Transport and Degradation of Toluene and o-Xylene in an Unsaturated Soil with Dipping Sedimentary Layers

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ABSTRACT

A lysimeter trench was established at the Gardermoen delta (50 km north of Oslo, Norway) to study the flow of water and transport and degradation of aromatic jet fuel components (toluene and o-xylene) in the undisturbed unsaturated zone. Site investigations with ground-penetrating radar revealed the presence of dipping sedimentary layers within the forested unit. This study has shown that the foreset bed of the Gardermoen delta structure provided a preferential flow path for the transport of the solute plumes, but did not have dramatic effects on the degradation potential under the current conditions. The degradation potential for toluene and o-xylene in the unsaturated zone at Gardermoen was very high and almost all of the injected hydrocarbons were biodegraded before reaching the saturated zone. However, the horizontal displacement of the plume showed that knowledge about sedimentary structures in the unsaturated zone is important for a sufficient monitoring of contaminant transport and for remediation purposes. Carbon dioxide and O₂ were measured in situ simultaneously with extraction of water samples, and indicated aerobic biodegradation of toluene and o-xylene. Overall, first-order degradation coefficients were calculated to be in the range of 0.19 to 0.21 d⁻¹ and 0.10 to 0.11 d⁻¹ for toluene and o-xylene, respectively.

The new Oslo airport is situated on the Gardermoen delta sediments, which make up the largest confined aquifer in Norway. At airports, large quantities of jet fuel are stored and handled with the inherent risk of accidental spills. Spills during refuelling may lead to surface runoff and high infiltration rates of water-soluble contaminants along impermeable surfaces.

Preferential flow paths may have drastic effects on contaminant transport, as the flow bypasses most of the soil matrix, and hence reaches the ground water faster than if it had moved through the entire soil matrix. Different processes such as fingering arising from wetting front instability, and physical conduits such as bio-pores and cracks may lead to preferential flow (Beven and Germann, 1982; Sililo and Tellam, 2000). Inclined layers of different textures that work as either hydraulic or capillary barriers may also cause preferential flow. A hydraulic barrier is formed when the hydraulic conductivity of a layer is lower than the flow rate through the overlying layer. A capillary barrier is caused by textural discontinuities between a fine layer overlying a coarse layer, which leads to a type of preferential flow called funneled flow. The development of funneled flow depends both on the recharge rate and on the soil layering structures. Preferential flow due to the funnelling effect on water flow of inclined layers has been extensively studied in the laboratory and field, and through numerical models (Kung, 1990a,b; Kung, 1993; Ju and Kung, 1997; Walter et al., 2000). Both hydraulic and capillary barriers increase the danger of ground water contamination due to a reduced travel time and contact area.

In connection with soil and ground water polluted with jet fuel hydrocarbons, emphasis has been placed on the aromatic fraction, consisting mainly of the components benzene, toluene, ethylbenzene, and xylene (BTEX) and naphthalene, as this fraction is water soluble and mobile. Batch, column, and field studies, as well as numerical models, have been applied to study the fate of these components in the unsaturated zone (e.g., Allen-King et al., 1994, 1996; Breedveld et al., 1997) and in the saturated zone (e.g., Bjerg et al., 1996; Nielsen et al., 1996). Both aerobic (e.g., Bjerg et al., 1996; Nielsen et al., 1996) and anaerobic (e.g., Evans et al., 1991; Edwards et al., 1992) biodegradation of BTEX compounds have been reported. In laboratory experiments the soil is usually homogeneous and the growth conditions tend to be optimized. Natural soil, however, is a heterogeneous medium and preferential flow paths may lead to reduced residence time in the unsaturated zone, and thus a reduced degradation capacity. Laboratory studies have often focused on the degradation pattern of single substrates. In the field, however, biodegradation involves simultaneous metabolism of structurally related hydrocarbon substrates. Hence, field studies are important for realistic predictions of the fate of mixtures of organic contaminants under natural conditions.

The objective of this work was to quantify the influence of the soil structure on the transport and degradation of water-soluble jet fuel components in the unsaturated zone of the heterogeneous soil at the Gardermoen delta. In this work, the chosen boundary conditions represent an infiltration rate that is much higher than the natural infiltration rate. However, to study the influence of the soil structure on the transport and degradation of water-soluble hydrocarbons, a high infiltration rate was needed to ensure that the hydrocarbon solution reached the foreset bed before being completely degraded. An understanding of flow mechanisms in the unsaturated zone is required before describing the fate of contaminants. Hence, this paper first gives a description of the water flow, and then describes the transport and degradation of two aromatic jet fuel components, toluene and o-xylene.

Abbreviations: BTEX, benzene, toluene, ethylbenzene, and xylene; GPR, ground-penetrating radar.
EXPERIMENTAL SITE AND METHODS

Geological Setting and Field Site

The Gardermoen delta, situated 50 km north of Oslo, was deposited approximately 9500 yr ago, during the deglaciation of Scandinavia (Sørensen, 1979; Longva and Thoresen, 1989). The delta contains a classic tripartite deltaic stratigraphy: the delta topset unit, the delta foreset unit, and the delta bottomset unit. The delta contains the Gardermoen aquifer, an unconfined, precipitation-recharged reservoir. The research station, Moreppen, is situated in the distal part of the Gardermoen delta (close to the airport), on the ground water divide, with a ground water table approximately 4 m below the ground surface. The Moreppen field station includes two lysimeter trenches. The first lysimeter trench (T1) is 2.4 m deep (French, 1999), while the second trench (T2), used in this experiment, is 3.9 m deep and penetrates the whole unsaturated zone (Fig. 1).

Ground-Penetrating Radar

In hydrogeological studies, a detailed description of the subsurface is important because the sedimentary structures and texture influence the contaminant transport. Ground-penetrating radar (GPR) is a method for visualizing the subsoil (Beres and Haeni, 1991; van Overmeeren, 1994), which was found suitable for describing the sedimentary structure of the unsaturated zone at Moreppen, especially since the soil contains little clay (a conductive material in which electromagnetic signals are attenuated).

An earlier GPR study (Fig. 1) (Langsholt et al., 1998) indicated that the unsaturated zone at Moreppen consists of a thin topset unit (1.5–2.0 m) overlying 2.0 to 2.5 m of westward dipping layers of the foreset unit. Proper monitoring of a plume following preferential flow paths in the unsaturated zone requires installation of suction cups along the flow paths, as well as below and above the paths. Identifying possible preferential flow paths in the soil is thus important. This required a more detailed study of the soil next to Lysimeter Trench T2. An area of 12.0 × 5.0 m south of the already established trench was examined with GPR. The GPR grid was oriented in an approximately north–south, east–west direction (Fig. 1), with the north–south profiles corresponding to the regional strike of the delta foreset beds. We used a PulseEKKO 100 radar (Sensors & Software, Mississauga, ON, Canada) with a 400-V transmitter. The antennae frequency was 200 MHz and the spacing between the emitting and receiving antennas was 0.5 m. The step size was 0.1 m. The program GRADIX (INTERPEX, Golden, CO) was used to process the data. The GPR profiles are given in time domain. To identify the depth of the different layers, a transformation from time scale to depth scale is needed; this requires the average velocity of the electromagnetic signal in the ground. The southern wall of the trench was detected on Profiles GP7 through GP9 (Fig. 1), and an average traveling velocity of 0.11 m ns⁻¹ was calculated based on this information. This was confirmed by comparing the two-way travel time down to the ground water reflector on Profile GP3 with the actual depth measured in a near-by ground water well.

Ground-penetrating radar profiles, visual inspection of the trench walls, and grain size analysis of soil samples acquired during installation of the trench were used to divide the soil volume at the studied site into five different hydrostratigraphical units (Fig. 2). The topset unit (pebbly sand) (Tuttle, 1997) was divided into two parts. The upper part (TFS) was wetter than the lower part (TCS) due to a greater amount of fine-textured material. As the direct airwave masked the upper 2 m of the ground-penetrating radar profiles, the division of the topset unit into two layers was based upon the grain size distribution of the soil samples. The foreset unit contained alternating dipping layers of fine (FFS) and coarse (FCS) sand. We defined fine sand as material where >70% of the grain size was within the range 0.06 to 0.6 mm and <20% of the grain size was >0.6 mm, while coarse sand was defined as material where >20% of the grain size was within the range 0.6 to 2 mm and <70% of the grain size was <0.6 mm. A thin
Fig. 2. The vertical soil profile at GP2, where the suction cups and gas samplers were located (○ and □, respectively). The figure indicates the location of the water and gas samplers in relation to the soil structure. The numbers of the suction cups are indicated on the figure. TFS, topset unit, fine sand; TCS, topset unit, coarse sand; FFS, foreset unit, fine sand; FCS, foreset unit, coarse sand; FSS, foreset bed, silty sand. The location of the TDR probes (thick, vertical lines), the walls of the trench (thin, vertical lines), the application line, and the width of the trench are indicated on the figure. Only the segments of the TDR probes that were working are shown. The local coordinate system uses the southeastern corner of the trench as the point of origin.

Layer of silty sand (FSS) (Sveistrup, 1984) was enclosed in one of the sand layers. Table 1 gives the soil characteristics of the five hydrostratigraphical layers.

### Lysimeter Trench

In the southern wall of the trench (T2), 25 suction cups (Prenart probes made of porous teflon mixed with silica powder and stainless steel powder) (Prenart Super Quartz, Prenart Equipment ApS, Frederiksberg, Denmark) were horizontally installed (Fig. 2). The GPR profiles, as well as soil samples, indicated that the silty sand layer was dipping in the east–west direction; however, it was approximately horizontal in the south–north direction. Hence, the cups were installed on an approximate vertical cross-section plane. The distance from the wall to the cups varied between 1.9 and 2.4 m. The exact location of the cups was chosen based on the sedimentary structure observed from the trench wall and the GPR profiles. Holes for installation were made by inserting stainless steel tubes into the soil. Inspection of the soil removed from inside the tubes ensured installation of the suction cups in the appropriate layer. A small hole was drilled at the end of the tube, and dry silica powder blown into the hole. The suction cups were placed under suction in a mixture of silica powder and water before being inserted into the wall. The steel tubes were left in the soil to avoid collapse of the soil structure. The suction cups were placed under a constant suction of 25 kPa. All tubes used were of teflon. Preliminary, simplified simulations (Holm, 1998) indicated that flow of water would follow the thin, dipping silty sand layer. Nine of the cups were therefore inserted in the silty sand layer, three below the layer and the remainder above the layer (Fig. 2). Due to economical reasons, we were provided with a limited number of cups; hence the setup is not optimal, as there were no cups above or below the silty sand layer in the western part of the trench.

Six gas samplers were installed in the southern wall of the trench (Fig. 2). They consisted of thin stainless steel tubes perforated at the end. The gas samplers were installed to examine the O₂ and CO₂ concentrations in situ during the hydrocarbon experiments.

Time domain reflectometry (TDR) (MP-917 Moisture Point System; ESI Environmental Sensors, Victoria, BC, Canada) is an indirect method for measuring soil moisture based upon the relation between volumetric water content and the dielectric constant. The TDR probes were installed at two different locations (Fig. 2). Probe TDR1 had 30-cm segments down to a depth of 1.5 m, and 15-cm segments from 1.5 to 3.0 m. Probe TDR2 had 15-cm segments down to 3.0 m, and 30-cm segments from 3.0 to 4.5 m. Some segments did not function, thus continuous depth profiles were not obtained. The volumetric water content was measured every half-hour except at the very be...

### Table 1. Averaged saturated hydraulic conductivity ($K_s$), the range of the silt content, $d_{50}$, $d_{25}$, $d_{75}$, as well as total organic carbon (TOC) and pH for each layer type. Standard deviations are given within parentheses.

<table>
<thead>
<tr>
<th>Layer†</th>
<th>$K_s$‡</th>
<th>Silt $d_{50}$</th>
<th>$d_{25}$</th>
<th>$d_{75}$</th>
<th>TOC¶</th>
<th>pH#</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFS</td>
<td>$2.4 \times 10^{-4}$ (1.3 \times 10^{-4})</td>
<td>2.3–6.1</td>
<td>0.516 (0.126)</td>
<td>0.267 (0.054)</td>
<td>1.153 (0.483)</td>
<td>0.6</td>
</tr>
<tr>
<td>TCS</td>
<td>$6.3 \times 10^{-4}$ (6.1 \times 10^{-4})</td>
<td>0.0–6.7</td>
<td>1.037 (0.524)</td>
<td>0.436 (0.152)</td>
<td>3.134 (2.688)</td>
<td>0.2</td>
</tr>
<tr>
<td>FFS</td>
<td>$1.3 \times 10^{-4}$ (2.2 \times 10^{-4})</td>
<td>0.0–18.6</td>
<td>0.190 (0.063)</td>
<td>0.118 (0.035)</td>
<td>0.325 (0.338)</td>
<td>0.2</td>
</tr>
<tr>
<td>FCS</td>
<td>$3.2 \times 10^{-4}$ (1.9 \times 10^{-4})</td>
<td>0.0–9.0</td>
<td>0.438 (0.177)</td>
<td>0.241 (0.091)</td>
<td>0.854 (0.595)</td>
<td>0.2</td>
</tr>
<tr>
<td>FSS</td>
<td>$3.2 \times 10^{-4}$ (2.0 \times 10^{-4})</td>
<td>20.0–59.3</td>
<td>0.094 (0.028)</td>
<td>0.049 (0.020)</td>
<td>0.136 (0.037)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

† FCS, foreset unit, coarse sand; FFS, foreset unit, fine to medium sand; FSS, foreset bed, silty sand; TCS, topset unit, coarse sand; TFS, topset unit, fine to medium sand.
‡ $K_s$ was estimated with the Gustafson’s equation (Andersson et al., 1984). The mean and standard deviation of $K_s$ were calculated as for a lognormal distribution (Dougherty, 1990).
§ Grain size corresponding to weight percentages of 50, 25, and 75%, respectively, in grain size distribution diagrams.
¶ Total organic carbon was measured with a CR-412 carbon analyzer (Leco, St. Joseph, MI).
# The pH was measured in a mixture of 10 mL soil and 25 mL water.
inning of the experiment (because of power failure). Because of these initial problems, measurements from the summer of 1997 were used as background values.

**Application of Tracers**

A continuous background application of water was applied through a set of Typhoon 20 dripper lines (Drypptvanning AS, Bøverbru, Norway) with 20- by 20-cm spacing. Previous experiments indicated approximately equal dripping rates from all dripper points. Water for irrigation was supplied from a ground water well. Mean daily evapotranspiration was approximately 5 mm d\(^{-1}\) during summer months (Langsholt et al., 1996). The test site was irrigated for one week with a net background application rate of 30 mm d\(^{-1}\) before starting the tracer experiment. During the experiments the net background application rate was increased to 43 mm d\(^{-1}\). To prevent natural precipitation from infiltrating the ground, a roof was built above the test site. This roof may have caused the rate of evapotranspiration to decline, as incoming radiation was built above the test site. This roof may have caused the rate of evapotranspiration to decline, as incoming radiation was built above the test site. This roof may have caused the rate of evapotranspiration to decline, as incoming radiation was built above the test site.

Raoult’s law (Cline et al., 1991). By decreasing the number below the soil surface. A solution containing 50 mg L\(^{-1}\) limits the water solubility of the compounds as given by identical to those used in the field, were installed 8 and 23 cm twice each day for the first few days, and later once a day. this loss. A column (length: 0.5 m, diameter: 10 cm) was filled fourth hour for the first three days, then every eighth hour, loss of mass during extraction of water samples was expected. The hydrocarbons were extracted from the water phase by application rate due to the tracers was about 100 mm d\(^{-1}\) of toluene and \(o\)-xylene.

The amount of CO\(_2\) and O\(_2\) in the profile was measured every day with a direct reading CO\(_2\)–O\(_2\) analyzer with built-in sampling pump (Multiwarn 2; Dräger, Lübeck, Germany). The temperature in the soil during the experimental period was not measured; however, French and van der Zee (1999) measured the soil temperature in a nearby trench (T1) during the summer 1994. According to their measurements, the temperature at the depth of 90 cm varied between 11 and 15°C, while at the depths of 140 and 240 cm the temperature range was 9 to 13°C and 7 to 11°C, respectively.

**Laboratory Sorption Experiment**

Sorption characteristics for the mixture of toluene and \(o\)-xylene (1:1) in soil samples from Gardermoen were obtained in a laboratory batch experiment. A topsoil sample (a mixture of soil from the upper 1 m) and a subsoil sample (a mixture of soil from below 1 m) were collected. The organic carbon contents of the topsoil and the subsoil samples were 1.08 and 0.13%, respectively. Dried soil samples of 20 g were weighted into 30-mL glass vials with teflon screw caps. One milliliter of 0.6 mM CaCl\(_2\) (equivalent to the ionic strength of the ground water at Gardermoen) was added and left overnight to humidify the soil samples. The next day, 19 mL of 0.6 mM CaCl\(_2\) with a specific concentration of toluene and \(o\)-xylene was added. Concentrations of 0.5, 1.0, 2.0, 3.0, 5.0, 10.0, and 50.0 mg L\(^{-1}\) for each of the two components were used. Experiments were prepared in triplicate. To prevent biodegradation, we added 0.1% Na\(_2\)S to all solutions. The glass vials containing the mixtures, as well as the blanks (without soil), were shaken for 24 h, and then centrifuged at 2000 rpm for 10 min. Extraction of the hydrocarbons from the water phase was performed as described above. Loss caused by volatilization during the experimental procedure was quantified by comparing the concentration of the blanks with the initial concentration of the different solutions. The amount of sorbate at the solid phase was calculated as the difference between the sorbate concentrations in water at the beginning and at equilibrium.

**Quantifying Loss Due to Volatilization**

Toluene and \(o\)-xylene are volatile compounds, and hence loss of mass during extraction of water samples was expected. A laboratory column experiment was conducted to quantify this loss. A column (length: 0.5 m, diameter: 10 cm) was filled with sand from the subsoil at Gardermoen. Two suction cups, identical to those used in the field, were installed 8 and 23 cm below the soil surface. A solution containing 50 mg L\(^{-1}\) of toluene, 50 mg L\(^{-1}\) of \(o\)-xylene, and 0.1% Na\(_2\)S was added to the column. A closed system was obtained by pumping column leachate into a reservoir from where it was supplied to the

**Table 2. Physical and chemical properties of toluene and \(o\)-xylene**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Molecular weight (g mol(^{-1}))</th>
<th>Vapor pressure (Pa)</th>
<th>Solubility (mg L(^{-1}))</th>
<th>log (K_{\text{ow}})</th>
<th>(H_t)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>92.1</td>
<td>3800</td>
<td>515</td>
<td>2.69</td>
<td>0.27</td>
</tr>
<tr>
<td>(o)-Xylene</td>
<td>106.2</td>
<td>1170</td>
<td>220</td>
<td>3.15</td>
<td>0.23</td>
</tr>
</tbody>
</table>

† Dimensionless Henry's law coefficient.
top of the column. A bag of N₂ gas was attached to the top of the column to replenish sampled water. The column was kept at 12°C throughout the experimental period, which is about the same temperature as at the depth of 1.4 to 1.9 m in the soil at Moreppen during July (French and van der Zee, 1999). The volumetric water content at the top of the column was about 0.14 to 0.15 assuming a porosity of 0.35 m³ m⁻³, which is about the same as in the fine and coarse sand in the Moreppen soil. The application rate in the laboratory was 0.8 mL min⁻¹. This corresponds to 150 mm d⁻¹, which is approximately the same application rate as used in the field during the period of application of the hydrocarbons.

With a known equilibrium concentration in the column and a measured concentration in the water sampled through the two suction cups (applying the same suction as in the field, 25 kPa), the loss of mass caused by the sampling procedure was quantified. Extraction of the hydrocarbons from the water phase was performed as described earlier.

**Data Processing**

Point observations of concentration may show considerable variation because of small-scale variability in the hydraulic properties of an aquifer. Spatial moments of the point concentration distribution provide an integrated measure of the total mass:0.8 mL min⁻¹ was kept at 12°C throughout the experimental period, which is about the same as in the fine and coarse sand in the Moreppen soil. The application rate in the laboratory was about 0.14 to 0.15 assuming a porosity of 0.35 m³ m⁻³, which is about the same as in the fine and coarse sand in the Moreppen soil. The application rate in the laboratory was 0.8 mL min⁻¹. This corresponds to 150 mm d⁻¹, which is approximately the same application rate as used in the field during the period of application of the hydrocarbons.

The center of mass in the horizontal and in the vertical directions (x, z) is found by normalizing the first moments by the total mass:

\[ x_c(t) = \frac{\int x \theta(x, z, t) dx dz}{\int \theta(x, z, t) dx dz} \quad \text{and} \quad z_c(t) = \frac{\int z \theta(x, z, t) dx dz}{\int \theta(x, z, t) dx dz} \]

The second central spatial moments about the origin are:

\[ M_{2x}(t) = \int \int (x - x_c(t))^2 \theta(x, z, t) dx dz \quad \text{and} \quad M_{2z}(t) = \int \int (z - z_c(t))^2 \theta(x, z, t) dx dz \]

Spatial moments based on the measuring points are calculated as discrete sums. No interpolation between the measuring points was performed since it is impossible to know whether an interpolated field represents the real field. Based on the water contents measured in TDR1 and TDR2, and a strong correlation between water content and structure (Fig. 3), the volumetric water content was estimated for each measuring point. Water volumes collected at each point during the period of application of the hydrocarbons.

\[ M_{0}(t) = \int \int \theta(x, z, t) dx dz \]

\[ M_{0}(t) = \int \int \theta(x, z, t) z dx dz \]

The relation between the silt content and the volumetric water content for TDR1 and TDR2. The background values of the volumetric water content (from summer 1997) are also shown.

![Fig. 3](image-url)
a specific time span combined with the TDR measurements indicated that the soil volume, from which the suction cups extracted water, was between 15 and 60 mL. Based on this, the concentration in each suction cup was assumed to represent an average soil volume of 30 mL. Multiplication of this soil volume with the volumetric water content and the tracer concentration gave an estimate of the mass withdrawn by each suction cup.

Because Suction Cups 9, 10, and 11 were placed isolated from the main monitoring setup and only along the assumed preferential flow path (Fig. 2), they may inflict a serious bias to the results. Measurements from these points were therefore disregarded in the calculations of the spatial moments. Hence, the results of the spatial moment analysis refer to the time period when the plumes were above the silty layer. In this part of the soil, the suction cups were not located according to any specific pattern.

Based on the vertical centers of mass (Eq. [4]), the retardation factor, \( R(t) \), is given by:

\[
R(t) = \frac{z^c_x(t)}{z^i_x(t)} \tag{8}
\]

where \( z^c_x(t) \) and \( z^i_x(t) \) are the vertical centers of mass of the inert tracer and the reactive solute, respectively. Because tritium was only applied with the first pulse of hydrocarbons, it could not be used for calculation of retardation factors according to Eq. [8]. We therefore assumed that the bromide-tracer experiment and the hydrocarbon experiment took place under the same steady state conditions. As the hydrocarbons were injected during 14 d, and bromide during 3 d, only the first three days of the two experiments were directly comparable. The term \( R(t) \) has thus been calculated for this time period.

First-order biodegradation is expected when the concentration of biomass is constant and the concentration of reactive solute is low compared with the half-saturation constant \( (K_d) \) (Monod kinetics) (Alexander, 1994). From a batch experiment using aquifer material under aerobic conditions, Alvarez et al. (1991) estimated the \( K_d \) value for toluene to be 17.4 mg L\(^{-1}\). Bekins et al. (1998) stated that in general, first-order approximations should be used with caution when the total BTEX concentration is greater than 5 mg L\(^{-1}\). In this study the initial concentration of toluene and \( o \)-xylene was 50 mg L\(^{-1}\), well above the limit proposed by both authors. However, most field experiments have used first-order degradation constants; hence, to be able to compare our results with literature values, a first-order approximation was chosen in the present work. First-order kinetics is given by:

\[
\frac{dS}{dt} = -kS \tag{9}
\]

where \( S \) is the substrate concentration and \( k [\text{T}^{-1}] \) is the first-order degradation coefficient. Integration of Eq. [9] gives:

\[
S = S_0 e^{-kt} \tag{10}
\]

where \( S_0 \) is the initial substrate concentration. Plotting \( \ln(S/S_0) \) against \( t \) gives an estimate of the first-order degradation coefficient \( k \). Because tritium was only applied with the first pulse of hydrocarbons, it could not be used for calculation of the first-order degradation coefficient, hence bromide was used as the inert tracer. To overcome the difference in application time of the bromide tracer and the hydrocarbons, degradation was calculated for each suction cup separately. The total mass recovered in a suction cup is described by the zeroth temporal moment:

\[
M_{00}(x,z) = \int_0^t \theta(x,z,t) Vc(x,z,t) \, dt \tag{11}
\]

where \( c(x,z,t) \) is the concentration distribution field, \( \theta(x,z,t) \) is the volumetric water content, \( V \) is the soil volume from where the cup extracts water (30 mL), \( x \) and \( z \) are spatial coordinates, \( t \) is time, \( t_i \) is the initial breakthrough time in the suction cup, and \( t_f \) is the time when the concentration returned to the background value again. The recovery of solute relative to the total mass injected \( (M) \) is given by the normalized zeroth moment:

\[
\bar{M}_{00}(x,z) = M_{00}(x,z)/M \tag{12}
\]

By normalizing the total mass recovered by the total mass applied, it is sought to compensate for the different application periods. An estimate of the fraction of the reactive solute in solution, \( F(x,z) \), is obtained by dividing the normalized zeroth moment of the reactive solute, \( \bar{M}_{00}(x,z) \), by the normalized zeroth moment of the inactive tracer, \( \bar{M}_{00}(x,z) \):

\[
F(x,z) = \bar{M}_{00}(x,z)/\bar{M}_{000}(x,z) \tag{13}
\]

Changes in the concentration of the conservative tracer are used to correct for changes in the concentration of contaminants due to effects of dispersion. As bromide is a nonsorbing chemical, the concentration of hydrocarbons was not corrected for sorption. Based on results from Zhang and Bouwer (1997), we assumed that the adsorbed hydrocarbons did not degrade at the same rate as the dissolved compounds, and a correction for the adsorbed fraction was needed. As \( F(x,z) \) is the fraction of solute in solution, \( F(x,z) \cdot K_d \) represents the adsorbed fraction, and the fraction of solute not biodegraded will thus be:

\[
F(x,z) = F(x,z) + F(x,z) \cdot K_d \tag{14}
\]

where \( K_d \) is the dimensionless distribution coefficient \((\text{mg/20 g soil})/\text{(mg/20 g water)}\). As both \( F(x,z) \) and \( S/S_0 \) represent the fraction of solute not degraded, a combination of Eq. [10] and [14] gives an expression for first-order degradation in the field:

\[
F(x,z) = S/S_0 = e^{-kt} \tag{15}
\]

The first-order degradation coefficient \( k \) is found by plotting \( \ln(F(x,z)) \) versus time. The term \( F(x,z) \) is a time-integrated value, representing the entire time span from the start of the experiment to the final breakthrough in each cup. First-order degradation coefficients \( k \) were estimated for each suction cup using the gradient between the starting point in \( F = 0 \) and \( F_{50%} \), where \( t_{50%} \) indicates the time of 50% breakthrough of the hydrocarbon. The concentration measured in one suction cup is the integrated result of transport and degradation above the specific point. Therefore, the first-order degradation coefficient will be representative of the degradation in the entire soil profile above each specific suction cup.

RESULTS

Laboratory Experiments—Sorption Isotherms

The blanks used in the sorption experiment had a headspace of 13.9 mL compared with the headspace of 5.1 mL in the vials containing soil and water. Hence, the blanks had a greater loss of hydrocarbons than the samples with soil and water. The calculated loss to the headspace using Henry’s law constant (Table 2) explained approximately 100% of the measured loss in the blanks. Concentrations in theoretical blanks with a headspace of 5.1 mL were thus calculated using Henry’s
law constant. Using the concentrations of the theoretical blanks as initial concentrations, we obtained linear sorption isotherms for both components in both the top- and subsoil. The term $K_d$ was calculated as the slope of the isotherms. For toluene, $K_d$ was 0.15 mL g$^{-1}$ in subsoil and 0.83 mL g$^{-1}$ in topsoil. For o-xylene, $K_d$ was 0.19 mL g$^{-1}$ in subsoil and 1.71 mL g$^{-1}$ in topsoil.

**Laboratory Experiments—Volatilization Loss during Sampling**

In the volatilization experiment, the outlet concentration from the column of both components increased with time until it reached the inlet concentration. As the $K_d$ of o-xylene was higher than for toluene, a lower concentration of o-xylene in the column at equilibrium was as expected (Table 3). A decrease in the concentration of both toluene and o-xylene was observed in water samples extracted through the suction cups. This corresponds to a recovery of 42 to 54% and 20 to 36% for toluene and o-xylene, respectively (Table 3). Toluene is more volatile than o-xylene while o-xylene is more strongly sorbed than toluene. Lower extraction efficiency for o-xylene than for toluene indicates that in addition to loss of mass due to volatilization, sorption, either to the suction cup or to the silica powder, could have contributed to the observed mass loss.

**Field Experiments—Volumetric Water Content**

The volumetric water content (average values for the experimental period, summer 1999) in relation to the percentage of silt in the soil at the location of the TDR probes is shown in Fig. 3. The upper part of the topsoil had slightly higher water content than the lower part, probably caused by more fine-textured material in the upper section. The TDR1 probe was located close to the border of the irrigation area, hence a suction gradient out of the affected soil volume may have reduced the volumetric water content in the topsoil of TDR1 compared with TDR2. For TDR1, the silty sand layer, with a silt content of nearly 60%, had significantly higher water content than the soil above and below. For TDR2, the silty sand layer was less distinct with a silt content of 20%, and a volumetric water content of 0.22 (compared with 0.35 for TDR1). There is a sudden drop in the water content within the layer TCS (150–160 cm) for TDR2. This could be caused by a lens of very coarse material. Background water contents measured during the summer of 1997 are also shown (Fig. 3). It is seen that artificial irrigation led to increased water content for all layers.

The volumetric water content (daily average) as a function of time for selected TDR segments was fairly constant at most depths (Fig. 4a,b). The data represent the time period for both the bromide and the hydrocarbon tracer experiments. The hydrocarbon solution applied was very dilute (<100 mg L$^{-1}$), hence the dielectrical constant of the water should not be influenced. For TDR1 (Fig. 4a), the silty sand layer (segments 195–210 and 210–225 cm), as well as the layer above (180–195 cm), experienced an increase in the water content during the tracer application periods. For TDR2 (Fig. 4b), the surface layer had the highest volumetric water content, around 0.4. For the upper part of the silty sand layer (240–255 cm) and the soil layer above the silty sand layer (225–240 cm), an increase in the water content occurred during the application of bromide and the hydrocarbons. Electricity cut (stopping the water supply to the dripper lines) and a water spill caused bumps that are marked on both graphs.

The volumetric water content measurements indicate water flow on top of the silty sand layer. An immediate increase in the water content of the silty sand layer and the soil layer above it occurred during the application of bromide and hydrocarbons (Fig. 4a,b). This indicates that the infiltration rate of the tracers was larger than the unsaturated hydraulic conductivity of the silty sand layer, thus causing water to accumulate and flow on top of the layer.

**Field Experiments—Water Flow**

Bromide concentrations measured at individual suction cups on selected days after start of the application period are shown in Fig. 5. A fast vertical movement down to about 1 m was observed. Parts of an old tree trunk were present close to the application line, and a root channel could have led to the fast penetration of the first meter. Near Suction Cup 13, the plume moved toward west, probably caused by the general dipping structures at this depth (Fig. 2). Relatively high concentrations of bromide were measured in all suction cups installed in the silty sand layer and no bromide was detected in the Cups 2, 3, 4, 24, 25, and 26. The described setup documents that the dipping silty sand layer at least partly acted as a flow barrier. The radius of influence of the suction cups was not examined. We realize that the suction applied through the cups may have distorted the flow pattern of water. However, even though the same suction was applied to all cups, no bromide was detected in Cups 2, 3, 4, 24, 25, and 26. Thus, we believe that the flow pattern observed was not a result of the suction applied to the cups, but was governed by the soil structure. The total residence time of the inert tracer in the unsaturated zone (down to a depth of 3.5 m) was about 20 d.

As no suction cups were installed below the silty sand layer in the western part of the trench, a possible penetration of parts of the plume through the silty sand layer could not be documented. However, data from the TDR2 probe could indicate a partial breakthrough of water through the layer. The silty sand layer is not as distinct for TDR2 as it is for TDR1, and the volumet-

### Table 3. Extracted concentrations of toluene and o-xylene in water samples from the upper and lower suction cup, as well as the column concentration of each component. The numbers in parentheses give the extraction efficiency.

<table>
<thead>
<tr>
<th>Component</th>
<th>Upper suction cup</th>
<th>Lower suction cup</th>
<th>Column concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>9.5 (54)</td>
<td>7.4 (42)</td>
<td>17.7</td>
</tr>
<tr>
<td>o-Xylene</td>
<td>4.4 (36)</td>
<td>2.5 (20)</td>
<td>12.2</td>
</tr>
</tbody>
</table>

mg L$^{-1}$ (%)
Fig. 4. The volumetric water content as a function of time for selected segments of the TDR probes (a) TDR1 and (b) TDR2. The silty sand layer for TDR1 is situated at the depth of 190 to 212 cm, while for TDR2 it is situated at the depth of 237 to 250 cm. The time spans when bromide and hydrocarbons were applied are indicated on the figure.

The water content was 0.2 to 0.25 (Fig. 3b). This water content extended from 2.4 to 2.9 m. In contrast, the TDR1 probe had an abrupt decrease in the water content from the silty sand layer to the soil below. A partial overlap between the TDR segments (15 cm long at this location) and a thin silty sand layer may partly explain the relatively high water content seen below the silty sand layer for TDR2. However, as the height of the silty sand layer is only between 10 and 15 cm, a partial overlapping would not lead to a high water content across a depth of 45 cm. The explanation could be that the contrast between the silty sand layer and the surrounding sand layer at this location was too small to form an effective flow barrier.

In Fig. 6a and b, the slopes of the curves of the horizontal and vertical centers of mass plotted against time provide an estimate of the horizontal and vertical velocity of the plume, respectively. As the plume approached the silty sand layer, these velocities seemed to increase. This suggests that the soil structure may lead to an increased transport velocity of contaminant plumes in this soil, and hence a less efficient degradation of contaminants within the unsaturated zone. The horizontal displacement of the tracer plume is also important to take into account when observation wells are established to monitor plume development. Two plateau values were observed for both the vertical and the horizontal variances (Fig. 6c–f). The first plateau value represents the plume extension in the topsoil. As the plume reached the foreset bed the spatial variances in-
Fig. 5. Measured concentrations of bromide in the suction cups after 2 h, and 4, 8, and 16 d (the profile is the same as in Fig. 2). Injection continued until Day 3 as indicated by the half circle at the top of the graphs. The size of the big circles is proportional to the percentage of the input concentration measured at each cup. The dots indicate the suction cups. The local coordinate system uses the southeastern corner of the trench as the point of origin.

creased to the second plateau (0.06 and 0.23 m$^2$ for the horizontal and vertical variances, respectively). The final increase in the spatial variances occurred when the plume reached the silty sand layer. The asymptotic dispersivity of an aquifer can be estimated from correlation lengths and heterogeneity of the hydraulic conductivity (Dagan, 1989). The increase of the variance observed for the bromide plume (Fig. 6c–f) could thus be caused by a sudden increase in the correlation length or an increased heterogeneity. The last point seems most reasonable. As the plume moved vertically through the profile it encountered new soil units, for example, the dipping layers of the foreset unit, which increased the degree of the heterogeneity and thus increased the variance.

The horizontal and vertical variances of the bromide plume reached plateau values that were in the same range as the values reached in transport studies in Trench T1 (where no dipping layers were observed within the sedimentary deposits) during autumn rains and snowmelt (French et al., 1999). Although the boundary conditions were quite different (an average application rate of 1.87 mm d$^{-1}$ for the autumn period and 9.5 mm d$^{-1}$ during the snow melting period in T1, compared with an application rate of about 143 mm d$^{-1}$ in T2), this did not seem to affect the horizontal and vertical spread of infiltrating plumes in the upper parts of the unsaturated soil at Gardermoen.

Field Experiments—Transport and Retardation of Hydrocarbon Plumes

The maximum concentrations in the water samples extracted from the soil were 15.6 mg L$^{-1}$ (measured in Cup 20) and 17.2 mg L$^{-1}$ (measured in Cup 22) for toluene and $o$-xylene, respectively (Fig. 7b,c). This corresponds to an extraction efficiency of approximately 33% for both components compared with the applied concentration of 50 mg L$^{-1}$. In the bromide tracer experiment, a maximum breakthrough concentration of $C/C_0 = 1$ was observed for Suction Cups 13, 20, and 22 (Fig. 7a; see Fig. 2 for location of suction cups). Hence, the maximum breakthrough concentration in the suction cups in the upper parts of the soil was not reduced due to dilution. A high concentration of hydrocarbons (50 mg L$^{-1}$) combined with an application period of two weeks led to a saturation of the soil around the uppermost cups, as suggested from Fig. 7b and c where it is seen that the concentration of toluene and $o$-xylene reached a plateau value in both Cups 20 and 22. It was thus assumed that neither sorption nor dilution played a role concerning the reduction of the maximum extracted concentration of hydrocarbon. Comparing the extraction efficiency in the field with that observed in the column experiment (Table 3), it is seen that the reduction in concentration was of the same order of magnitude. Hence, we assume that the reason for a maximum concentration in the field of only one-third of the applied concentration was a result of the sampling method.

The plumes of toluene and $o$-xylene as functions of time are shown in Fig. 8 and 9, respectively. The size of the circles is proportional to the percentage of the average maximum concentration observed for toluene and $o$-xylene (16 mg L$^{-1}$), measured in each suction cup. The hydrocarbon plumes followed the same flow path as was seen for the nonreactive tracer, bromide...
(Fig. 5). The plumes moved westward close to Suction Cup 13, and followed the dipping silty sand layer toward the saturated zone. Only small amounts of hydrocarbons were measured in the Suction Cups 10 and 11. Spatial moment analysis has been used to describe the transport and spread of the hydrocarbon plumes. The spatial moments analysis of the bromide experiment indicated an increase in the horizontal and vertical velocity as the plume approached the silty sand layer, which indicate that the dipping soil layers could lead to a faster transport of contaminant plumes. However, both the horizontal and vertical velocity (given as the gradient in Fig. 10a,b) of the hydrocarbon plumes remained fairly constant with time. Thus, sorption and degradation of the hydrocarbon plumes counteracted the effect of the dipping soil layers. Comparing the velocities of the two hydrocarbon plumes, a slightly faster transport of toluene compared with o-xylene was observed. The plume of toluene also showed a greater spread than the plume of o-xylene, indicated by greater vertical and horizontal variances (Fig. 10c,d). These results are as expected as the sorption experiment showed lower $K_d$ values for toluene than for o-xylene.

By comparing the first part of the breakthrough curves for toluene and o-xylene with the first part of the breakthrough curve for bromide, we see that both components were retarded compared with the nonreactive tracer (results from Suction Cups 20 and 13 are given as examples, Fig. 11a,b). Even though Cup 13 was situated in the subsoil, which had a lower $K_d$ value than the topsoil where Cup 20 was situated, the retardation compared with bromide seemed to be in the same order of magnitude. Average retardation factors based upon the slopes of the breakthrough curves in Cups 13, 16,
Fig. 8. The plume of toluene after 1, 7, 10, and 15 d (the profile is the same as in Fig. 2). Application continued until Day 14 as indicated by the half circle at the top of the graphs. The size of this half circle is proportional to 16 mg L\(^{-1}\) toluene. The sizes of the other circles are proportional to the percentage of this concentration measured in each suction cup. The dots represent suction cups. The local coordinate system uses the southeastern corner of the lysimeter trench as the point of origin.

20, 22, and 23 were 2.0 and 2.2 for toluene and o-xylene respectively. Retardation factors calculated according to Eq. [8] were 1.05 and 1.12 for toluene and o-xylene, respectively. Retardation factors may also be theoretically calculated with the equation:

\[
R = 1 + \left(\frac{\rho_b}{\theta}\right)K_d
\]  

where \(\rho_b\) (g mL\(^{-1}\)) is the bulk density and \(\theta\) is the volumetric water content (m\(^3\) m\(^{-3}\)). With \(\rho_b\) equal to 1.7 g mL\(^{-1}\) and \(\theta\) equal to 0.2, and \(K_d\) values for the subsoil of 0.15 and 0.19 mL g\(^{-1}\), average retardation factors for toluene and o-xylene were calculated to be 2.3 and 2.6, respectively. The two methods used for calculating retardation factors based upon field measurements gave different results. As spatial moments give an integrated measure of the plume distribution, the calculation using vertical centers of mass is believed to be more reliable than the calculation based upon separate suction cups. However, retardation factors calculated for the separate suction cups were more in accordance with the theoretically calculated retardation factors (based on \(K_d\) values from the batch experiments). The difference between the retardation factors using Eq. [8] and Eq. [16] was probably caused by a lower effective sorption in the field than what was determined in the laboratory.

Field Experiments—Biodegradation

Loss of mass of jet fuel components in the unsaturated zone is caused by volatilization, sorption to organic and inorganic phases, and biodegradation. To verify that biodegradation takes place, the evolution of biodegradation products should be measured simultaneously with the decrease in the concentration of pollutants. Combined measurements of O\(_2\) consumption and CO\(_2\) production are suitable parameters for evaluating the progress of in situ aerobic biodegradation (Breedveld, 1997). At Morepenn, an increase in the CO\(_2\) concentra-

tion and a simultaneous decrease in the O\(_2\) concentration were observed during the experimental period, thus suggesting that aerobic biodegradation took place. Results from Cups 13 and 20 are shown as examples (Fig. 11c–f). The concentration of O\(_2\) never became less than 17.5% (v/v) (Fig. 11e,f), indicating that oxygen was not a limiting factor in this experiment. The respiration quotient (RQ = \(\Delta\text{CO}_2/\Delta\text{O}_2\)) for each gas sampler varied between 0.5 and 0.8 in the time period of maximum CO\(_2\) and minimum O\(_2\) concentration. Theoretical RQ values with 0, 30, and 50% biomass production are 0.77, 0.69, and 0.63, respectively. Hence, biomass production probably occurred during degradation of the hydrocarbons. The initial background concentration of CO\(_2\) was rather high and the background concentration of O\(_2\) rather low (Fig. 11c–f); this was especially true for Suction Cup 20. Breedveld et al. (1997) observed background concentrations of >20% (v/v) of O\(_2\) and <0.5% (v/v) of CO\(_2\). Enhanced leaching of organic matter from the top layer of the soil due to the high background infiltration might have resulted in the increased background concentration of CO\(_2\) observed in our work.

Breakthrough curves for Cups 20 and 22 are most suitable for identification of lag periods, as the hydrocarbon concentration in these cups reached stable plateau values before degradation was observed. The degradation of o-xylene started about 10 d after the application was initiated (Fig. 7c and 11a). A lag period of 10 d was also seen for toluene in Suction Cup 22, while the degradation of toluene in Cup 20 seemed to start after only 3 d (Fig. 7b and 11a). The difference in lag periods observed for toluene may be due to a greater biomass in the soil around Cup 20 (0.6-m depth) compared with Cup 22 (1.1-m depth). In batch studies with an initial concentration of 50 mg L\(^{-1}\) of each chemical, Alvarez and Vogel (1991) reported lag periods of 2 and 22 d for toluene and p-xylene, respectively. The combination of
Fig. 10. Spatial moments of the hydrocarbon plumes plotted against time: (a) horizontal centers of mass, (b) vertical centers of mass, (c) horizontal variances, and (d) vertical variances. The centers of mass are related to the southeastern corner of the lysimeter trench.

the two chemicals led to an increased lag period for toluene (7 d), while a decreased lag period for \( p \)-xylene was found (10 d). These lag periods are in accordance with those found in our work.

This experiment used very high concentrations of hydrocarbons and a high application rate, but the natural attenuation caused nearly 100% reduction of contaminants within the first 3 m of the unsaturated zone. This suggests that the unsaturated zone at Gardermoen has a high potential for removal of water-soluble jet fuel components. \( o \)-Xylene was seen to be the most recalcitrant of the two components (Fig. 7b,c and Fig. 8 and 9). One day after application ceased the concentration of toluene was very low throughout the entire soil profile, while appreciable concentrations of \( o \)-xylene were still left.

Field Experiments—First-Order Degradation Constants

First-order degradation coefficients were calculated for each suction cup as described in the Data Processing section, above. The total mass of solute recovered in a suction cup relative to the total mass injected was calculated both for the hydrocarbons and the inactive tracer (Fig. 12a,b, using Cup 22 as an example). To correct for the abiotic loss during water sampling, a concentration of 16 mg L\(^{-1}\) (an average maximum concentration of the hydrocarbons measured in the upper parts of the soil profile) instead of 50 mg L\(^{-1}\) was used when normalizing the total mass recovered of the hydrocarbons by the total mass injected (Eq. [12]). The fraction of reactive solute in solution was obtained by dividing the normalized zeroth moment of the hydrocarbons by the normalized zeroth moment of the inactive tracer (Eq. [13]). The fraction in solution was corrected for sorption (Eq. [14]) and the natural logarithm of the \( F(x,z) \) was related to the time value where 50% of the hydrocarbon mass had passed the suction cup (Fig. 12c). Plotting ln[\( F(x,z) \)] against this time value results in a graph with only two points (Fig. 12d), and the slope of the regression line gives an estimate of the first-order degradation coefficient for a separate suction cup. The average of the degradation coefficients calculated for the separate suction cups led to an overall degradation coefficient within the range 0.19 to 0.21 d\(^{-1}\) for toluene and 0.10 to 0.11 d\(^{-1}\) for \( o \)-xylene. These degradation coefficients were corrected for sorption, and were respectively 8.5 and 13.9% lower than the uncorrected ones. The uncertainties in the calculated degradation coefficients were caused by an uncertainty of 5% (relative uncertainty) in the extraction procedure and the gas chromatography measurements of the hydrocarbons.

A slight change in the flow pattern due to an increased application period (14 d for the degradation experiment compared with 3 d for the bromide tracer test) was observed. This led to an increase in the fraction of the total plume passing the Suction Cups 12, 16, and 17, and hence relatively more hydrocarbons than bromide passed these cups. Thus, the overall degradation coefficient is the average of the separate degradation coeffi-
Fig. 11. Breakthrough curves (BTC) for toluene and o-xylene in (a) Cup 20 and (b) Cup 13 compared with the BTC for bromide. Bromide was applied during 3 d, thus only the first 3 d of this experiment was directly comparable with the hydrocarbon experiments. That is why only the first part of the BTC of bromide is shown. The concentration of CO\textsubscript{2} and O\textsubscript{2} as functions of time are shown for Cup 20 in (c) and (e), respectively, and for Cup 13 in (d) and (f), respectively. The vertical line indicates the cease of hydrocarbon application.

In the literature, a wide range of first-order coefficients for biodegradation of BTEX compounds is reported. In a contaminated aquifer subject to mixed aerobic and denitrifying conditions, Borden et al. (1997) found coefficients ranging from 0.0005 to 0.0063 d\textsuperscript{-1} for toluene and 0.0007 to 0.0017 d\textsuperscript{-1} for o-xylene. Chiang et al. (1989) report about a total first-order degradation coefficient of 0.01 d\textsuperscript{-1} for benzene, toluene, and xylene in an aerobic sandy aquifer. These reported coefficients are for saturated conditions and are much lower than the ones calculated in this study. However, first-order degradation coefficients in the range 0.1 to 0.4 d\textsuperscript{-1} and 0.04 to 0.1 d\textsuperscript{-1} for toluene and o-xylene, respectively, are reported from an in situ microcosm study in the saturated zone subject to aerobic conditions (Nielsen et al., 1996). Furthermore, Lahvis et al. (1999) estimated first-order degradation coefficients in the unsaturated zone to be in the range 0.09 to 0.3 d\textsuperscript{-1} for toluene and in the range 0.1 to 0.31 d\textsuperscript{-1} for the xylenes. These values are in the same range as the values reported in our work, and indicate that degradation rates in the unsaturated zone are higher than in the saturated zone. The large variation in degradation coefficients may, in addition to oxygen availability, be caused by variations in temperatures and available essential nutrients. As the degradation experiments in our work were performed during summer months, they probably represent optimal conditions for degradation in the Gardermoen soil.

CONCLUSIONS

Sedimentary structures present in the forest unit, and especially a dipping silty sand layer, were found to have a profound influence on the water flow in the unsaturated zone at this specific location under the applied boundary conditions. At a depth of about 3 m, the inactive tracer plume was detected more than 5 m to the west of the injection point, indicating channeling flow along the silty sand layer. The total residence time of the bromide tracer in the unsaturated zone with the applied boundary conditions was about 20 d. No suction cups were installed below the silty sand layer in the western part of the trench, hence it was not possible to tell if a partial breakthrough of water through the silty sand layer occurred. However, high water content below the silty sand layer seen for TDR2, compared with an abrupt decrease in the water content below the silty sand layer for TDR1, indicated a less effective flow barrier at the location of TDR2. Although the chosen setup of suction cups could have been improved in the western part of the trench, it still captured the main flow pattern in the layered soil profile. A combination of suction cups and TDR measurements proved to be very useful for the overall understanding of the water flow.

The hydrocarbon plumes followed the same flow pattern as the bromide plume. The dipping layers did not seem to increase the vertical velocity of the plumes of contaminants. However, the horizontal displacement in itself might be necessary to take into account in the case of a contaminant spill at the airport. The degradation potential of the soil at Moreppen was high. The concent-

trations of toluene and o-xylene were very low at all sampling points one and two weeks, respectively, after application ceased. This experimental setup used very high concentrations of the components studied and a high application rate; but still nearly 100% reduction in concentration was obtained within the first 3 m of the unsaturated zone. First-order degradation coefficients were calculated to be within the range of 0.19 to 0.21 d⁻¹ for toluene and 0.10 to 0.11 d⁻¹ for o-xylene.

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