Feasibility Study of In-Well Vapor Stripping Using Airlift Pumping

by Haim Gvirtzman and Ori Gonen

Abstract

This study tests the feasibility of an aquifer remediation concept proposed by Gvirtzman and Gorelick (1992) that involves the removal of volatile organic compounds (VOCs) dissolved in ground water. The principal is to inject air into a well, creating airlift pumping, which is used as a means of in-well vapor stripping. The partially treated water is diverted away from the well and infiltrates back to the water table, thus allowing remediation of a larger aquifer volume.

A remediation well prototype, constructed in a laboratory aquifer model, was used to demonstrate the processes involved. The removal rates of trichloroethylene, toluene, and chloroform were monitored using eight triple-level observation wells. The continuous decrease of VOC concentrations during the short-term experiment has yielded macroscopic evidence that the process offers some promise. It was found that the flow field in the saturated zone, involving the continuous water circulation between the pumping well and the recharging area, caused temporal and spatial variation in remediation efficiency.

Introduction

During the last decade, many resources and much effort were devoted to the research of ground water pollution and for actual remediation of contaminated aquifers (Porter 1989). In the quest for cost and time-effective remediation methods, new remedial concepts have been introduced (Abelson 1989; Mackay and Cherry 1989). This laboratory investigation focuses on a new remediation technique that aims to remove VOCs dissolved in ground water. VOCs are commonly found in sites contaminated by petroleum products, oil, and industrial solvents. Most contamination of ground water of this type has been caused by leakage, spillage, or disposal of organic liquids immiscible with water into ground water (Domenico and Schwartz 1990). Common VOCs are trichloroethylene (TCE), 1,1,1 trichloroethane (TCA), tetrachloroethylene (PCE), chloroform, carbon tetrachloride, and their degradation products.

The customary treatments for soil and ground water contaminated by VOCs include the following: excavation of contaminated soils (Thornton and Wooton 1982); pump and treat using air towers (Mackay and Cherry 1989; McFarland 1989); enforced ventilation of the unsaturated zone (Baehr et al. 1989); and biodegradation (Wilson and Wilson 1985; Thomas and Ward 1989; Corapcioglu et al. 1991). Each of these methods aims to treat a different part of the contaminated site (e.g., soil, unsaturated zone, or sat-
urated zone, and each has advantages and disadvantages. For example, the latter two have the advantage of being in situ treatments, which are sometimes preferable.

Subsurface air sparging was recently introduced as an innovative technology. It uses circulated air to remove dissolved VOCs from the saturated zone. This method can be advantageous over conventional pump-and-treat systems because no aboveground installations are needed, and injecting air is more efficient and less costly than pumping water. Furthermore, air sparging may stimulate natural bioremediation.

Focusing on subsurface air sparging treatments, three new methods have been introduced, all aiming to force VOC into the gas phase: (1) an under pressure vaporizer well (Herrling et al. 1990); (2) air sparging involving injection of air into the porous media (Angell et al. 1992); and (3) vapor stripping by in-well air injection and consequent airlift pumping (Gvirtzman and Gorelick 1992). The feasibility of the third technique is reported herein. The major advantage of in-well technology compared to injection of air into the aquifer is that stripping occurs in the well, thus avoiding channeling problems.

The principal of this remediation concept is to use airlift pumping and subsurface recirculation as a means of in situ vapor stripping (Gvirtzman and Gorelick 1992). Air that is injected into a well creates bubbles that rise inside the well (Figure 1). Due to the difference between the density of ground water outside the well and the density of the water/air bubble mixture inside the well, a lift is created (Govier and Aziz 1972; Taitel et al. 1980; Driscoll 1986). During the pumping, VOCs are stripped by diffusional mass transfer from the water phase into the air bubbles. The bubbles containing VOCs are separated from the water, and the VOC vapor is collected at the top of the well and treated. The partially treated water is diverted away from the well and recharged back to the aquifer by gravitational seepage from a pond through the unsaturated zone. Consequently, circulation of water is created around the well, which allows remediation of a larger aquifer volume. As water continues to circulate, the VOC concentration is further reduced. The aquifer volume that is remediated by this method is controlled by planning the flow field around the well. Given the local ground water flow regime and the geometry of the aquifer and the contamination plume, the flow field can be controlled by designing the locations of the pumping well and the recharge pond.

The objective of this research was to prove the feasibility of the new remediation method by building a well prototype and a running short-term controlled laboratory experiment.

Material and Methods

A remediation well prototype, constructed in a laboratory aquifer model, was used to demonstrate the remediation process. The removal rates of trichloroethylene, toluene, and chloroform were monitored using eight triple-level observation wells.

Figure 1. Schematic configuration of a remediation system, in which airlift pumping is used as a means of in-well vapor stripping. Water (solid arrows) is lifted in the well, diverted away from the well, infiltrates through the unsaturated zone back to the aquifer, and flows back to the well. Air (outlined arrows) is injected into the well, bubbles rise and are collected at the top of the well (after Gvirtzman and Gorelick 1992).

Figure 2. The aquifer model, 200-cm long, 65-cm wide, and 100-cm high, includes the remediation well prototype and eight observation wells. The sand-filled aquifer contains a 50-cm-thick unsaturated zone, overlying a 50-cm-thick saturated zone. The ground water table is controlled by the water levels at the two storage tanks.

The Aquifer Apparatus

The experimental apparatus is illustrated in Figure 2. It included an aquifer model in which a well prototype, a recharge pond, and eight observation wells were constructed. The container was made of Plexiglas walls, with outer dimensions of 250 × 70 × 100 cm, and inner dimensions of 245 × 65 × 98 cm. The central part of the 200-cm-long container, which held the porous material, was separated from two water tanks at both sides of the aquifer by a dense stainless steel screen. The
water table in the aquifer was regulated by the water levels in both tanks using vertically adjusted overflow outputs. The tank was partially filled with water, creating a 50-cm-thick saturated zone, overlain by a 50-cm-thick unsaturated zone. Coarse quartz sand, 0.05 to 0.08 cm in diameter, which had been washed thoroughly, was used in the experiments. The properties of the aquifer material are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density (^\d)</td>
<td>(\rho_p)</td>
<td>(2.65\pm0.01)</td>
<td>g/cm(^3)</td>
</tr>
<tr>
<td>Bulk density (^\d)</td>
<td>(\rho_b)</td>
<td>(1.85\pm0.05)</td>
<td>g/cm(^3)</td>
</tr>
<tr>
<td>Porosity (^\d)</td>
<td>(n)</td>
<td>(0.30\pm0.02)</td>
<td></td>
</tr>
<tr>
<td>Hydraulic conductivity (^\d,\d)</td>
<td>(K)</td>
<td>(150\pm10)</td>
<td>m/day</td>
</tr>
<tr>
<td>Ground water level (^\d)</td>
<td>(h)</td>
<td>(50.0\pm0.1)</td>
<td>cm</td>
</tr>
</tbody>
</table>

\(^\d\) Measured in columns filled with aquifer material.
\(^\d\) Measured using the aquifer model itself.

The Well Prototype

An airlift pumping well made of Plexiglas pipes was constructed and placed at the center of the aquifer model. It included three pipes, one inside the other (Figure 3). The outer pipe (O.D. = 60 mm; I.D. = 50 mm) was the well casing, which was fully screened and further wrapped with fine stainless steel screening to prevent grains from entering the well. The inner pipe (O.D. = 13 mm; I.D. = 9.4 mm) was an air line through which air was injected into the well. The middle pipe (O.D. = 30 mm; I.D. = 24 mm) was an eductor pipe through which a mixture of water and air bubbles was lifted. The injected air was released at a depth of 40 cm below the water table through a bubblter (O.D. = 20 mm) containing a dozen 0.03-cm-diameter holes (Figure 3), creating tiny bubbles that rise. The air injection rate was controlled by a pressure valve and was measured by a flowmeter.

Water and air bubbles were lifted in a 100-cm-long eductor pipe, which passed through 40 cm of the saturated zone, 50 cm in the unsaturated zone, and 10 cm above the top surface, entering a water/air separation cylinder. In this chamber, water remained temporarily immobile; thus, air bubbles were released upwards into the chamber space (Figure 3). Then the air, including the VOC vapor from the popped bubbles, was sucked into a laboratory hood.

Observation Wells

Eight observation wells (two rows of four wells — Figure 2), each 1 cm in diameter, were emplaced within the aquifer model. The well casings were screened by 0.5-cm-diameter holes along the entire saturated zone and were wrapped with a dense stainless steel screen (size of openings about 0.2 mm). These wells were used to measure the water levels and sample water from the aquifer. Water levels were measured using a long, fine-threaded screw, with a precision of ±0.05 cm. Water samples were collected using a triple-level sampler (Figure 4), sucking water from three 3-cm-thick layers, the centers of which were located at 10, 25, and 40 cm above the aquifer bottom. Each of the samplers included three thin, elastic Tygon® tubes, each reaching to one of the three depths. Each of the depth intervals was separated at its top and bottom by disks wrapped with rubber O-rings (Figure 4), thereby preventing vertical water mixing. Disposable plastic 10-mL syringes were connected to each of the tubes at the well top, from which the water samples were drawn.

Experimental Conditions

Three dissolved compounds were used: trichloroethylene (TCE), chloroform, and toluene. Their properties are summarized in Table 2. The source solution for the experiment was prepared by dissolving the VOCs in methyl-alcohol and then further dissolving the solution in water. In this way, an emulsion did not form. For health and safety reasons, concentrations were always lower than 5 ppm in all experiments.

Preparing the aquifer was carried out one day before the start of the experiment. First the contaminated water was introduced through the storage tank on one side of the aquifer (Figure 2). After one day of quiescence,
each of the eight observation wells, from the two water tanks on the two sides of the aquifer, and from the bottom and the top of the well. Water samples were sucked using syringes and transferred immediately afterwards into 9-mL glass bottles for storage. The bottles were covered with Teflon™ disks and screw-on caps, wrapped with parafilm, and placed in the refrigerator at 4°C for not more than three weeks.

In order to test the possibility of VOC removal through bioremediation or direct evaporation, a controlled experiment was performed. The same initial conditions were prepared, but no airlift pumping was applied. Water samples were collected during 48 hours from the 24 sampling points for subsequent chemical analysis.

**Analytical Procedure**

Preparation of standard solutions and calibration of analytical equipment were carried out following the guidelines of the U.S. EPA Method 601 for purgeable halocarbons and Method 602 for purgeable aromatics (Longbottom and Lichtenberg 1982). A known standard solution was run at the beginning and end of each day to verify the system’s stability. Total analytic errors are estimated to be ±8 percent, including ±3 percent for the system calibration and ±5 percent for instrumental errors (reproducibility). All samples were analyzed within three weeks of collection.

Monitoring equipment, placed in the same room at the experimental setup, included a complete gas chromatograph system. VOCs dissolved in water were stripped using a Purge and Trap Concentrator, Tekmar LSC 2000. Then samples were automatically injected into a Perkin Elmer Autosystem gas chromatograph, separating the compounds and determining their concentrations. Helium was used as a carrier gas, using a column of 20-feet-long, ½-inch-inner diameter, packed with PT 10 percent Alltech At-1000 on Chromosorb W- AW, 80/100. Compressed air and H2 (produced by a Packard 9200 hydrogen generator) were used for burning at the FID detector. The whole system was controlled by a PE Nelson, 1020 GC Plus Integrator.

**Results and Discussion**

When airlift pumping was started, a cone of depression was developed around the well, and, concurrently, infiltrating water started to mount beneath the recharge pond. A steady-state velocity field was established.
Figure 5. Computed steady-state distribution of ground water head (cm), exhibiting the cone of depression in the well, and water mounting below the recharge pool. The locations of the eight observation wells are also shown.

Table 3
Experimental Results as Average Concentrations ± Their Standard Deviations (in ppm)

<table>
<thead>
<tr>
<th>Time</th>
<th>0 Hours$^1$</th>
<th>12 Hours</th>
<th>48 Hours</th>
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<tr>
<td><strong>Remediation Experiment</strong></td>
<td></td>
<td></td>
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<tr>
<td>Wells 1–6$^2$</td>
<td>TCE</td>
<td>2.5±0.5</td>
<td>0.6±0.1</td>
</tr>
<tr>
<td></td>
<td>Chloroform</td>
<td>3.5±0.5</td>
<td>1.4±0.3</td>
</tr>
<tr>
<td></td>
<td>Toluene</td>
<td>2.0±0.5</td>
<td>0.5±0.1</td>
</tr>
<tr>
<td>Wells 7, 8$^3$</td>
<td>TCE</td>
<td>2.2±0.6</td>
<td>1.6±0.6</td>
</tr>
<tr>
<td></td>
<td>Chloroform</td>
<td>2.9±0.8</td>
<td>2.2±0.9</td>
</tr>
<tr>
<td></td>
<td>Toluene</td>
<td>1.7±0.5</td>
<td>1.4±0.6</td>
</tr>
<tr>
<td><strong>Controlled Experiment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Wells</td>
<td>TCE</td>
<td>2.6±0.4</td>
<td>2.4±0.5</td>
</tr>
<tr>
<td></td>
<td>Chloroform</td>
<td>3.3±0.3</td>
<td>3.2±0.3</td>
</tr>
<tr>
<td></td>
<td>Toluene</td>
<td>2.4±0.4</td>
<td>2.2±0.4</td>
</tr>
</tbody>
</table>

$^1$Initial conditions.

$^2$Six observation wells (each at three sampling points) located within the pumping well influence zone; thus, rate of VOC concentration reduction is faster.

$^3$Two wells (each at three sampling points) located away from the pumping well; thus, rate of VOC concentration reduction is slower.

Given the aquifer properties (Table 1), the aquifer geometry (Figure 2), and rates of water pumping and reinfiltration (both 0.75 L/min), a two-dimensional flow numerical package, called Aquifer Simulation Model (Kinzelbach and Rausch 1989), was used to estimate the steady-state flow conditions. Computed results are presented in Figure 5. As can be seen, at the depression center (in the well) the water table was stabilized at 48.2 cm, and below the recharge pond, at 51.2 cm above aquifer base.

In many cases, the whole aquifer flow field can be deduced from the water table distribution. However, in our experiment, the vertical flow component cannot be disregarded. Although the well is screened throughout, flow into the well took place mainly at the lower aquifer horizon, where the slots of the eductor pipe (Figure 1) and the air bubblers were located. Also, water infiltrated vertically from the recharge pond through the unsaturated zone, and thus discharged into the aquifer only at the water table. Figure 5 represents the computed head distribution in which a two-dimensional flow regime was assumed (i.e., the true flow regime was not predicted). Nevertheless, qualitatively the highest flow velocity should be found along the diagonal line connecting the water table beneath the recharge pond and the bottom of the pumping well. Quantitative modeling of the three-dimensional flow field is currently underway.

The well influence zone, wherein the removal efficiency of VOCs is significant, should therefore be defined by the flow field. Reinfiltration of partially treated water took place at the water table region between observation wells 1, 2, 3, and 4 (Figure 5). Pumping of contaminated water took place at the lower horizon between observation wells 3, 4, 5, and 6. It is postulated that along flow lines with relatively high velocity, circulation through the remediation well was efficient, and VOC concentrations were quickly
reduced. However, along slow-rate flow paths, circulation through the well was not efficient, and VOC concentrations decreased slowly. Indeed, experimental results of VOC concentrations, summarized in Table 3, exhibited a significant concentration reduction at observation wells 1 through 6. However, out of the pumping well influence zone, at observation wells 7 and 8, VOC concentrations have slightly reduced.

The actual remediation efficiency depends on the rates of two basic processes, the volatilization of VOCs from the water into air bubbles while water is pumped inside the well and the desorption of VOCs from the solid matrix into ground water (flowing toward the remediation well). Quantitative analyses of these two rate-controlling processes are beyond the scope of this paper but are underway. However, qualitative description is possible based on the spatial and temporal variations in VOC concentrations.

Selected concentration results of TCE, chloroform, and toluene during the two-day experiment are presented in Figures 6, 7, and 8. The remediation rate at a given point and at a given time can be qualitatively defined by the curve slope. The general pattern observed everywhere is a decrease of slope with time. For example, at one of the most effective remediation points, the upper horizon at well 2 (Figure 6), the chloroform concentration decreased by almost 3 ppm during the first 10 hours of the experiment, by about 0.5 ppm during the second 10 hours, and only by about 0.2 ppm during the third 10 hours. Similarly, the decreasing rate in TCE concentration (Figure 6) demonstrates the same phenomenon. This behavior is a result, at least in part, of the diffusional mass transfer of VOCs from the water into the air bubbles. As was shown by Gvirtzman and Gorelick (1992), the VOC removal rate is linearly proportional to the departure from the equilibrium concentration between the contaminated water and the air that is injected into the well. Therefore, as VOC concentration decreased, the mass transfer rate in the well decreased as well, and thus decreased within the whole aquifer.

A controlled experiment was performed to test the possibility of VOC removal by any other means. It was found that without the application of airlift pumping, VOC initial concentrations remained the same throughout the 48 hours of monitoring (Table 3). Thus, it is concluded that bioremediation or direct evaporation caused no significant effect.

Comparison between removal rates at various points at a given time, using their curve slopes, reflects the circulation pattern in different parts of the aquifer. For example, during the first 10 hours of the experiment, remediation efficiency observed in well 4 (Figure 7a) was higher than that observed in well 6 (Figure 7b). Moreover, even at a given well, remediation efficiencies varied between different horizons. For example, at
well 3, during the first five hours of the experiment, VOC concentrations were reduced at a higher rate in the middle horizon (Figure 8b) than those in the upper and lower ones (Figure 8, a and c). All these variations are attributed to the established flow field within the aquifer. Along flow lines with relatively high velocity, circulation through the remediated well was efficient, and VOC concentrations were quickly reduced. However, along slow-rate flow paths, circulation through the well was not efficient, and VOC concentrations decreased slowly. Finally, it is important to note that the initial concentrations of VOCs in the aquifer were not absolutely uniform (Figures 6, 7, and 8). Rather, slight variations were detected at the sampling points, resulting from the slight concentration variations in the source solution, which was continuously injected into the aquifer. When airlift pumping was started, circulation within the aquifer was initiated; thus, these initial variations were redistributed over time. It seems that the observed increases in VOC concentrations during the first two hours (for example, Figures 7b and 8) were the result of this effect.

Conclusions

The remediation concept of using airlift pumping as a means of in-well vapor stripping was tested in this study in the laboratory using a simulated aquifer, in which the well prototype was constructed. The results demonstrated the different rates of VOC removal from various parts of the aquifer. This study yielded macroscopic evidence that the process offers some promise. A quantitative analysis of the actual circulation within the aquifer and the mass transfer processes (volatilization into air bubbles and desorption from solid matrix) requires a three-dimensional model of flow and transport, which is beyond the scope of this paper, but is currently underway.

Finally, it is expected that application of the method in actual aquifers will be controlled by diffusion-limited transfer from low-permeability zones, as is the case with conventional pump-and-treat systems.

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References


Figure 8. Concentrations of toluene and TCE vs. time in the upper (a), middle (b), and lower (c) horizons of well 3, demonstrating the variations in VOC removal rate in a given well.


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**Biographical Sketches**

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