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Field monitoring and performance evaluation of a field-scale in-well aeration system at a gasoline-contaminated site

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Abstract

Several in-well aeration (IWA) technologies have been used since the early 1990s, but few field studies have been performed to evaluate the extent of water circulation around IWA systems. In this study, 27 discrete monitoring points (MPs) were installed at a gasoline-contaminated site to assess the efficacy of IWA. Pressure transducers and dissolved oxygen (DO) probes were sealed into the MPs, allowing them to be used to characterize subsurface changes in total head and DO with depth, distance and orientation from a central injection well. No change in DO or in hydrocarbon total mass or distribution occurred across the site during two trials (41 and 20 days) of the system. Water level fluctuations during the trials were similar in all MPs, and were due to seasonal water table changes and rainfall events. No circulation cell was established around the IWA well after 41 days of operation, and the impact of the well extended less than 90 cm from it. Groundwater only circulated through the sand pack around the well. Little, if any, recharge occurred through the lower screen. Silt accumulated in the well, limiting its operation time, even with a fabric filter sock over the lower screen. Obviously, IWA was ineffective at this site, probably because the horizontal hydraulic conductivity (K_h) of the soil opposite the lower screen was low (0.09 cm per day) and because the distance between the two screens was short relative to the borehole radius. Long remediation times would likely make IWA unattractive at this or other sites where the K_h of the soil is so low that the air injection rate would have to be low to prevent blowing the well dry. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Groundwater; Contamination; Monitoring; Remediation

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1. Introduction

Although many soil and groundwater contaminants will disperse over time or will transform naturally into substances which do not pose health and environmental concerns, often the risk or the time required for this “natural” reduction is unacceptable. Many contaminants can be transformed into non-toxic substances in the soil through aerobic biodegradation by indigenous organisms, and a variety of methods are currently used to provide oxygen to the contaminated region. Injection of air into the vadose zone has been successful at many sites [1–3]. Injection of air into the saturated zone has led to mixed results and is the subject of this paper.

The air injection scenarios used to remediate soil and groundwater can be divided into two categories: in situ air sparging (IAS) [4 and many others] and in-well aeration (IWA). In IWA, air is injected into a well below the water table and mechanical pumping or an air-lift pump effect is used to establish a circulation pattern in which groundwater moves into the bottom of the well, where it is oxygenated and forced back out through the top. If an air-lift pump is used [5,6], the induced head between the top and bottom of the well maintains circulation of the groundwater.

Models of common IWA systems predict that the majority of water flow into and out of the well occurs within the bottom and top 15% of a fully penetrated, confined aquifer [5,7–10]. For petroleum hydrocarbon (HC) contamination located near the top of an aquifer (light non-aqueous-phase liquid, or LNAPL), the groundwater flow out of the top of the well may provide dissolved oxygen (DO) to the region with the greatest oxygen demand. If the groundwater is captured as the streamlines return toward the bottom of the well, dilution may reduce potential toxicity without increasing the zone of contamination.

Fig. 1 illustrates one idealized IWA system called Density Driven Convection (DDC) [11,12]. In the DDC system, two-well screens are exposed to the soil, one above and one below a grout seal, which reduces short circuiting at the midpoint of the well. The upper screen spans the region of a fluctuating water table. A slug flow or Taylor bubble pattern [13,14] is used to achieve flow through the well by reducing the density of the fluid while increasing the height of the water column in the well.

Soil and groundwater monitoring results for IWA systems are available only for a limited number of sites [15–19]. A DDC well was installed at one site in fine to medium sand (average $K_{\mathrm{h}} = 30$ cm per day) with a lower screen at 4.9 to 6.4 m and an upper screen spanning 1.2 to 4.3 m below the surface. Initial evaluation indicated that operation of the DDC well resulted in increased oxygen concentration in the vadose zone, a head difference in the DDC well between the upper and lower screens of approximately 107 cm, an increase in DO in the groundwater at the upper screen, and evidence of circulation (tracer migration) extending out to 6.1 m from the well. The flow radius of influence (ROI) appeared to decrease with time and the oxygenated ROI did not expand after 19 days of operation due to mixing of oxygenated groundwater with contaminated water that was continually being drawn into the bottom of the well (personal communication with Les Pennington, Wasatch Environmental, Inc. (WEI), January 30, 1998).

According to WEI, costs, including installation and annual operation and maintenance expenses, generally range between US$ 20 to 30 per square meter of plume for their DDC systems. This figure was estimated from existing installations, regardless of the depth to ground-

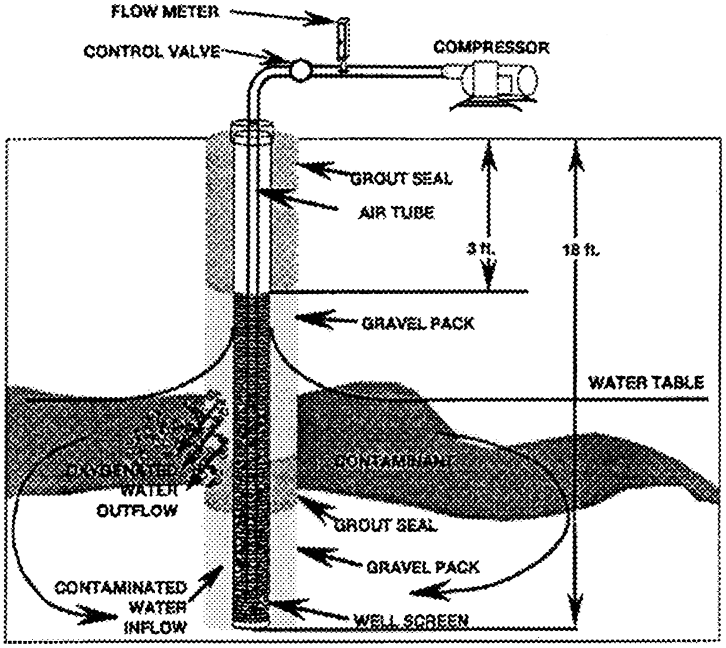

Fig. 1. Diagram of density driven sparging well construction [6].

water. Forty DDC systems have been installed since 1991, and 23 of these sites have been cleaned up and closed (personal communication with Les Pennington, WEI, June 16, 2000).

These few studies were not designed with monitoring systems and instrumentation adequate for assessing the efficacy of IWA. Therefore, a project [20] that included both laboratory and full-scale field evaluations of IWA was conducted. Results of the laboratory-scale work which supports the conclusions presented here are presented elsewhere [21].

The first step was to design a monitoring and sampling scheme at a field site that would allow characteristics like oxygen transfer and contaminant removal rates to be estimated. The Wasatch Trailer sales (WTS) site in Layton, UT was selected. A sample collection system grid was installed at the site and continuous monitoring, in situ sensors were installed in this grid. The monitoring grid and instrumentation system were used to measure subsurface changes during IWA and to evaluate its efficacy in removing contaminants and distributing DO at the site. The WTS site was originally a retail gasoline station. The commercial history, geology, total petroleum hydrocarbon (TPH) distribution and characterization monitoring results for the WTS site are included in detail in [22].

2. Methods

2.1. Monitoring system

The first step in evaluating IWA at the WTS site was to design and install a grid of monitoring points (MPs). The WTS site was also used to study IAS [22] and the monitoring

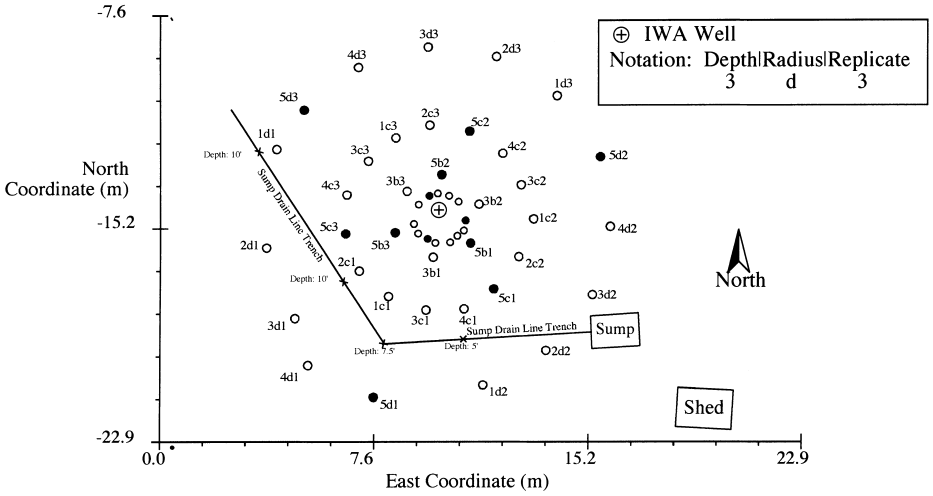

Fig. 2. Driven monitoring point locations.

grid was designed to evaluate the efficacy and allow comparison between the two types of air injection systems. The grid consists of four concentric circles of MPs around the central IWA well. Three MPs were installed at each radius at each of five depths. The grid is shown in plan view in Fig. 2 and described in detail elsewhere [22,23]. This monitoring grid allows comparison across depth and distance and for evaluation of symmetry around the IWA well with a relatively simple three-factor analysis of variance (ANOVA) model. Continuous, in situ sensors were installed in this grid and subsurface conditions were monitored while a single IWA well was operating to evaluate its efficacy in circulating groundwater, removing contaminants, and distributing dissolved oxygen throughout the contaminant plume.

2.2. Installation of IWA well and test protocol

The IWA well is illustrated in Fig. 3. The casing was 10 cm diameter PVC with 0.51 mm slots in the upper screen and 0.25 mm slots in the lower screen. The latter was covered with a fabric filter sock to reduce entry of fines. A bentonite seal was placed at about 5.2 m below the surface to reduce problems of short-circuiting down through the 16/40 mesh sand pack. Two 1.3 cm diameter piezometers were located in the sand pack about 7.5 cm beyond the casing at 3.1 and 7.3 m below the surface to monitor water level changes at depths representing the middle of the upper screen and the bottom of the lower screen, respectively. Pairs of 0.6 cm diameter polyethylene sampling tubes were installed at depths of 1.8, 3.1, 5.8, and 7.3 m along the casing so that one would be available for collecting soil gas or water samples while the other was used to monitor water levels or to inject tracers. Air was injected into the bottom of the well through a 1.3 cm diameter polyethylene tube that extended from a Gast 1023 blower through a flow meter at the top of the well.

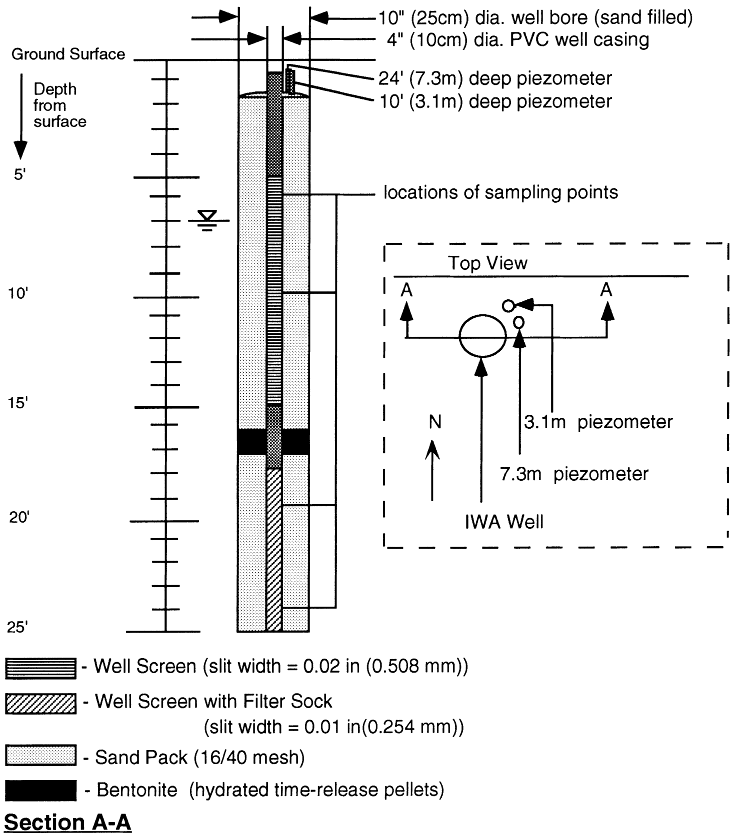

Fig. 3. In-well aeration system well configuration.

The IWA well was located at the center of the monitoring grid at the same location where an IAS well had been installed [23]. Because the IAS well was installed using a direct push technique and was removed by pulling it straight out of the ground, it was anticipated that there would be little, if any, disruption of the native soil in that area.

The IWA well was drilled to a depth of 7.6 m below the surface using a 25 cm diameter hollow-stem auger. The casing was lowered into the hollow center of the auger, and the auger was removed in small increments (approximately 15 cm) as filter sand was poured into the hollow stem to prevent native soil from moving into the annular space around the casing. When the bottom of the auger was approximately 5.2 m below the surface, bentonite pellets were poured into the hollow stem to form a 10 cm thick seal around the casing. More filter sand was added in small increments above the bentonite seal until the auger was removed completely from the ground.

Flowing soil caused native material to move into the annulus around the casing as the auger was being removed during the first two attempts to install the IWA well. Complete removal of the casing and redrilling of the borehole was required. Additional precautions were taken during the installation of the third well such as filling the hollow-stem auger with water to provide back pressure against the flowing soil, use of a larger auger to drill a fresh borehole (20.3 cm augers had been used on the first two attempts), and even slower removal of the auger. On the third attempt, there was no indication that native material had moved in around the IWA well during installation.

The air flow rate into the well was controlled at 5.1 standard cubic meters per hour (scmh), which was the same rate used during previous testing of an IAS well at the same site. The original plan was to operate the IWA system until some steady-state flow or oxygenated volume was established. Preliminary trials indicated that a long-term test was needed to achieve a steady-state condition. One long-term test (IWA 3, 41 days) was followed by a second, shorter-term test (IWA 4, 20 days). The long-term test was not repeated because after 41 days of operation, there was no evidence that the IWA well was circulating an adequate volume of groundwater to affect flow or DO levels even 90 cm from the well.

Two water flow rate tracer tests were conducted using bromide as a tracer during IWA 3. The first test was conducted after 3 days of IWA system operation. The second test was conducted using a higher bromide concentration after the system had been operating for 20 days. The estimated IWA water flow rate was 0.63 l/min from the first test and 0.47 l/min from the second test [21]. An average flow rate of 0.55 l/min was used for all calculations.

In situ instrumentation bundles, described in detail by Hall et al. [22], containing a DO probe, a pressure transducer, a thermocouple, and a sampling tube, were sealed in each MP during IWA 3. Information from all bundles throughout the injection period and during a 2-week recovery period was recorded. Soil gas and groundwater samples were collected 2 weeks after IWA 4.

3. Results and discussion

3.1. IWA 3

In an effective IWA well, water moves out into the aquifer through the upper screen and never reaches the top of the casing. At the WTS site, the Taylor bubbles often broke over the top of the casing, and when this occurred water ran down through the sand pack and back into the well through the upper screen. This splashing of water was not expected and was an early indication that the well was not performing effectively. When water was spilling out of the well faster than it was able to drain back into the sand pack, it had to be pumped out of a concrete cylinder that encircled the well to protect monitoring system instrumentation.

Fig. 4 illustrates the rapid changes in the depths to water for the two piezometers within the sand pack after the blower was turned on at the start of IWA 3. Within 7 min, the depth to water had increased from 2.5 to 3.4 m in the 7.3 m piezometer and had decreased from 2.5 to 2.1 m in the 3.1 m piezometer, indicating that a head difference had been established between the upper and lower screens. From that point there was a steady decrease in the depth to water in the 3.1 m piezometer to a steady-state value of approximately 1.8 m. However, there was also a steady decrease in the depth to water in the 7.3 m piezometer to about 2.7 m, so the head difference between the screens when the blower was turned on remained at 0.9 to 1.3 m throughout IWA 3.

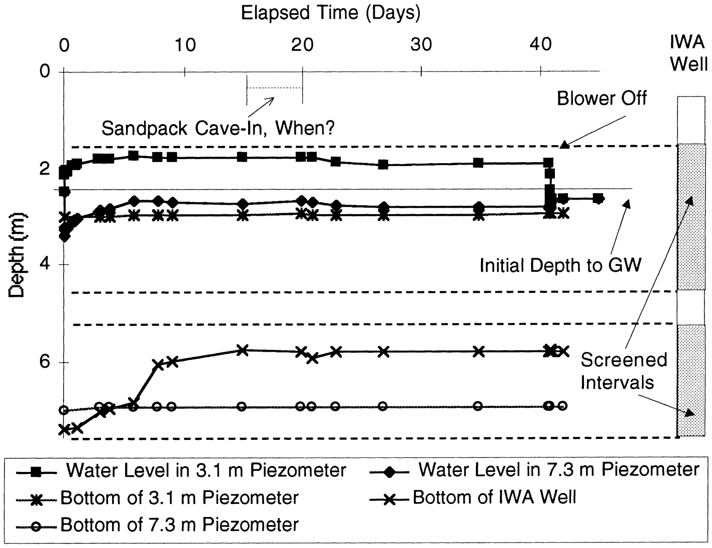

Fig. 4. IWA well characteristics during IWA 3, 6/24/97 to 8/4/97.

The depths to the bottoms of the IWA well and the two piezometers during IWA 3 are also shown in Fig. 4. The original depth to the bottom of the IWA well was 7.4 m. However, as soon as the blower was turned on, silt began moving into the well and collecting at the bottom. By Day 15, the depth to the bottom of the IWA well was only 5.8 m, a change of 1.6 m. This silting did not occur in either the 3.1 or 7.3 m piezometers, which were located only 7.5 cm from the well. As the lower screen of the IWA well was covered with a fabric filter sock during installation to prevent fines from entering the well and water was observed splashing out of the top of the well, one explanation for the rapid accumulation of silt in the well is that any water entering the casing was moving in through the upper screen.

Sometime between the site visits on Days 15 and 20 of the test, the sand pack collapsed approximately 75 cm into the augered annulus, and water no longer occasionally spilled over the top of the casing. The exact time of the cave-in is unknown and there was no obvious reason for its occurrence. One possible explanation is that the rapid decrease in the depth to the bottom of the IWA well between Days 5 and 7 was caused by fines moving out of the area surrounding the casing and into the well, which may have left a cavity around the casing and eventually caused the sand pack to collapse.

IWA 3 was terminated after 41 days when concerns with the temperature dependence of the pressure transducers [23] led to a decision to operate the IWA system without the instrument bundles sealed into the monitoring points (MPs) so that water levels could be measured by hand. Within 15 min of shutting off the blower, water levels in the IWA well and the 7.3 m piezometer had returned to their original static levels, and within 4 h water levels in the IWA well and both piezometers had reached steady-state depths about 15 cm deeper than their original static levels. This difference was most likely due to a seasonal decline in the water table elevation, and is reflected in water level data for other wells across the site [23].

The fluctuations in the pressure transducer responses during IWA 3 could not be attributed to operation of the IWA well and seemed to correlate with the ambient temperature fluctuations at the site. The smallest water level change that could be distinguished from the fluctuations (i.e. the noise) of the pressure transducers from all MPs, including background points on radius *d*, was 15 cm, which was approximately the magnitude of the water level changes anticipated had the IWA well been operating properly. Consequently, it was not possible to discern, from the pressure transducer data, whether any circulation cell was created during the 41-day period of IWA 3.

The pressure transducer used in the instrumentation bundle was selected, in part, because it was a "temperature compensated" sensor. When problems were identified during IWA 3, laboratory tests were conducted to evaluate the temperature compensation capabilities of the sensor [23]. These tests indicated that over a temperature change of 20 to 50°C (as might be expected under the asphalt at the WTS site in late fall or early spring), up to 15 cm of fluctuation in transducer response occurred with no change in the height of the water column that was being measured. The 15 cm of noise in the field data and the 15 cm of fluctuation in the laboratory tests suggests that the IWA well might not have had an effect on water levels during IWA 3.

Each MP in radii *a*, *b*, and *c* was instrumented with a bundle of sensors that measured the DO, total head, and temperature in the saturated zone, or oxygen concentration in the vadose zone. The DO probes were calibrated before IWA 3 and again 6 or 8 days into the test, and all probes were within a specified 10% calibration check throughout the test. There was no overall change in the DO in any of the MPs during IWA 3.

3.2. Determination of horizontal hydraulic conductivity (K_h) distribution

The in situ sensor data obtained during IWA 3 indicated that the operation of the IWA well had little, if any, effect on water levels in the radius *a* MPs. Also, during both IWA 3 and IWA 4, fluorescein and bromide tracers were used to evaluate flow patterns into, through, and out of the well. Preliminary evaluation of the tracer data indicated that small amounts of tracer were moving out from the top of the well, but that tracer was not moving back into the bottom of the well [21], indicating that water migration was much slower than anticipated. Slug tests were conducted to determine the K_h distribution in an effort to explain the inefficient operation of the well. MPs representing all three depths in the saturated zone and all four radii in the grid were used for K_h determinations.

The individual slug tests were performed by first measuring the static water level in a MP, removing a slug of water from it, and then monitoring the water level during recharge. Water level measurements were collected frequently either with an electric well sounder or with a submersible pressure transducer. The slug test data were analyzed using the Bouwer and Rice [24] method for partially penetrating wells in an unconfined aquifer.

The K_h values measured from across the monitoring grid are provided in Table 1. Values from the Level 3 MPs are lower but the same order of magnitude as those estimated by Dupont et al. [25] in three original monitoring wells at the site (24 to 95 cm per day). The monitoring wells were screened across the water table from 2.1 to 5.2 m and, therefore,

Table 1
Horizontal hydraulic conductivity estimates for monitoring grid points

Point	K_h (cm per day)		
	Value	Level average	Level σ
3a1	18		
3a2	49		
3a3	52		
3b1	3		
3b2	6	16.8	18.2
3b3	15		
3c1	3		
3c2	9		
3c3	12		
3d1	1.5		
4a1	0.6		
4a2	1.2		
4a3	3.0	1.5	1.2
4c3	2.4		
4d3	0.3		
5a2	0.09		
5b2	0.09	0.09	0.00
5b3	0.09		

spanned the higher hydraulic conductivity region of the Level 3 MPs (screened from 3 to 3.5 m). It is clear from Table 1 that the K_h decreases by about one order of magnitude at each level as one moves deeper into the soil.

3.3. IWA 4

The IWA well was operated for 20 days for IWA 4, and there were no bundles in the MPs. Silt that had accumulated in the well was removed prior to IWA 4, so the bottom was at the original depth of approximately 7.6 m. The water levels and the depths to the bottoms of the IWA well and the two piezometers during IWA 4 are shown in Fig. 5. The pattern of water level changes is similar to that for IWA 3, except that in IWA 3 the piezometers indicated steady-state operation of the system within 3 to 5 days, while in IWA 4 a similar condition was reached in 1 day. The steady-state head difference between the upper and lower screens was also similar to IWA 3 (about 107 cm). The well silted up during IWA 4 at a slower rate (125 cm in 20 days versus 162 cm in 20 days during IWA 3), and there was no noticeable increase in the silting rate as occurred during IWA 3 between Days 5 and 7. Also, there was no evidence of sand pack collapse during IWA 4.

During IWA 4, the water levels in the saturated zone MPs were measured several times during the first hour of operation, less frequently for the next 23 h, and then every 3 to 4 days for the remainder of the test. The depths to water in all wells displayed a steady decrease of about 3 to 6 cm until Day 8, an increase of about 9 cm between Days 8 and 16, and another decrease of about 4.5 cm between Days 16 and 22 (the blower was turned off on Day 20).

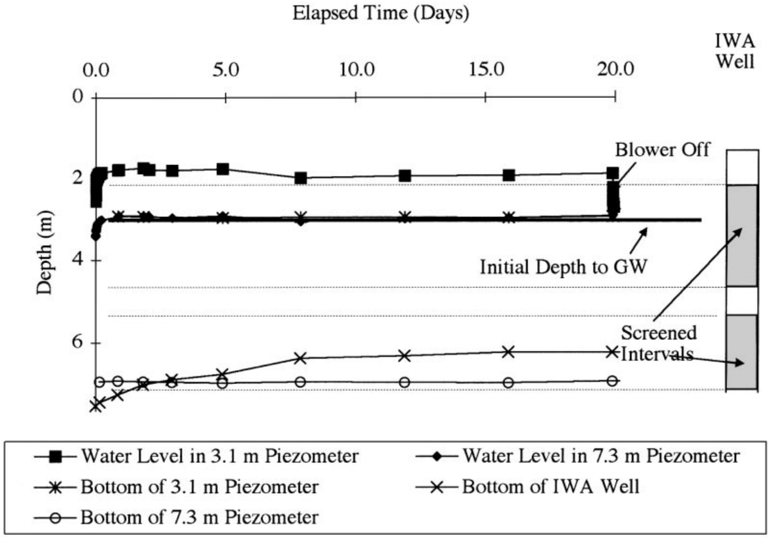

Fig. 5. IWA well characteristics during IWA 4, 9/10/97 to 9/30/97.

These water level fluctuations were well below the lower limit of the pressure transducers. Climatological data indicated that on Days 9, 10, and 11, a total of 2.3 cm of rain fell at the site. The depths to water were corrected for the rain event by extrapolating the rate of water level decline for Days 0 to 8 through Day 12, and are illustrated for an *a*, *b*, *c*, and *d* radius well in Fig. 6.

Water level fluctuations can sometimes be correlated with barometric pressure changes [26,27]. For this reason, barometric pressure fluctuations, obtained at 3 h intervals from

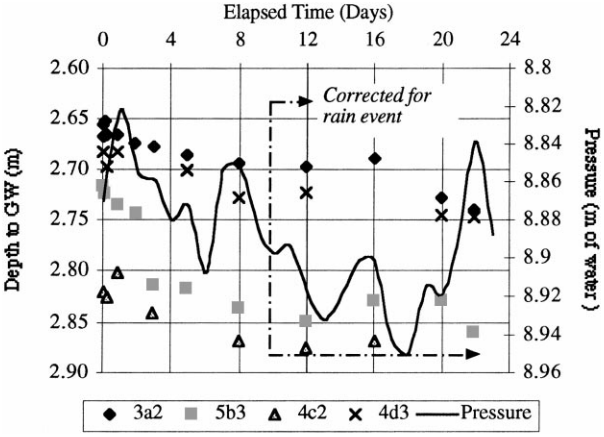

Fig. 6. Depth to ground water for four monitoring points during IWA 4 corrected for rain events between Days 9 and 12.

Salt Lake City climatological data provided by the National Climatic Data Center, have also been included in Fig. 6. As illustrated, there is no consistent relationship between the water level changes and the barometric pressure changes during IWA 4. The change in water levels in all of the MPs only reflects the typical seasonal decline in the water table elevation, and there appears to be no relationship between the operation of the IWA well and the water level changes even at a distance of as little as 90 cm from the well.

3.4. Contaminant response

Groundwater samples were collected approximately 1 month before and 2 weeks after the two IWA tests (pre- and post-IWA sampling events). There was no difference in the average concentrations across all MPs throughout the tests for all compounds analyzed [23].

4. Post-testing sand pack evaluation

4.1. Sand pack evaluation procedure

Because the IWA system did not appear to establish a circulation cell in the subsurface, and the well silted up and the sand pack collapsed during IWA 3, there were concerns about the integrity of the sand pack around the upper and lower screens. A soil core had been collected in the area that was then augered out for installation of the IWA well. The pre-IWA soil core was divided into 60 cm segments and composite samples of each section were sent to the Utah State University Soil Testing Laboratory for hydrometer analysis of soil texture. Another soil core, called the “sand pack core”, was collected in the IWA well sand pack after IWA 4 for comparison with the pre-IWA core of the native soil.

The sand pack core was collected by directly pushing a hollow-tipped, clear, plastic sample tube down into the sand pack. Coloration in the core was noted and it was split into sequential, vertical groups based on similarity in visible and textural characteristics. Samples with visible silica sand were analyzed for grain size and all other samples were analyzed for soil texture by hydrometer.

The sand pack consisted of a 16/40 sieve (40 openings/in. = nominal particle diameter of 0.5 mm) silica sand. Had the sand pack been acting as a filter to reduce migration of fines into the well, the sand pack core samples should have contained a large percentage of sand greater than 0.5 mm in diameter, with a smaller percentage of smaller diameter fines that were trapped in the filter. Also, the bentonite seal installed at approximately 5.2 m should have been apparent in the sand pack core.

4.2. Results of sand pack core analysis

Fig. 7 illustrates the results of the grain-size analysis performed by mechanical shaking (ASTM D421 and D422; and AASHTO T87 and T88) of samples from six depths in the sand pack core. Sample Groups A through E are from the top 4 m of the sand pack. Group K (from 5.6 to 6.1 m) was the only other sample containing a visible amount of silica sand. The largest grain diameter (left most) was the #40 sieve. Had this core been collected just

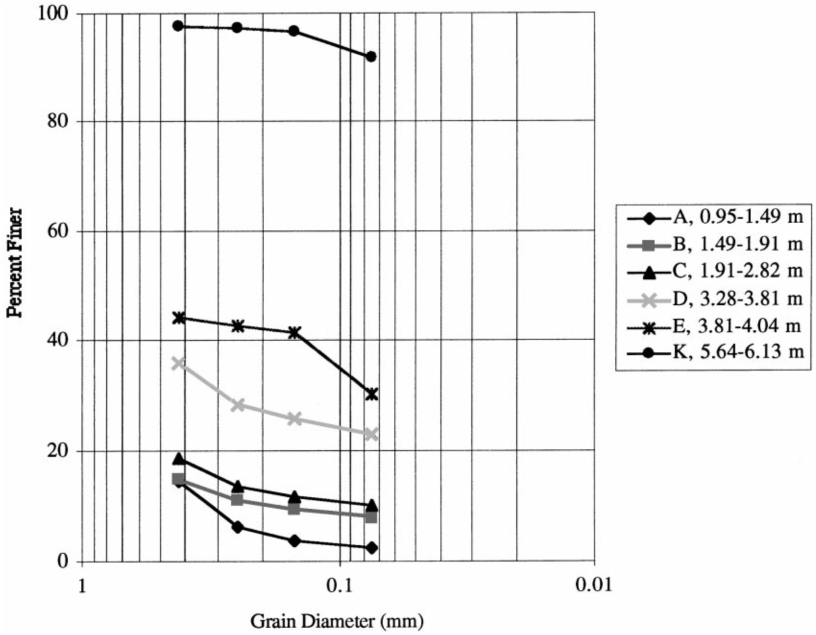

Fig. 7. Particle size distribution of soil core from IWA well sand pack after >60 days of operation. Ascending letters = descending elevations.

after the well was installed, the percent finer than #40 sieve should have been close to zero. The percent finer than #40 sieve increases with depth, and even though there was some visible sand in the Group K sample, less than 3% (by weight) of the material was retained by a #40 sieve. To try and understand why there was a steady increase in fines in the sand pack with depth, the textures of the soil and sand pack cores were compared.

Fig. 8 illustrates the percent sand for each of the sample groups. The *y*-axis value is the mean depth of each grouping range. The solid squares represent the soil core that was collected before the IWA well was installed, and the open circles represent the sand pack core that was collected after IWA 4. There was 20 to 50% sand throughout the soil core except in a region with higher sand content at about 3.7 to 4.6 m and in the aquitard at the bottom of the borehole. As expected, there was nearly 100% sand near the top of the sand pack core. However, this percentage decreased gradually down to about 3.7 to 4.6 m and then dramatically below 4.6 m. The sand pack core material contained less sand (more fines) after operation of the well than was initially present in the soil. The material at the bottom of both cores appears to be native, undisturbed soil.

From Fig. 8, it appears that the sand pack was almost completely replaced with fines from the native soils during operation of the IWA well. It is possible that the sand was flushed out of the annulus below 4.6 m by flowing soils during well installation. A bentonite seal was installed from 4.9 to 5.2 m, about the depth below which there was consistently less than 20% sand in the sand pack core. Another possibility is that above the seal the sand

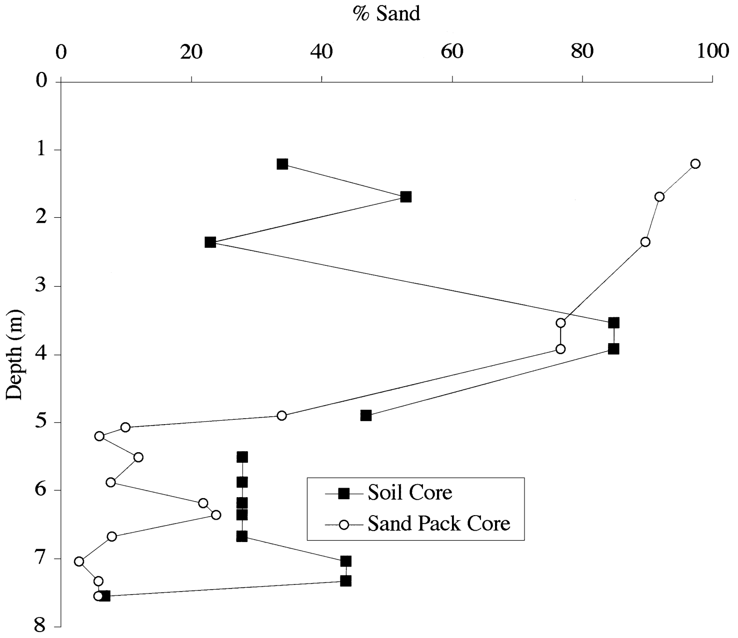

Fig. 8. Percent sand in the soil core segments for before installation of the IWA well and in the sand core after operation of the well.

pack remained intact but that the sand below the seal was flushed out sometime between Days 5 and 7 of IWA 3 (see Fig. 4) and replaced with native soils. Then, sometime between Days 15 and 20, the sand pack above the seal collapsed into the void that was created. The bentonite seal was not obvious in the sand pack core, but there were some grayish nodules in the Group H sample (5.0 to 5.2 m depth) that might have been the expanded pellets.

Another explanation is that the IAS well operated at the site prior to the installation of the IWA well may have altered the soils. When the IAS casing was removed, a circumferential crack was identified at approximately 4.9 m. The crack surface appeared oxidized, indicating that the crack had been present and exposed to corrosion for some time prior to the removal of the IAS well. If air was exiting the IAS well from this crack, a pocket could have formed in the soil. It is possible that sand from the IWA well annulus moved into this pocket, creating voids around the well that were filled with fines during installation or operation of the IWA well.

Regardless of the mechanism by which the sand pack was replaced by native material, it is obvious that the condition of the IWA well sand pack prevented effective circulation of the groundwater by this well at the Layton site. The accumulation of silt in the well during IWA 3 and IWA 4, along with this replacement of the sand pack material, suggests that the soil at the WTS site is not suitable for effective operation of an IWA system.

5. Conclusion

A cylindrical monitoring grid consisting of 49 MPs was installed around a single IWA well at a gasoline-contaminated site and operated for one 41-day (IWA 3) and one 20-day (IWA 4) test. There was no change in DO in the inner-most wells (radius *a*) during IWA 3, indicating that a circulation cell was not established even within a distance of only 90 cm from the IWA well. Also, there was no change in the HC total mass or distribution across the site during IWA 3 or IWA 4.

The instrumentation bundles were removed from the MPs and the water levels were measured by hand during IWA 4 due to lack of temperature compensation by the pressure transducers. Results of IWA 4 indicate that water level changes in any MP can be explained by a regional rain event and seasonal water table decline. As with IWA 3, any circulation of water through the IWA well must have occurred at a distance of less than 90 cm, was probably just in the sand pack around the casing, and was reflected only in the piezometers in the sand pack.

There was substantial accumulation of fines in the IWA well during both tests, even with a fabric filter sock over the lower screen, leading to the conclusion that groundwater entered the well primarily through the upper screen. In addition, comparison of a soil core collected before the IWA well was installed and a core collected from the sand pack after IWA 4 indicated that the percentage of sand around the bottom (intake) portion of the well was less after operation than it had been before. The sand pack material added during installation of the IWA well appears to have been replaced by native fines during installation or operation of the well, preventing effective circulation by the well at this site. It seems likely that water moved up through the well, out into and down through the sand pack, and back into the casing along the upper screen above the bentonite seal.

No circulation cell was established around the IWA well after 41 days of operation, extreme silting up in the well limited the operation time between well maintenance, and the well did not impact water levels or DO even 90 cm from it. For these reasons, it is apparent that the IWA system installed at the WTS site was ineffective in remediating the contamination at the site. Slug tests indicate that the K_h is relatively low near the water table (17 cm per day) and decreases with depth to 0.09 cm per day at 6.1 m below the surface. It seems likely that the low K_h of the soil surrounding the lower screen of the IWA well was an important factor that contributed to the ineffectiveness of the system.

Another problem that may have contributed to the ineffectiveness of the IWA well installed at the WTS site was that the distance between the two screens was relatively short compared to the radius of the borehole. A modeling study of a typical IWA system design performed by Peursem et al. [28] demonstrates that the percentage of flow short-circuited through the sand pack is roughly 10 times greater when the ratio of the distance between the two well screens to the borehole radius is reduced from about 100 to about 20. This ratio for the IWA well installed at the WTS site is 27.6, suggesting that had the screens been shorter, thus lengthening the distance between them, the problem of water short-circuiting through the sand pack along the upper screen might have been less severe.

Another modification that may reduce problems with short-circuiting along the sand pack would be to install IWA wells by a direct push technique rather than placing a sand pack around them. Conceptually, this should enhance horizontal flow through the two screens.

However, the K_h at the WTS site is so low and recharge at Level 5 is so slow that the air injection flow rate would have to be low to prevent blowing the well dry. With low air injection rates, remediation times would likely not be accelerated enough to make the technology attractive at this site even with this modification.

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