Transport and degradation of perchlorate in deep vadose zone: implications from direct observations during bioremediation treatment

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Abstract

An in situ bioremediation experiment of a deep vadose zone (~40 m) contaminated with a high concentration of perchlorate (>25,000 mg L\(^{-1}\)) was conducted through a full-scale field operation. Favorable environmental conditions for microbiological reduction of perchlorate were sought by infiltrating an electron donor-enriched water solution using drip irrigation underlying an airtight sealing liner. A vadose-zone monitoring system (VMS) was used for real-time tracking of the percolation process, the penetration depth of dissolved organic carbon (DOC), and the variation in perchlorate concentration across the entire soil depth. The experimental conditions for each infiltration event were adjusted according to insight gained from data obtained by the VMS in previous stages. Continuous monitoring of the vadose zone indicated that in the top 13 m of the cross section, perchlorate concentration is dramatically reduced from thousands of milligrams per liter to near-detection limits with a concurrent increase in chloride concentration. Nevertheless, in the deeper parts of the vadose zone (<17 m), perchlorate concentration increased, suggesting its mobilization down through the cross section. Breakthrough of DOC and bromide at different
depths across the unsaturated zone showed limited migration capacity of biologically consumable carbon and energy sources due to their enhanced biodegradation in the upper soil layers. Nevertheless, the increased DOC concentration with concurrent reduction in perchlorate and increase in the chloride-to-perchlorate ratio in the top 13 m indicate partial degradation of perchlorate in this zone. There was no evidence of improved degradation conditions in the deeper parts where the initial concentrations of perchlorate were significantly higher.

1 Introduction

In situ bioremediation of a contaminated unsaturated zone (also termed vadose zone) depends mainly on the ability to control the hydrological, physical and chemical conditions in the subsurface (Bombach et al., 2010; EPA, 2015; Höhener and Ponsin, 2014). Chemical and hydrological manipulations are primarily aimed at enhancing the activity of specific indigenous degrading bacteria. The optimal conditions for specific contaminants' degradation are usually determined in microcosm experiments, where the preferred electron donor and acceptor for degradation can be controlled and examined (Gal et al., 2008; Megharaj et al., 2011; Sagi-Ben Moshe et al., 2012). The optimal degradation conditions, evaluated through laboratory experiments, usually form the basis for selecting a strategy for in situ remediation in field-scale operations. Nevertheless, implementation of desired biodegradation conditions in the deep vadose zone through full-scale field setups requires control of the vadose zone hydrogeochemical conditions. This is often achieved through either infiltration of water enriched with electron donors or nutrients (Battey et al., 2007; EPA, 2004; Frankel and Owsianik, 2005), or injection of a gaseous mixture capable of promoting optimal biogeochemical conditions for microbial pollutant degradation (Evans et al.,
Due to the complex nature of flow and transport processes in the unsaturated zone, application of water with specific chemical conditions near land surface does not necessarily result in promoting the desired geochemical and hydraulic conditions in deeper parts of the vadose zone (Allaire et al., 2009; Flury and Wai, 2003; Jarvis, 2007; Rimon et al., 2011a). Therefore, in the vadose zone, and particularly in its deeper parts, a proper understanding of the transport process is key to the success of in situ remediation operations (Baram et al., 2012a; Dahan et al., 2009; Kurtzman et al., 2016; Rimon et al., 2011a).

Assessment of water percolation and solute transport in the vadose zone is considered a major challenge in hydrological sciences. It is often characterized by unstable flow that is highly sensitive to hydraulic, chemical and microbial conditions (Bauters et al., 2000; Dahan et al., 2009; DiCarlo, 2007; Germann and al Hagrey, 2008; Hallett et al., 2013; Rimon et al., 2011a; Sher et al., 2012; Stumpp et al., 2009). Moreover, the chemical composition of the percolating water [e.g., dissolved organic carbon (DOC), oxygen and nutrients] is subjected to frequent changes due to natural hydroclimatic and biological cycles (Stumpp et al., 2009, 2012). Accordingly, contaminant attenuation in the vadose zone is dependent on the complex hydrological, chemical and biological states of the sediment. Continuous measurements of the hydrological and chemical properties of the unsaturated zone may be achieved with a vadose-zone monitoring system (VMS) (Dahan et al., 2009). The VMS provides high-resolution measurements of variation in sediment water content (Dahan et al., 2008; Rimon et al., 2007) and evolution of the pore water's chemical composition across the unsaturated profile (Rimon et al., 2011a; Dahan et al., 2014; Turkeltaub et al., 2014, 2016).
Perchlorate is an environmental pollutant that is often associated with the explosives manufacturing industry (Roote, 2001; Urbansky, 2002; Trumpolt et al., 2005). It is mostly produced, and consequently released to the environment as ammonium perchlorate. Its high solubility (220 g L$^{-1}$) and stability in aerobic environments makes it very mobile and persistent in the subsurface (Motzer, 2001; Urbansky and Brown, 2003). Microbial reduction of perchlorate to harmless chloride and oxygen in the unsaturated zone requires elevated water content, negative redox potential, available electron donors and the presence of suitable indigenous bacteria (Coates and Achenbach, 2004). In the vadose zone, natural attenuation and biodegradation of perchlorate are considered very limited (Gal et al., 2009). Nevertheless, studies have shown that perchlorate can be metabolized in unsaturated soil whenever reducing conditions ($<110$ mV) (Attaway and Smith, 1993; Shrout and Parkin, 2006) are achieved and an available electron donor is introduced (Tipton et al., 2003; Frankel and Owsianiak, 2005; Nozawa-Inoue et al., 2005; Evans and Trute, 2006; Cai et al., 2010).

Here, the efficiency of a remediation operation of a perchlorate-contaminated vadose zone was assessed using a VMS, which provided continuous information on the chemical composition of the vadose-zone pore water. Promotion of perchlorate-degrading conditions in the vadose zone was based on infiltration of water enriched with ethanol (as a source of electron donor) from land surface. Real-time information on the depth of the enriched water's propagation, along with variations in the concentrations of perchlorate, chloride and bromide (applied as a tracer), was used to assess transport and degradation of perchlorate across the unsaturated profile. Water- and ethanol-application strategies were adjusted in each flow phase to obtain real-time feedback on the chemical and hydrological state of the vadose zone.
2 Study site

The study area is located in the central part of the Israeli coastal plain, east of the city of Ramat Hasharon. The site is a former unlined earthen pond that was used to store industrial wastewater for several decades. A hydrogeological survey conducted in the study area revealed substantial perchlorate contamination in the vadose zone and groundwater under the pond area (Gal et al., 2008, 2009). It was concluded that percolation of untreated wastewater from the ponds had crossed the 40m thick vadose zone and created a large perchlorate pollution plume in the underlying phreatic aquifer with concentrations exceeding 1,000 mg L⁻¹. In the vadose zone, however, the investigation revealed extreme perchlorate pollution, reaching concentrations exceeding 2,000 mg kg⁻¹ dry soil (equivalent to ~25,000 mg L⁻¹ in the sediment pore water), along with high total salinity and chloride concentration exceeding 25,000 mg L⁻¹. Because this area is under consideration for future urban development, remediation of both the vadose zone and groundwater there is of major concern.

The stratigraphy of the area is characterized by Neogene and Pleistocene sediments, mainly of sands and sandstones with interbedding of clay lenses (Gvirtzmen, 2002). The vadose zone lithological profile at the site was assessed again through a borehole that was drilled at the pilot site in 2012 (Table 1, Fig. 1). Most of the profile is composed of yellow and red sand layers with low clay content (<5 %), with interbeds of brown sand containing variable clay content of up to 11 %. A single ~1m thick clay layer (27.5 % clay content) was observed at a depth of 13.3 m. To improve infiltration capacity in deep sections of the vadose zone during the remediation experiment, a shallow clay layer with low permeability, known as “nazaz” (Singer, 2007), was removed from a depth of 2.5–3 m by excavation. The excavated area, 10 × 30 m,
which was primarily assigned for the pilot infiltration experiment, was backfilled with the sandy loam from the excavated site after removal of the 0.5m thick nazaz layer. This layer is therefore presented in the profile as disturbed soil.

The climate in the area is characterized as subtropical Mediterranean with a hot and dry summer from May to October and a colder wet winter from November to April. The average air temperature on summer and winter days is 30 °C and 17 °C, respectively. The average annual precipitation is 530 mm year⁻¹, mostly as rain occurring mainly in four to seven rainy episodes during the winter season (IMS, 2011).

3 Experimental setup

3.1 Vadose-zone monitoring setup

Real-time characterization of flow and transport processes in the vadose zone, as well as assessment of chemical transformation of the percolating water during the remediation experiments were carried out with a VMS that was installed across the entire unsaturated profile, from land surface to a depth of 37 m (Fig. 2). A detailed description of the VMS, its structure, installation procedure and performance, can be found in previous publications (Dahan et al., 2009; Rimon et al., 2011a) and in the supplementary material. In particular, the VMS that was used at this site was composed of a 44m long flexible polyurethane sleeve hosting 11 monitoring units distributed along its length. Each monitoring unit included: (a) a flexible time-domain reflectometer (FTDR) sensor for continuous measurement of variations in the sediment water content (Dahan et al., 2008; Rimon et al., 2007), and (b) vadose-zone sampling ports (VSPs), which enable frequent sampling of the vadose zone pore water for chemical analysis (Baram et al., 2012a; Dahan et al., 2009; Rimon et al., 2011b;
The VMS flexible sleeve was installed in a 0.16m diameter uncased borehole drilled slanted at a 55° angle (to the horizon) to a vertical depth of 37 m. In addition to the 11 monitoring units that were installed with the VMS, four additional monitoring units were installed directly in the soil at depths of 0.5 m and 1.5 m. It should be noted that the slanted installation is preferred to ensure that measurements carried out by each monitoring unit take place in separate undisturbed sediment columns. In addition, the flexibility of the monitoring sleeve and its filling with non-shrinking cement grout ensured complete sealing of the borehole void and prevention of cross-contamination through preferential flow in the borehole.

3.2 Field setup

Water amended with ethanol as the electron donor for perchlorate-reducing bacteria was infiltrated into the vadose zone through an area of 8 x 30 m at the pilot site using a drip-irrigation system. Dripping lines with drippers having a nominal discharge rate of 2.2 L h⁻¹ were set up in a 0.3 x 0.3 m spatial distribution to create fairly even water distribution over the area. Accordingly, the total discharge rate of the irrigation system was set to 5 m³ h⁻¹, which is equivalent to an infiltration rate of 0.02 m h⁻¹. To promote anaerobic conditions in the unsaturated zone, a polyethylene liner covered with soil was placed over the dripper system after its installation. Ethanol was selected as the electron donor and carbon substrate because it is a natural, soluble compound that is commonly used by perchlorate-reducing bacteria (Bardiya and Bae, 2011). Moreover, it eliminates the increased soil salinity associated with other common sources of electron donors such as acetate (Gal et al., 2008).

3.3 Infiltration experiments
Three infiltration experiments with variable amounts of water and ethanol were implemented at the pilot site over a period of 7 months. To trace the percolating water across the unsaturated zone, bromide (as KBr) was added to the infiltrating water at the early stages of the experiment. The infiltration rates, as well as the concentrations and application sequence were assigned for each experiment with insight gained from the previous experiment (Table 2). Accordingly, information obtained by the VMS on depth propagation of the ethanol and tracer and variations in perchlorate and chloride concentrations across the unsaturated zone during and after each infiltration experiment were used to adjust the infiltration procedure in the following stage.

The first experiment (8 Aug 2010) consisted of infiltration of 50 m$^3$ water (equivalent to 210 mm) (Table 2). The first 6 m$^3$ were applied as untraced fresh water with no ethanol to wet the topsoil. This wetting stage is essential to promoting deep transport and preventing accumulation of tracers and ethanol in the low-flow zone located on the margins of the dripper’s influential zone. Following the initial wetting phase, 0.4 m$^3$ of bromide tracer solution (as KBr) at a concentration of 12.5 g L$^{-1}$ was applied, followed by 1 m$^3$ of water with 5% ethanol. Immediately after the application of the carbon and tracer solution, the rest of the water (42.6 m$^3$) was applied to enhance transport of the ethanol and tracers to deeper parts of the vadose zone.

After obtaining the results pertaining to the wetting process, as well as tracer and ethanol migration in the vadose zone during the first infiltration experiment, a second experiment was performed (1 Sep 2010). This experiment was conducted with 100 m$^3$ of water (equivalent to 420 mm). Here the first 7 m$^3$ of water was injected into the topsoil as untraced fresh water, followed by 1 m$^3$ of water with 5% ethanol, and then the rest of the water dose (92 m$^3$). No tracers were used in this experiment. The
amount of water used after application of the ethanol was doubled to enhance migration of the ethanol to deep sections of the unsaturated zone.

Results from the first two experiments indicated limited migration of tracer and ethanol to deeper parts of the vadose zone. A third infiltration experiment was therefore conducted 5 months later with increased discharge of 300 m\(^3\) (equivalent to 1250 mm). This experiment started with 24 m\(^3\) of untraced water followed by 0.4 m\(^3\) concentrated (50 %) ethanol solution. Then, the rest of the water (275.6 m\(^3\)) was used to push the ethanol down into the vadose zone. The large quantity of water applied after the concentrated ethanol solution was designed to enhance quick migration of the ethanol to deep parts of the vadose zone while minimizing its biodegradation in the upper soil layers.

### 3.4 Analytical procedure

Perchlorate was analyzed with a perchlorate ion-selective electrode (ISE; Laboratory Perchlorate Ion Electrode, Cole-Parmer, USA). All samples measured with the ISE were adjusted by dilution to a concentration range of 10–100 mg L\(^{-1}\). Duplicates were frequently analyzed by injecting 25 µL sample into a Thermo Scientific™ Dionex™ ion chromatography system (ICS 5000) equipped with Ion Pac AS19 column (detection limit of ±0.01 mg L\(^{-1}\)). Because results from the two methods were not significantly different, most of the data reported here are from the perchlorate electrode with a detection limit of 1 ppm. Bromide and chloride were analyzed by ion chromatography with a detection limit of 30 ppb (Gal et al. 2008). Total organic carbon (TOC) was analyzed to examine the success of delivering carbon to the vadose zone. Because porewater samples from the vadose zone are obtained through the VSP, which uses a porous ceramic interface (pore size < 2 µm), TOC values reflect DOC.
TOC was analyzed through a combustion TOC analyzer (Teledyne Tekmar, Apollo 9000) with a detection limit of 2 ppm. Ethanol concentration in the vadose zone pore water was analyzed in a gas chromatograph (Varian, CP3800). Water samples (1.5 μL) were injected by autosampler. The FID and injector temperatures were set to 270 and 250 °C, respectively. The GC oven temperature was first held at 50 °C for 1 min, increased to 220 °C at a rate of 25 °C min⁻¹, and then held for 4 min. The separation was performed by Stabilwax® capillary column (60 m, 0.32 mm, 0.25 μm, Restek Corporation, USA); helium was used as the carrier gas (1 mL min⁻¹). For quantification, five external standards were used.

4 Results and discussion

All of the data obtained by the VMS are presented here as variations in measured parameters with depth, as commonly done to describe depth profiles. However, to ensure measurements under undisturbed vertical profiles, the VMS was installed in a slanted orientation (Fig. 2 and supplementary material). Thus, each monitoring unit faces an undisturbed profile that is shifted horizontally and vertically from the other units. Accordingly, although the data are presented as depth profiles, they should be regarded as individual points distributed across the 3D space of the vadose zone (Dahan et al., 2007; Rimon et al., 2011a).

Prior to detailed discussion on the results a general outline of the rationale behind the experimental setup will be presented here. Three infiltration experiments were conducted with variable amounts of water, ethanol as electron donor, and bromide as a tracer (all of which is presented above in chapter 3.3 Infiltration experiment). Nevertheless, the experimental conditions in each experiment were set following the results obtained from the previous stage. The first infiltration experiment was
conducted as a first trial to infiltrate ethanol-enriched water-solution into the unsaturated zone. This experiment was also conducted with bromide as a tracer in order to mark the water front propagation across the unsaturated zone. As will be discussed further on, results the first infiltration experiment indicated that the migration capacity of both ethanol and bromide across the unsaturated profile was very limited. Accordingly a second infiltration experiment was conducted with a double amount of water and the same amount and concentration of ethanol in order to enhanced deep migration of the ethanol down the unsaturated zone. Following the results from the first two experiments a third infiltration experiment was conducted with larger water volumes and higher ethanol concentration in order to avoid quick ethanol degradation in the shallow soil. all of which will be presented and discussed below.

4.1 Water percolation

Temporal variations in the vadose zone water content provide a direct indication of percolation processes in the vadose zone (Rimon et al., 2007; Dahan et al., 2008; Turkeltaub et al., 2015). Each infiltration experiment launched a wetting wave that propagated sequentially through the unsaturated zone (Fig. 3). Down-migration of the wetting wave was expressed as a quick rise in water content followed by a recession caused by water redistribution and drainage. Referring the wetting sequence in the vadose zone to the infiltration events on land surface enabled a direct calculation of the flow velocity across the unsaturated zone (Rimon et al., 2007; Dahan et al., 2008). All three infiltration experiments produced wetting fronts that moved down the vadose zone at a velocity of ~0.18 m h⁻¹, even though the water volumes that were used in each experiment were significantly different (50, 100 and 300 m³).
Observations of regulated flow velocities at constant rates across the vadose zone under variable surface hydraulic conditions have also been reported in other studies (Dahan et al., 2008; Amiaz et al., 2011; Rimon et al., 2011a).

The high salinity of the deeper parts of the vadose zone (>13 m) (Fig. 1) limits the reliability of the TDR technology for measuring water content at those depths (Nadler et al., 1999). Therefore, variation in water content, as an indication of deep percolation, is presented here only down to a depth of 11.2 m, where the salinity was low enough to achieve reliable moisture measurements with the FTDR sensors. Nevertheless, indications of deep percolation in the deeper layers (>13 m) are further discussed through the variation in chemical composition of the percolating water across the entire thickness of the unsaturated zone (40 m).

4.2 Perchlorate transformation and mobilization

Initial analysis of porewater samples from the vadose zone, prior to initiation of the infiltration experiments, revealed very high concentrations of perchlorate and chloride, both reaching maximum values of ~22,500 mg L\(^{-1}\) (Fig. 1), and total dissolved solids (TDS) of 43,000 mg L\(^{-1}\), at a depth of 21 m. Note that at this stage, the concentrations of perchlorate and chloride are nearly identical throughout the entire profile. These high concentrations, sampled by the VMS, are in accordance with concentration profiles obtained previously in extracts of sediment samples (Gal et al., 2009).

Frequent sampling of the vadose zone pore water showed dynamic variations in perchlorate concentration during the percolation experiments. In the upper section of the vadose zone (0–13 m), perchlorate concentrations decreased dramatically, from as high as 9000 mg L\(^{-1}\) to below detection levels (Fig. 4). Such a reduction in
concentration in a relatively thick portion of the vadose zone (13 m) over the short
period of 10 months is clearly desirable and may even be considered a great success.
Nevertheless, closer inspection of the variations in perchlorate concentration in deep
parts of the vadose zone (17–40 m) showed an increase at most of the measurement
points (Fig. 5). Perchlorate concentration rose from 12,700 mg L⁻¹ to 27,400 mg L⁻¹ at
a depth of 17 m during the same period. A similar increase in concentration was also
found in deeper parts of the cross section at depths of 25, 28, and 36 m. Note that
during this period, an increase in perchlorate concentration was even observed in the
groundwater (represented at a depth of 41 m in Fig. 5). Obviously, the mixed trend in
variations of perchlorate concentration implies that transformation and mobilization
processes take place simultaneously. As such, the conditions for both biodegradation
and mobilization should be examined along with the variation in perchlorate
concentration.

4.3 Electron donor availability

Available organic carbon as an electron donor is crucial for perchlorate reduction. To
increase the concentration of DOC in the vadose zone, ethanol was mixed with the
percolating water during the early stage of each infiltration experiment. Analysis of
ethanol and DOC in the water samples from the vadose zone throughout the
experiment revealed a similar concentration pattern (1 g ethanol = 2 g DOC). Therefore, we assume that the variation in DOC was due to transport of ethanol or
ethanol-degradation products with the percolating water.

During the first infiltration experiment, an increase in DOC above background levels
was observed only at shallow depths, down to 1.5 m (Fig. 6). No signs of increasing
DOC were observed in the deeper parts of the cross section at this stage. Twenty-three
days later, before initiation of the second infiltration experiment, DOC values had
dropped back down to background levels. This implies that the ethanol was
microbiologically consumed in the soil before it could be leached further down.

As a result of the limited transport of ethanol in the first infiltration experiment, a
second experiment was conducted with the same mass and concentration of ethanol.
However, it was flushed with double the amount of water to promote its quicker
migration to deeper layers (Fig. 4). In this experiment, no signs of increasing DOC
were observed at any depth. On the contrary, DOC level decreased to values below
background levels (Fig. 6). Obviously, the rate of ethanol metabolism in the soil
increased following the first experiment, where both water content of the sediment
and substrate required for efficient microbial activity increased. As a result, ethanol-
degradation efficiency in the topsoil (<0.5 m) was significantly enhanced.

To overcome the limitation of electron donor delivery through the shallow soils, a
third infiltration experiment was designed. In this experiment, the ethanol was
injected in a 0.4m$^3$ high-concentration (50 %) pulse followed by a large volume of
water. Application of ethanol at a very high concentration was aimed at suppressing
its biological degradation in the shallow soil. The ethanol pulse was introduced after
application of 24 m$^3$, the latter to provide high initial wetting conditions under the
ethanol front. Then the ethanol slug was pushed down with 276 m$^3$ of water. At this
stage of the study, which was conducted 6 months after the previous one, a substantial
increase in DOC was observed in the entire top 13 m of the cross section (Fig. 6).
Obviously, an increase in DOC serving as electron donor is an essential prerequisite
for perchlorate degradation. Apparently, application of ethanol at a high
concentration, which inhibited its degradation in the upper layer, succeeded to drive
the ethanol all the way down to 13 m, just above the clay layer. Nevertheless, no signs of DOC increase were observed below 13 m.

4.4 Transport and degradation

The mechanism controlling down-propagation of a non-conservative substance such as ethanol may be elucidated by looking at the migration pattern of a conservative tracer such as bromide. Bromide was injected with the percolating water in the early stages of the first infiltration experiment. Results on bromide migration are presented here only for the top 13 m, where the background concentrations prior to the initiation of the infiltration experiment were below detection limits. Concentration profiles during the infiltration experiments clearly demonstrated sequential progress of the percolating water across the top 13 m of the unsaturated zone (Fig. 7). Mass balance calculation of bromide on the basis of the concentration profiles (Fig. 7) and sediment water content (Fig. 3) on various dates after the infiltration experiment resulted in high recovery rates of 85–127 %. A comparison of the transport patterns of bromide and DOC confirmed that biodegradable material such as ethanol is rapidly consumed in the vadose zone.

An increase in chloride concentration in the vadose zone is usually attributed to evaporation processes near land surface, a mechanism that is unlikely to occur in this particular setup where the surface is isolated from the atmosphere. Accordingly, variations in chloride concentration across the vadose zone may be attributed to chloride mobilization with the percolating water and perchlorate reduction. Therefore, degradation of perchlorate is expected to result in an increase in chloride mass.

Prior to the infiltration experiments, chloride-to-perchlorate ratios in the vadose zone were very similar, exhibiting nearly identical profiles (Fig. 1) with equivalent
concentration proportions of 2.4–5.5 (Fig. 8). Following the infiltration experiment, a significant increase in ionic ratios was observed in the top 13 m, while in the rest of the profile—from a depth of 17 m to the water table, the concentration ratio of chloride to perchlorate remained relatively unchanged. Obviously, since both perchlorate and chloride are very soluble and mobile, infiltration water with a low concentration of chloride (~100 mg L\(^{-1}\)) and zero perchlorate is also expected to result in an increased chloride-to-perchlorate ratio, even if no perchlorate degradation takes place. Since both chloride and perchlorate are very mobile and easily displaced with the percolating water, quantification of the perchlorate-degradation rate with respect to its down-leaching is not straightforward.

5 Conclusions

The infiltration experiments were primarily aimed at improving the environmental conditions for perchlorate-reducing bacteria across the vadose zone. This included an increase in water content along the soil profile and amendment of the electron donor. The results, which were based on continuous monitoring of the entire vadose zone, exhibited notable variation in the concentrations of perchlorate, DOC and other solutes in the unsaturated zone. Increased concentrations of DOC with a concurrent reduction in perchlorate concentration (from thousands to a few milligrams per liter) and increased chloride-to-perchlorate ratio (from ~2.5 to ~300) in the upper 13 m indicated that perchlorate is partially reduced in this part of the vadose zone. On the other hand, no evidence of improved reducing conditions was observed in the deeper parts, where the initial concentrations of perchlorate were significantly higher. Nevertheless, since assessment of redox conditions in deep vadose zone is not yet
feasible, we can only rely on variations in the chemical composition to assess the existence of degradative conditions.

The limited ability to deliver a soluble electron donor across a microbiologically reactive medium, such as topsoil, is a major limiting factor for remediation of the deep vadose zone through gravitational percolation of enriched solution. Note that temporal variations in the concentrations of perchlorate, as well as other solutes, in the deep parts of the vadose zone, i.e., under the clay layer at 14 m, indicate that the clay layer does not play any role in limiting infiltration capacity. Similar observations on the role of clay layers in infiltration in the unsaturated zone have been reported in previous publications (Baram et al., 2012b, 2012c; Dahan et al., 2009; Rimon et al., 2007; Turkeltaub et al., 2015b).

The attempts to leach the ethanol down into the vadose zone with large quantities of water inevitably drove down-leaching and displacement of the dissolved solutes, including perchlorate. Although there were indications of partial degradation of perchlorate in the upper part of the vadose zone, its downward displacement toward the water table was evident from the sequential increase in perchlorate concentration with depth (Fig. 5). It seems that the entire column of perchlorate mass was pushed down by the percolating water toward the water table, which also resulted in an increased concentration of perchlorate in the observation well, which was located under the infiltration zone.

The study demonstrates that application of vadose-zone monitoring technology during a remediation operation provides real-time information on the chemical and hydrological state of the subsurface. Linking the temporal variation in the chemical
composition of the vadose zone pore water, sediment saturation degree and flow velocities are vital for efficient management of remediation operations.

**Author contribution:** Ofer Dahan (PI, Vadose zone hydrology) design of the experimental and monitoring setup. Idan Katz (MSc student) conducted the field experiment and laboratory analysis. Zeev Ronen (PI, Microbiology) design the bio treatment setup. Data analysis and manuscript preparation - all coauthors.

**Competing interest:** The authors declare that they have no conflict of interest.

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Sagi-Ben Moshe, S., Dahan, O., Weisbrod, N., Bernstein, a., Adar, E. and Ronen, Z.:


### Table 1. Sedimentological Composition of the Vadose Zone at the Pilot Site

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Description</th>
<th>Clay Content (%)</th>
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<tbody>
<tr>
<td>0–3</td>
<td>Red sand (disturbed)</td>
<td>7.5</td>
</tr>
<tr>
<td>3–5</td>
<td>Red sand (Hamra)</td>
<td>5</td>
</tr>
<tr>
<td>5–7</td>
<td>Red-yellowish sand</td>
<td>5</td>
</tr>
<tr>
<td>7–10</td>
<td>Yellow sand</td>
<td>5</td>
</tr>
<tr>
<td>10–13</td>
<td>Brown sand</td>
<td>5</td>
</tr>
<tr>
<td>13–14</td>
<td>Dark brown clay</td>
<td>27.5</td>
</tr>
<tr>
<td>14–17</td>
<td>Red-brown clayish sand</td>
<td>12.5</td>
</tr>
<tr>
<td>17–20</td>
<td>Brown clayish sand</td>
<td>3.75</td>
</tr>
<tr>
<td>20–27</td>
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</tr>
<tr>
<td>28–29</td>
<td>Brown sand</td>
<td>11.75</td>
</tr>
<tr>
<td>29–33</td>
<td>Red-clayish sand (Hamra)</td>
<td>3</td>
</tr>
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<td>33–41</td>
<td>Yellow sand</td>
<td>0</td>
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</tbody>
</table>

### Table 2. Infiltration experiment conditions

<table>
<thead>
<tr>
<th>Date</th>
<th>Water Volume (m³)</th>
<th>Equivalent Depth (mm)</th>
<th>Water Ethanol (l)</th>
<th>Bromide (Kg)</th>
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<tbody>
<tr>
<td>8 Aug 2010</td>
<td>50</td>
<td>210</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>1 Sep 2010</td>
<td>100</td>
<td>420</td>
<td>50</td>
<td>-</td>
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<tr>
<td>27 Feb 2011</td>
<td>300</td>
<td>1250</td>
<td>200</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 1. Initial concentration profiles of chloride and perchlorate in the vadose zone pore water under the former waste lagoon, along with the lithological profile.
Figure 2. Schematic illustration of the vadose-zone monitoring system installed in the vadose zone under the infiltration pilot site. In the picture above the vadose zone, the irrigation system at the site is being covered.
Figure 3. Temporal variations in sediment water content in the top 13 m of the vadose zone during the infiltration experiments. Dates are given as day/month/year.
Figure 4. Perchlorate concentration profile across the top 13 m of the vadose zone under the pilot site during the infiltration experiments. The profiles emphasize the gradual decrease in perchlorate concentration with time (marked in red arrows). Dates are given as day/month/year. Note that data points are aligned in a slanted orientation and interpolated as time intervals.
Figure 5. Perchlorate concentration profile across the entire vadose zone and top groundwater under the pilot site during the infiltration experiments. The profiles emphasize the gradual increase in perchlorate concentration with time (marked in red arrows). Dates are given as day/month/year. Note that data points are aligned in a slanted orientation and interpolated as time intervals.
Figure 6. Variations in dissolved organic carbon (DOC) across the top 13 m of the vadose zone following infiltration of water enriched with ethanol. Dates are given as day/month/year.
Figure 7. Variations in bromide concentration profile across the top 13 m of the vadose zone during the infiltration experiments. Dates are given as day/month/year. Note that data points are aligned in a slanted orientation and interpolated as time intervals.
Figure 8. Chloride-to-perchlorate equivalent concentration ratio profiles before and after the infiltration experiments. Dates are given as day/month/year. Note that data points are aligned in a slanted orientation and interpolated as time intervals.