et al. (1994).

Background

The Savannah River Integrated Demonstration was a multi-phased experiment designed to investigate the utility of using paired horizontal boreholes to simultaneously inject and extract gas to/from the subsurface to achieve removal and/or destruction of VOCs that reside in the subsurface (WSRC, 1991). Two horizontal wells were installed at the site in 1989 (Kaback et al., 1989). These wells are illustrated in Figure 1 both in map view and cross section. During Phase I of the Demonstration (July to December, 1990), air was injected into the lower well at a variety of rates up to 300 standard cubic feet per minute (scfm) and air was extracted from the upper well at approximately 600 scfm (Looney, 1991). In transit, the air bubbled up through the saturated sediments to the water table and then travelled through the vadose zone to the extraction well. The extraction rate was maintained well above the injection rate to ensure good communication between the two wells and to prevent the injected air from enlarging the contaminant plume. As the air travelled through the subsurface, the VOCs in the groundwater and in the vadose zone were volatilized and extracted from the subsurface along with the air. During the course of the experiment, a total of 16,000 pounds of VOCs were removed from the subsurface by this process. During Phase II of the project, which lasted for 14 months from

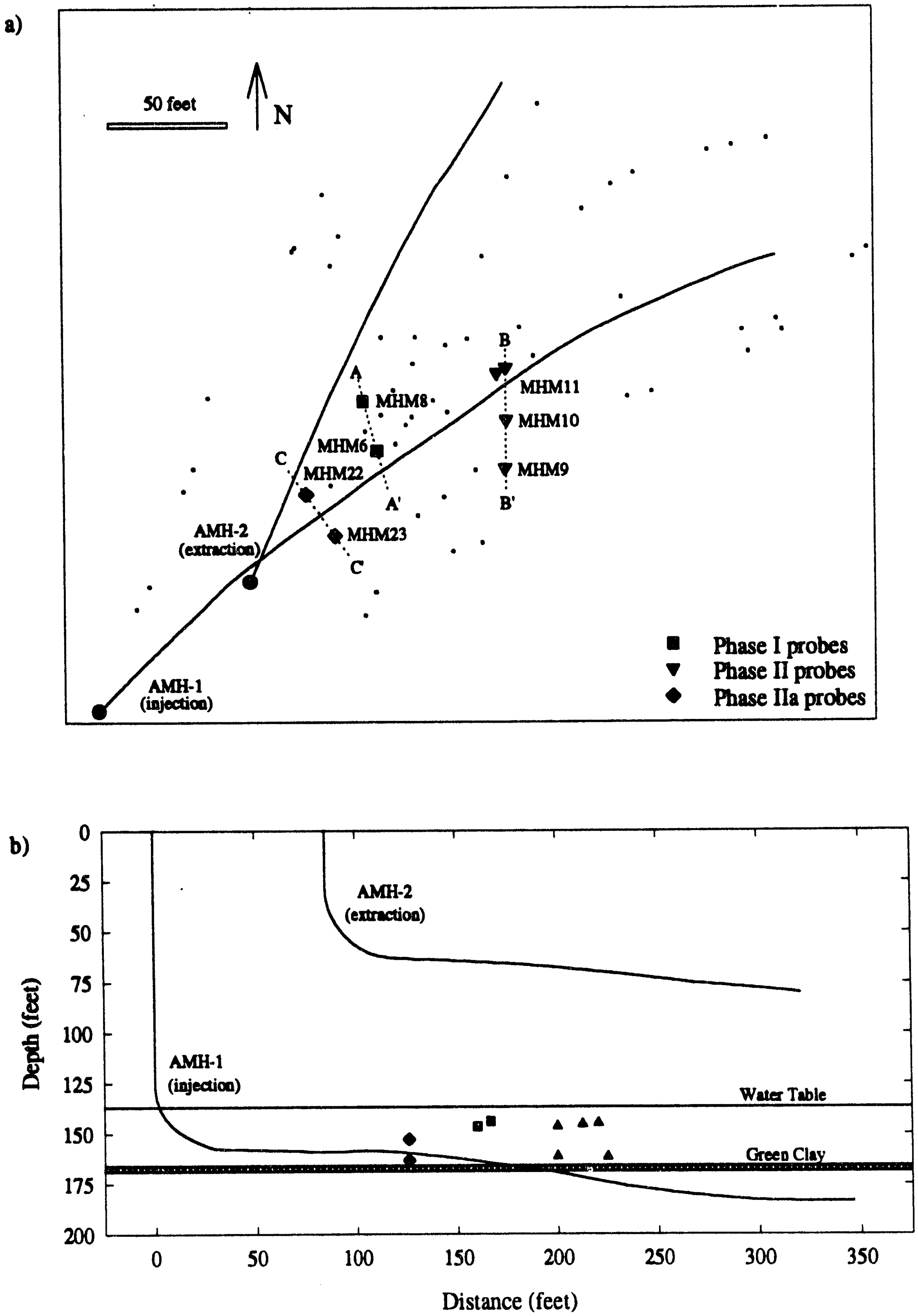

Figure 1 - a) Map of the Integrated Demonstration site. The small dots show the location of some of the monitoring wells at the site. Lines A-A', B-B' and C-C' refer to the locations of cross sections in Figures 2, 3 and 4. b) Cross section approximately along the trace of the injection well, AMH-1. North refers to plant north which is 36° west of true north.

February, 1992 through April, 1993, a few percent methane was mixed with the injected air to stimulate the growth of indigenous microorganisms which degrade VOCs.

An important aspect of assessing the success of these remediation techniques is to understand the dynamics of the gas transport through the subsurface and to determine the zone of influence of the in situ air stripping process. In a perfectly homogeneous medium, equal amounts of gas would emanate from all sections of the injection well and rise in a uniform fashion to the extraction well. In fact, the subsurface at the site is decidedly inhomogeneous, being composed primarily of sand with lenticular clay horizons distributed throughout (Eddy et al., 1991, Eddy-Dilek et al., 1993). In all likelihood, more gas emanated from the sections of the injection well located in the more permeable sand horizons and less in the relatively impermeable silts and clays. Once the air was out in the formation, it probably followed rather tortuous preferential pathways upward through the subsurface rather than rising in a uniform fashion. It is important to try to understand the degree to which the air was constrained to flow within these preferential pathways because the relatively impermeable portions of the subsurface which did not experience significant gas flux were probably remediated to a significantly lesser degree than were portions which were subjected to more flux.

Another important consideration is the influence that the groundwater flow at the site had on the air injection process and vice versa. If the groundwater were stagnant, then the groundwater that lay in the path of the injected air as it moved upward through the saturated portion of the subsurface would be remediated and then no more VOCs would be extracted (except for those which diffused out of the relatively impermeable zones). On the other hand, if there were significant groundwater flow through the site then remediated groundwater would be continually removed from the zone of influence of the air stripping process while new contaminated water would flow into the zone of influence to be remediated in turn. A possibility that also needs to be considered is that the injected air could induce a groundwater circulation system which would continually remove remediated groundwater from the zone of influence of the air stripping process and bring in contaminated groundwater to replace it. In this scenario, the injected air would render the water column directly above the injection well less dense than the adjacent water, causing the water above the injection well to rise. As the water approached the water table it would be forced to flow laterally away from the location in the subsurface where the injected air was transferred from the saturated zone below the water table to the vadose zone. The water would ultimately flow downward and then back toward the injection well thereby forming a circulation cell that would resemble a thermal convection pattern. The driving force for this circulation cell would be buoyancy contrasts induced by the injected air rather than by thermal processes.

In Situ Permeable Flow Sensors were deployed at the site to monitor the interaction between the air injection system and the groundwater flow regime. The first set of flow sensors was installed prior to the initiation of Phase I of the project. The locations of those probes is illustrated in map and cross sectional views in Figures 1a and 2. The Phase I results are described in detail by Ballard (1992). Since these flow sensors were essentially prototypes and the first ones ever deployed for environmental purposes, they suffered from a number of design flaws which rendered them insensitive to the horizontal component of the groundwater flow velocity. They did, however, successfully measure the vertical component of the flow. Prior to Phase II, a suite of 5 redesigned flow sensors was installed at the site at locations illustrated in Figures 1a and 3. The problems with the first set of flow sensors were resolved prior to fabrication of the second set of sensors and the probes were able to monitor the full three dimensional flow velocity as a function of time during the air stripping operation. Just before

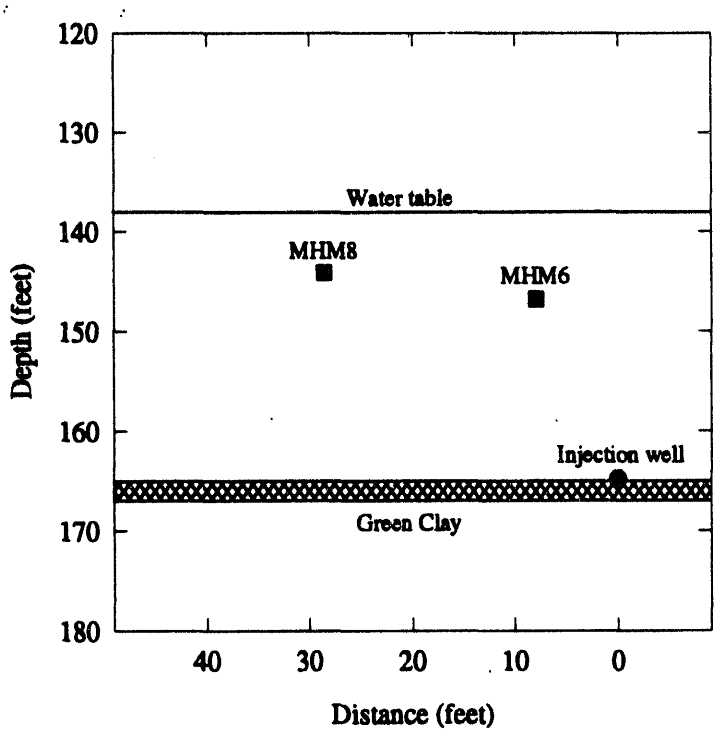

Figure 2 - Cross section A-A' showing the location of the Phase I probes.

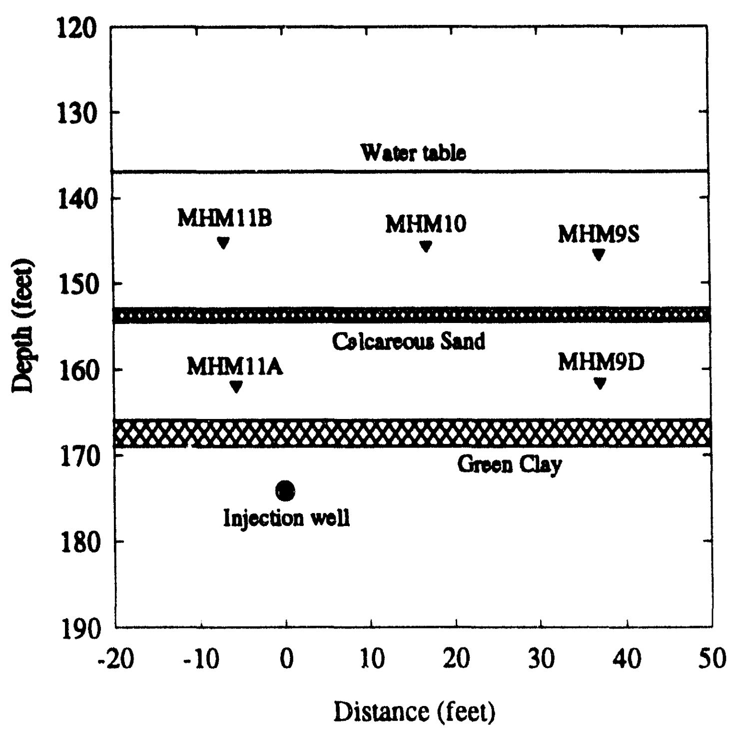

Figure 3 - Cross section B-B' showing the location of the first set of Phase II probes.

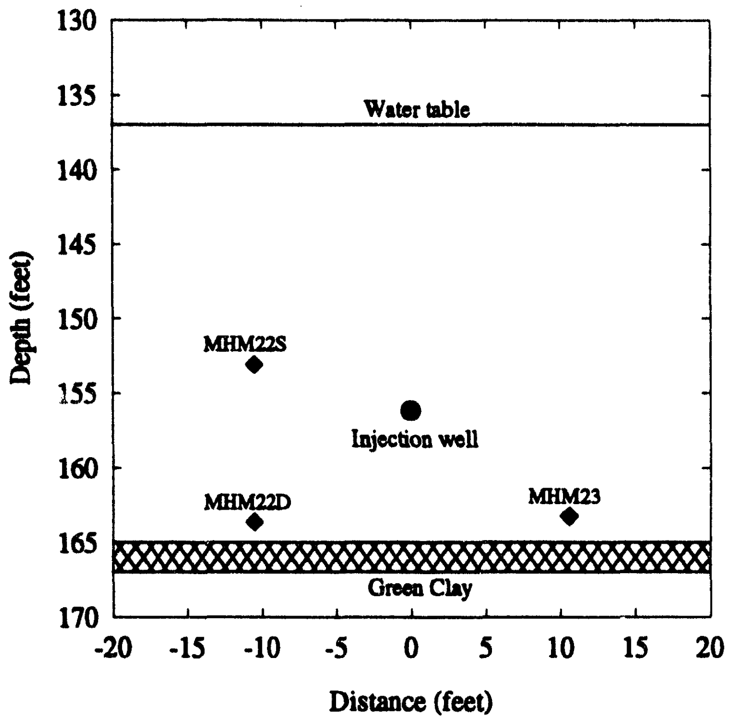

Figure 4 - Cross section C-C' showing the location of the second set of Phase II probes.

the end of Phase II operations, three more sensors were installed at locations illustrated in Figures 1a and 4. Note that two of these probes, MHM22D and MHM23 were emplaced just above the "green clay" at a depth of about 165 feet. The clay has thermal properties which are significantly different from those of the sand directly above it and since the flow sensors are so close to the clay this contrast in thermal properties has corrupted the vertical flow measurements obtained with these probes. The vertical components from these probes have not been reported in Table 1.

Results

Two flow regimes were observed during the course of the experiment. The first reflected the steady state flow velocity when the air injection system had been either on or off for more than several days, and the second was a transient flow regime observed immediately after the air injection system was turned on or off. These two flow regimes will be considered in turn.

Steady state flow velocity

The steady state flow velocities measured at the site are tabulated in Table 1 and the steady state velocities observed when the air injection system was off are illustrated in Figure 5. The data plotted in Figure 5 reflect the flow before the air injection operation was initiated, after it ended, or at times during the experiment when the air injection system had been turned off temporarily and had been off for more than a few days. In Figure 5, the length and orientation of each arrow reflects the magnitude and direction of the horizontal component of the groundwater flow velocity measured at the location at the base of the arrow. The horizontal flow

Table 1 - Steady state flow velocities.

Probe	Air Injection Off			Air Injection On		
	Vertical (ft/day)	Horizontal (ft/day)	Azimuth (°)	Vertical (ft/day)	Horizontal (ft/day)	Azimuth (°)
MHM6	.04	na	na	.22	na	na
MHM8	.08	na	na	.08	na	na
MHM9S	.04 ± .05	.05 ± .03	-150 ± 20	variable	variable	variable
MHM9D	.00 ± .01	.03 ± .02	-15 ± 40	.01 ± .02	.04 ± .03	-10 ± 454
MHM10	.11 ± .03	.03 ± .03	102 ± 96	.11 ± .02	.01 ± .02	102 ± 123
MHM11S	.11 ± .03	.07 ± .04	-30 ± 30	.11 ± .03	.04 ± .04	-30 ± 60
MHM11D	-.01 ± .01	.05 ± .02	-88 ± 20	-.01 ± .01	.04 ± .07	-88 ± 25
MHM22S	-.14 ± .04	.15 ± .06	-50 ± 20	.03 ± .03	.04 ± .04	20 ± 90
MHM22D	na	.16 ± .04	-120 ± 12	na	.14 ± .03	-110 ± 12
MHM23	na	.11 ± .02	-35 ± 10	na	.10 ± .02	-35 ± 10

velocity at MHM10 is not plotted in Figure 5 because it was not statistically different from zero. The data suggest that the background flow at the site is predominantly horizontal and oriented in a northwesterly direction. The magnitude of the flow is fairly low, about 0.1 ft/day. That these flow velocities are down near the lower detection limit of the flow sensors is indicated by the fact that the uncertainties in the measurements are almost as large as the measurements themselves (Ballard et al., 1994). These data correspond well to the expected groundwater flow direction, which is toward Three Runs Creek located to the northwest of the site (Eddy-Dilek et al., 1993).

The steady state flow velocity data in Table 1 also indicate that the flow velocities observed when the air injection system was on are indistinguishable from the velocities measured when the system was off, with a few exceptions. Three of the probes, MHM6, MHM9S and MHM22S all measured significant increases in the steady state, upwardly directed vertical flow velocity when the air injection system was operating as compared to when it was turned off. Only one probe, MHM22S, measured a significant change in horizontal flow. It detected a horizontal flow of .15 ± .06 ft/day when the air was turned off but statistically insignificant horizontal flow when the air was on.

Since changes in horizontal flow were not observed by most of the probes, it is unlikely that the changes in apparent vertical flow truly reflect groundwater flow since the water that some of the probes detected flowing upward would have to flow horizontally when it got to the water table. The observed changes in vertical flow are probably the result of air flowing past the probes rather than water. The velocity magnitudes reported in Table 1 were calculated assuming that the flow past the probes is purely water with no air bubbles in it. The probes are unable to distinguish the flow of air from the flow of water, particularly in a two phase system, so it is not

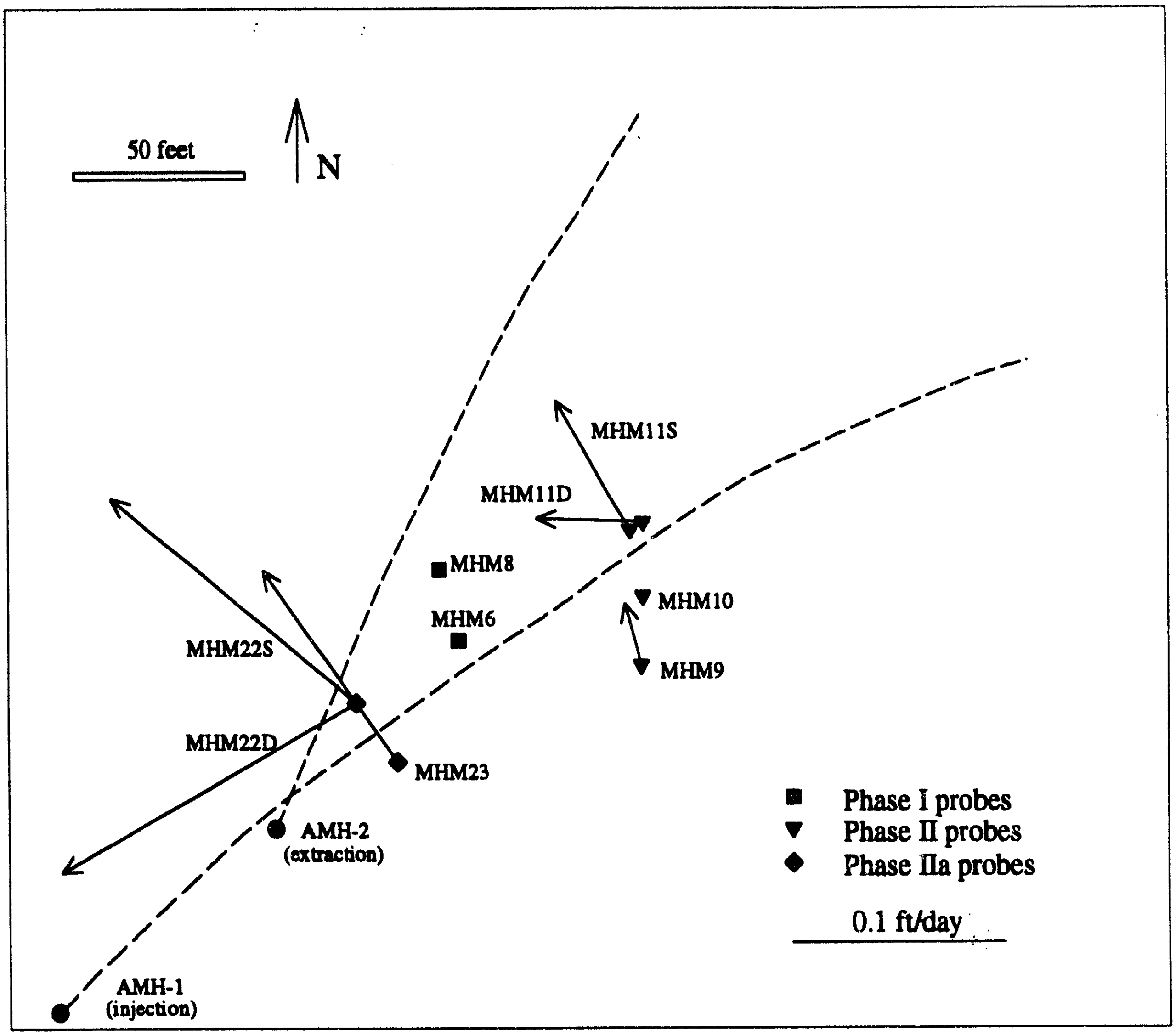

Figure 5 - Steady state horizontal flow velocities when the air injection system was turned off.

possible to determine the magnitude of the velocity of the air nor the amount of air in the water. The change in horizontal flow detected by MHM22S, which also observed a significant change in vertical flow when the air was on, probably reflects disruption of the background horizontal flow by injected air surrounding the probe.

To further substantiate the hypothesis that some of the probes are responding to the flow of air rather than water, consider the vertical flow velocity data from the probes in MHM9S and MHM9D, illustrated in Figure 6. Prior to time 336.55, the air injection system was operating and the probe in MHM9S was measuring a steady, vertically upward flow of .18 ± .03 ft/day. When the air injection system was turned off at time 336.55, the vertical flow observed by MHM9S decreased gradually to near zero and remained there until the air injection system was turned back on approximately 2 days after it had been turned off. When the air was turned back on, the apparent vertical flow increased abruptly back to almost the same level where it was before the air injection system was turned off. The flow sensor in MHM9D responded quite differently to the change in status of the air injection system. Prior to the time when the air injection system was turned off, the probe measured negligible vertical flow. When the air went off, a small,

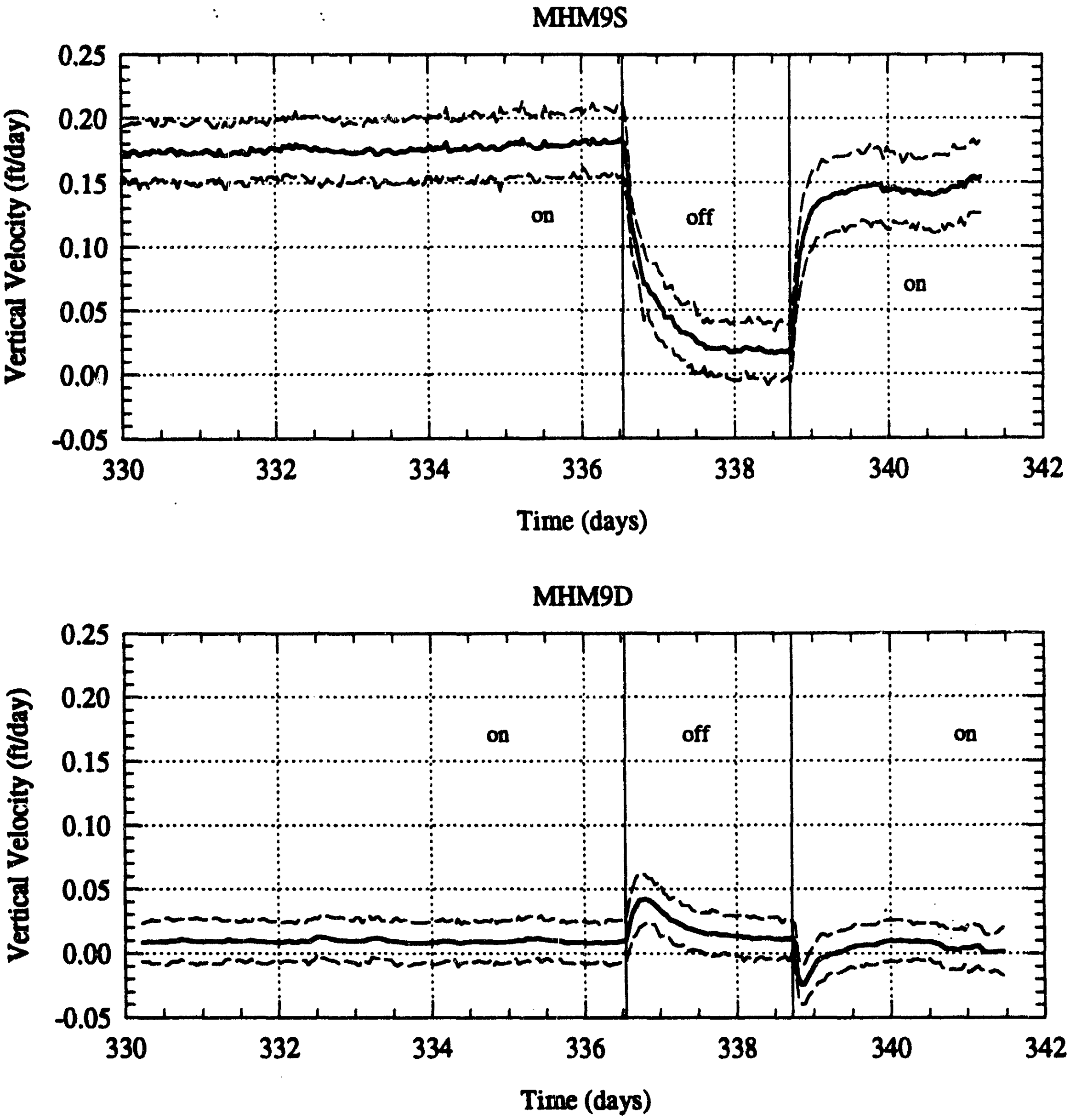

Figure 6 - Vertical flow velocity as a function of time measured by probes MHM9S and MHM9D. The vertical lines indicate times when changes in the status of the air injection system occurred. The dashed lines are uncertainty estimates.

transient, upwardly directed flow was observed. This transient flow decayed away after about 24 hours, at which time the vertical flow was once again statistically indistinguishable from zero. When the air injection system was turned back on again, another small, transient vertical flow was induced, but this time the flow was directed vertically downward rather than upward.

The most plausible explanation for these observations is that the probes are responding to the flow of air, and changes in the distribution of air, in the subsurface. Note that the two probes are deployed one above the other in the same borehole. All the cables for the lower probe pass through the interior of the upper probe. The hole in which these probes were deployed penetrated a thin, relatively impermeable calcareous sand layer at a depth approximately midway between the positions of the two probes (Eddy-Dilek et al, 1993). While the formation collapsed around the probes after emplacement so that there was no borehole per se when the measurements were made, there did exist a high permeability hole through the calcareous sand layer between the two probes. When the air injection system was on, it is possible that air accumulated beneath this sand layer and made its way upward through the hole created when the probes were emplaced. Once through the calcareous sand layer the air probably continued upward along the high permeability conduit created by the collapse of the formation around the pipe connecting the pair of probes with the surface. This air flow is observed by the probe in MHM9S which is above the calcareous sand layer but not by the probe in MHM9D which is below the sand layer. When the air was turned off, the air which was trapped below the sand layer gradually found its way through the calcareous sand layer until it was gone. The observed decrease in apparent vertical flow at MHM9S is consistent with this hypothesis. The air which was formerly trapped below the calcareous sand layer was replaced by water which had to flow into the space from adjacent regions. The transient, upwardly directed flow observed at MHM9D suggests that at least some of that water came from below. When all the trapped air was gone, the transient flow at MHM9D returned to zero. When the air injection system was reinitialized, air once again collected below the calcareous sand layer, displacing water which flowed downward past the probe in MHM9D. The steady, upwardly directed flow at MHM9S was reestablished.

Transient flow

As described above, most of the probes measured the same steady state flow velocity when the air was on as they observed when the air was off. Several probes did, however, observe dramatic transient changes in flow velocity immediately following changes in the status of the air injection system. The best example comes from the probe in MHM11D which was only 14 feet from the injection well (6 feet horizontally and 12 feet vertically). Figure 7 illustrates the flow velocity measured by that probe as a function of time over a one week period. Prior to time 213.55, the air injection system was operating and had been operating without interruption for almost two weeks. The groundwater flow velocity observed by the flow sensor in MHM11D was fairly low in magnitude, purely horizontal and oriented due west relative to plant north. On day 213.55, the air injection system was turned off for almost 5 days to perform system maintenance. Immediately after the air injection system was turned off the flow velocity changed abruptly. A vertically upward component of flow was induced, the horizontal component of flow increased more than fivefold and the orientation of the horizontal component shifted counterclockwise by about 40°, from due west to a more southwesterly direction. This transient flow velocity reached a maximum magnitude about 10 hours after the air injection system was turned off and then began to subside. By about 2 days after the air was shut off the flow velocity had returned to the level where it had been prior to the interruption in the air injection process. When the air injection system was turned on again roughly 5 days after it had been turned off another transient perturbation to the flow field was observed. A vertically upward flow was induced once again and the horizontal component again increased approximately fivefold. This time the direction of the horizontal component changed from roughly west relative to plant north to approximately due north.

The most plausible explanation for these observations is that when the air injection system was turned off the injected air which was still in the saturated subsurface rose to the water table and was replaced by water. This resulted in groundwater flow toward locations formerly

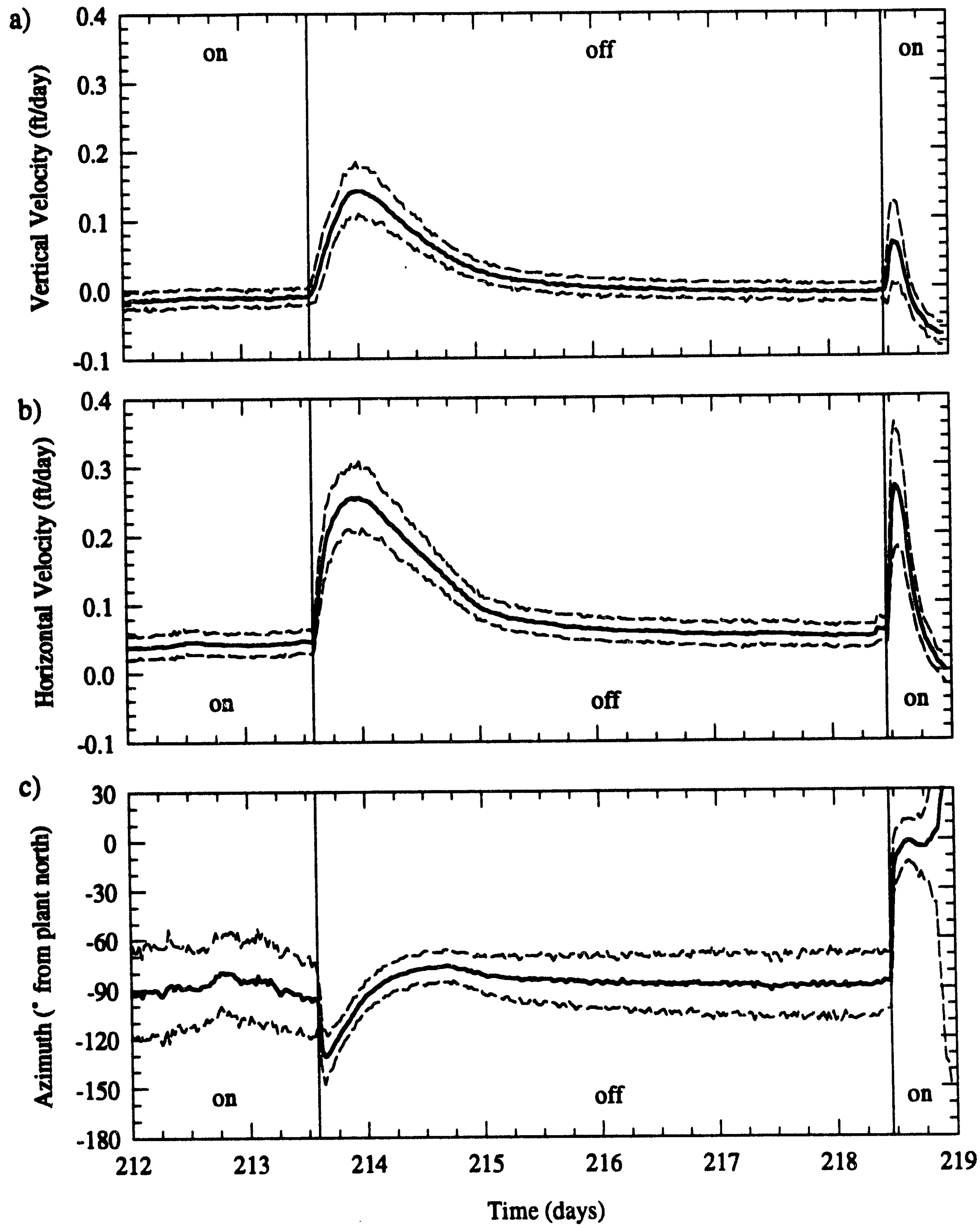

Figure 7 - Flow velocity measured by probe MHM11D. The vertical lines are times when changes in the status of the air injection system occurred. The dashed lines are uncertainty estimates.

occupied by air. When the air injection system was off and was turned back on, air would suddenly displace water at certain locations in the subsurface and water would be forced to flow away from those locations. The implication is that these transients can be used to locate positions in the subsurface where air was concentrated when the air injection system was on.

While most of the probes exhibited transient behaviors in response to changes in the status of the air injection system, the probes which showed significant upward apparent flow due to air flowing past the probes showed very erratic transient behaviors and will not be considered here. The maximum horizontal transient flow velocities from the other probes are illustrated in Figure 8. From probes MHM22D and MHM23, only transient data from an event where the air injection system went from on to off are available. When the air injection system went from off

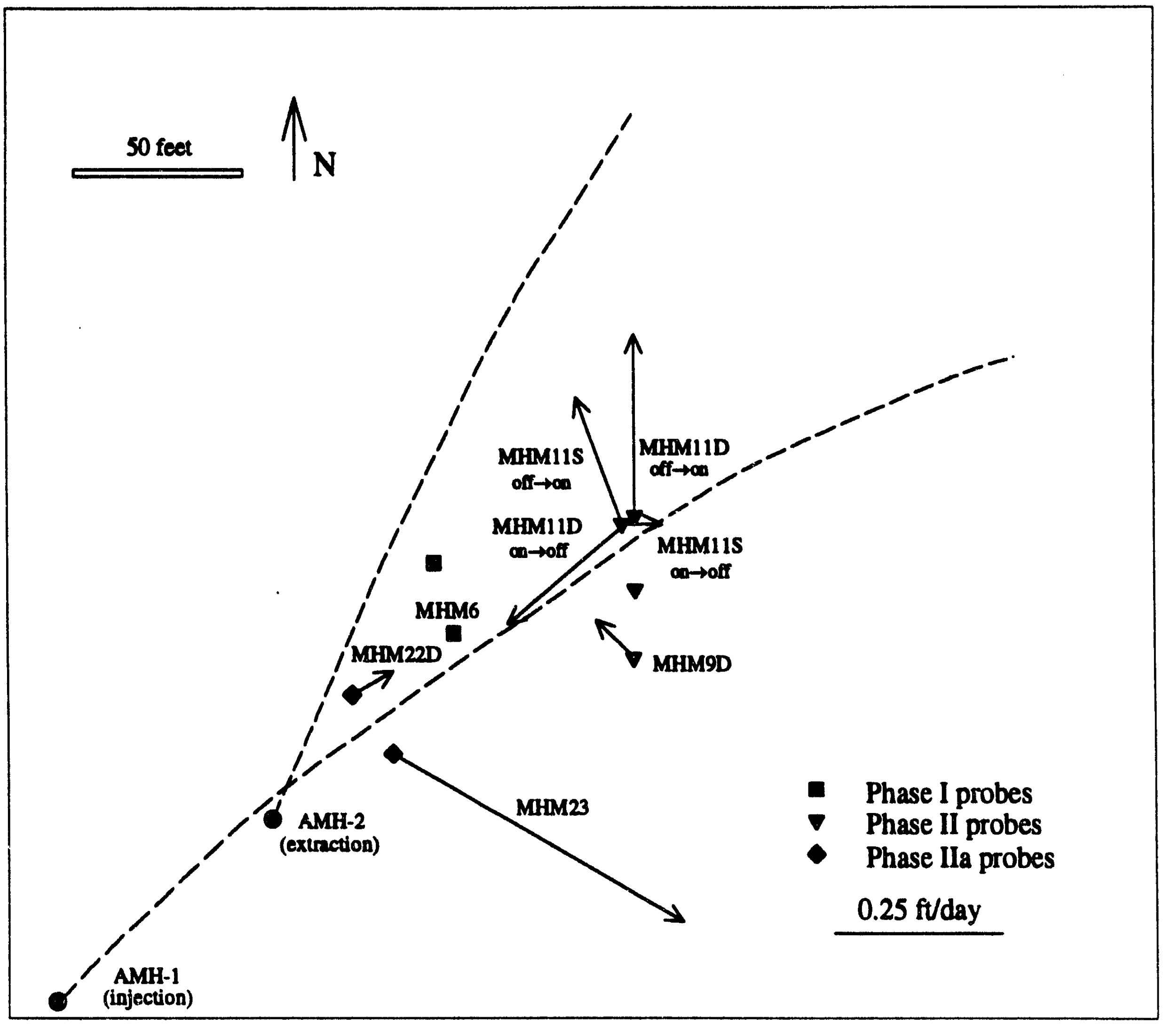

Figure 8 - Map showing the maximum transient horizontal flow velocities which occurred immediately following changes in the status of the air injection system. Unless otherwise noted, the velocities reflect the response observed at times when the air injection system was on and was turned off.

to on, the flow in MHM9D was reduced to near zero and hence is not illustrated in Figure 8. Probes MHM11S and MHM11D showed transient behavior on several occasions in response to both turning the air on and turning it off.

When the air went from off to on, probes MHM11S and MHM11D observed significantly enhanced flows in a direction away from the injection well. This is consistent with a scenario where air suddenly displaces water in the immediate vicinity of the air injection well and causes the groundwater to flow away from those locations. When the air went from on to off, it is expected that the flow should point to locations in the subsurface where air was concentrated. MHM11S, which is the only one of the 5 probes being considered which is not down near the top of the "green clay", indicated flow to the east. MHM23, which is just above the top of the clay, shows transient flow toward the southeast, for unknown reasons. The other three deep probes however, MHM9D, MHM11D and MHM22D, all point to a common location in the vicinity of MHM6, which is one of the probes where upward flow of air was observed. This location also coincides with the point where the horizontal air injection well, AMH1, steepens and penetrates the top of the "green clay" (see the cross section in Figures 1b and 2). These data suggest that this area may be the location of one of the preferred pathways used by the injected air to travel through the saturated subsurface from the injection well to the water table. It is possible that when the horizontal well penetrated the clay, it created a pathway through the relatively impermeable clay layer. Air that was subsequently injected into the formation below the clay may have exploited this hole to make its way upward to the water table and then to the extraction well. This would result in a concentration of air between the point where the injection well penetrated the top of the clay and the water table. When the air injection system was turned off, the air in this area would rise to the water table and be replaced by water which would flow toward this area from the surrounding formation. When all the air had risen across the water table, the flow would cease, explaining the transient nature of the observed flow.

Conclusion

In Situ Permeable Flow Sensors were used at the site of the Savannah River Integrated Demonstration Site to characterize the interaction between the in situ air stripping process and the groundwater flow regime. In particular, the possibility that the air injection process might itself induce a groundwater circulation system was investigated. Such a circulation system might be expected since air bubbles in the water column directly above the horizontal air injection well would render the water less dense than adjacent groundwater. A groundwater circulation system would be desirable since it would remove remediated groundwater from the zone of influence of the remediation system and bring in new contaminated groundwater for treatment.

While changes in the steady state vertical flow velocity were observed by some of the probes, none of the probes measured significant changes in the steady state horizontal flow velocity. The absence of such changes in horizontal flow velocity dictate that no significant groundwater circulation system was induced by the air injection system. The observed changes in the apparent vertical flow velocity probably reflect the flow of air past the probes, not water. This air could flow past the probes then leave the saturated subsurface at the water table without requiring any lateral flow in adjacent areas.

Transient changes in the groundwater flow velocity observed immediately following changes in the status of the air injection system point to portions of the subsurface where air was concentrated when the air injection system was on. When the air injection system was off and was turned on, air displaced groundwater near the injection well, forcing water to flow away from these locations. When the air injection system was on and was turned off, injected air that remained in the saturated subsurface travelled upward to the water table to be replaced by water, resulting in the flow of groundwater toward those locations. The results obtained at this site suggest that a preferred pathway for air flow was created through the relatively impermeable "green clay" directly above the point where the horizontal injection well intersected the top of the clay.

The results suggest that two phenomena were probably operative at this site which should be considered when implementing this type of remediation system. The first is that the air flow through the subsurface is likely to be channelized along high permeability pathways. The degree to which the flow will be channelized is highly dependent on the local geology which will vary significantly from site to site. The second phenomena which needs to be considered is that penetration of the subsurface by boreholes probably creates high permeability pathways for air flow through the relatively impermeable horizons.

References

Ballard, S., 1992, In Situ Permeable Flow Sensors at the Savannah River Integrated Demonstration: Phase I Results, SAND92-1952, Sandia National Laboratories, Albuquerque, New Mexico.

Ballard, S., Glenn T. Barker and R. L. Nichols, 1994, The In Situ Permeable Flow Sensor: A device for measuring groundwater flow velocity, SAND93-2765, Sandia National Laboratories, Albuquerque, New Mexico.

Eddy, C. A., B. B. Looney, J. M. Dougherty, T. C. Hazen and D. S. Kaback, 1991, Characterization of the geology, geochemistry, hydrology and microbiology of the in-situ air stripping demonstration site at the Savannah River Site, Westinghouse Savannah River Company Report, WSRC-RD-91-21, 118 pp.

Eddy-Dilek, C. A., B. B. Looney, T. C. Hazen, R. L. Nichols, C. B. Fliermans, W. H. Parker, J. M. Dougherty, D. S. Kaback and J. L. Simmons, 1993, Post-test evaluation of the geology, geochemistry, microbiology, and hydrology of the in-situ air stripping demonstration site at the Savannah River Site, Westinghouse Savannah River Company Report, WSRC-TR-93-369, 78 pp.

Kaback, D. S., B. B. Looney, J. C. Corey and L. M. Wright, 1989, Well completion report on installation of horizontal wells for in-situ remediation tests, Westinghouse Savannah River Company Report, WSRC-RP-89-784, 40 pp.

Looney, B. B., 1991, In situ air stripping final report (07/27/90 to 12/18/90), Westinghouse Savannah River Company Inter Office Memorandum, SRL-ESS-91-0220, 51 pp.

Westinghouse Savannah River Company, 1991, Cleanup of VOCs in Non-Arid Soils - The Savannah River Integrated Demonstration, WSRC-MS-91-290, Rev. 1.

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