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Electrokinetic Biofence, remediation of VOCs with solar energy and bacteria

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Received 1 June 2003; accepted 1 July 2004

Available online 11 September 2004

Abstract

Since April 2001, an Electrokinetic Biofence (EBF) is in operation at the site of a chemical laundry at Wildervank in the Province of Groningen in the Netherlands. The EBF is located at the western part of the building and covers an area of $10 \times 2 \text{ m} = 20 \text{ m}^2$. Prior to the installation of the fence, the top soil, heavily polluted with volatile chlorinated hydrocarbons (VOCs), has been removed. The fence consists of a row of alternating cathodes and anodes with a mutual distance of 5 m. Upstream of the line of electrodes, a series of infiltration wells were installed, which have been periodically filled with nutrients. The aim of the EBF is to enhance biodegradation of the VOCs in the groundwater at the zone of the fence by electrokinetic dispersion of the dissolved nutrients in the groundwater. After running the EBF for nearly 2 years, clear results have been observed. The concentration of nutrients in the zone has increased, the chloride index is decreasing, and VOCs are being dechlorinated by bio-activity. The electrical energy for the EBF is being supplied by solar panels.

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Keywords: Electrokinetic Biofence; VOCs; Solar energy; Biodegradation

1. Site characteristics

Previous investigations have indicated high grades (10 g/kg) of volatile chlorinated hydrocarbons (VOCs) underneath the building (Nipshagen and Olsman, 2000). In the groundwater at the front of

the building, concentrations of perchloroethylene (PCE) of 180 mg/l indicate mass transport of free product up to the clay layer at approximately 10 m below ground surface (bgs).

The heavily contaminated soil underneath and around the laundry acted and is still acting as a source for the downstream groundwater contamination. In this groundwater plume, *cis*-dichloroethylene (C-DCE) was found in concentrations above the Dutch intervention value at a distance of 250 m from the laundry and at a depth of 11 m bgs (Nederlandse Staatscourant, 2000).

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2. Electrokinetic biofence

An alternative for containment and remediation of polluted groundwater plumes is to deploy an EBF (Godschalk et al., 2002). Such a fence should be envisioned as an elongated and relatively narrow zone wherein nutrients and/or electron donors are being dispersed electro kinetically (Prausnitz and Reitsotter, 1931). The nutrients enter the groundwater either from the electrode wells or from upstream infiltration wells. Once dissolved in the groundwater, nutrients like nitrogen, phosphorus, oxygen donors, organic compounds, micronutrients, etc., required for biodegradation of organic contaminants, occur almost always as electrically charged compounds and can hence be dispersed electro kinetically through the soil. An EBF avoids the necessity to pump hundreds of thousands of cubic meters of groundwater and it also means that the groundwater flow regime is not influenced (Lageman and Pool, 2001).

Because of the intensified biodegradation, dispersion of the contamination via the groundwater will be controlled and eventually halted. The energy necessary to activate the fence depends on the velocity of the groundwater flow. The amount and composition of the nutrients depend on the amount of VOCs in the groundwater and on the nutrients already present in the groundwater (Schippers et al., 1997).

The basic set-up consists of a row of electrodes (anodes and cathodes) which are installed perpendicular to the main direction of groundwater flow at the boundary of a hot spot or groundwater plume, up to the maximum depth where contaminants are still present.

The infiltration filters contain pouches with nutrients in solid form. These nutrients dissolve slowly and are then dispersed homogeneously through the soil, under influence of the groundwater flow and the electrical field (Fig. 1). Part of the nutrients is captured in the electrolytes circulating around the electrodes. Nutrients are also added to the electrolytes. Since pH conditions should be neutral, the electrolytes coming from the acidifying anodes and the alkalinizing cathodes are mixed continuously above ground, and the nutrients which are intercepted at the cathodes will be drawn into the soil via the anodes; the nutrients intercepted at the anodes will be drawn into the soil via the cathodes (Lageman et al., 1988).

The amount of nutrients entering the groundwater per unit of time through the electrode filters, is managed electro kinetically, but the amount of nutrients entering the groundwater through the infiltration filters depends amongst others on the concentration of the nutrients in the infiltration filters and on the construction of the infiltration filters. The extent of homogeneous dispersal of the nutrients

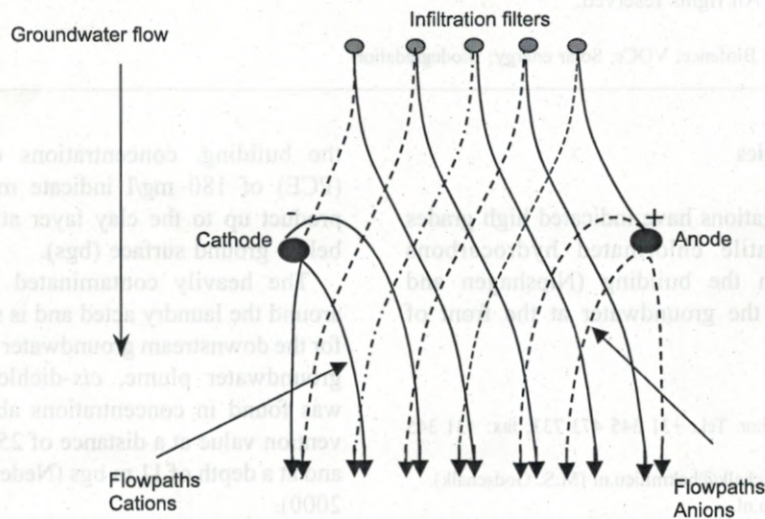


Fig. 1. Flow paths of positive (dashed lines) and negative (solid lines) charged nutrients and electron donors from the infiltration points upstream of the electrodes.

beyond the fence depends on the groundwater flow and the applied voltage over the electrodes. Another important aspect is the stability of the nutrients in the groundwater and the extent of adsorption on soil particles. Although parameters such as adsorption and retardation can be determined under laboratory conditions, the obtained results are often a mismatch with the actual situation in the field (Schippers et al., 1997).

The organic contaminants traveling via the groundwater are decomposed within the fence zone or downstream thereof, because of the highly increased microbial activity. The 'bulk' of induced nutrients will in principle be less adsorbed onto the soil particles, and they will hence catch up earlier with the contaminants traveling via the groundwater; this is then followed by bacteriological decomposition of these contaminants. The zone of biological activity will continue to expand over time in the flow direction of the groundwater.

3. Description of the electrokinetic biofence

The Electrokinetic Biofence consists of three cathodes and two anodes (Pool and Lageman, 2001). The electrode wells have been placed in a row at a mutual distance of 5 m, downstream of the chemical laundry up to 10 m depth. Upstream of the electrode wells, 20 infiltration wells have been installed (PE filter, diameter 50 mm, length 10 m, perforation from 1 to 10 m bgs). Each filter can be filled with approximately 13 kg of solid nutrients, consisting of sodium, calcium, nitrogen, phosphorus and ammonium compounds.

Apart from the 20 filters located directly upstream of the five electrodes wells, four reference wells have been placed adjacent to, but outside of, the zone with the electrode wells. Downstream 16 monitoring wells have been installed to follow the dispersion of nutrients and the concentration of VOCs.

Cathodes and anodes have been integrated into separate electrolyte circulation systems. Electrolyte management consists of preventing alkalisation at the cathodes and acidification at the anodes by mixing anolyte and catholyte and thus neutralizing (pH = 7) both electrolytes (Godschalk and Lageman, 2002a). An additional advantage of mixing anolyte and

catholyte is that anionic nutrients captured in the anolyte end up in the catholyte and likewise cationic nutrients end up in the anolyte. Thus, cathodes and anode are acting as new infiltration sources for nutrients.

4. Nutrients

For the optimal biodegradation of VOCs, electron donors (C) and nutrients nitrogen (N) and phosphorus (P) are required (van den Berg et al., 1998; Nipshagen et al., 1999). In Table 1, the average concentration of nitrogen Kjeldahl (N), phosphorus (P as *ortho*-PO₄) and dissolved organic carbon (DOC) are given.

Table 1 indicates that sufficient nutrients in the form of a carbon source (DOC), nitrogen (N-Kjeldahl) and phosphorus are present in the groundwater. The concentration of nitrogen increases with nearly a factor 10 and stabilizes at a concentration of about 30 mg/l. Phosphate increases five times and stabilizes at a concentration of 5.5 mg/l. The concentration of DOC increases with a factor 2, but decreases in the last period to 60 mg/l. It cannot be derived from the determination of DOC whether all present carbon forms a suitable source for the decomposition of VOCs. Experience and data from literature indicate that the nutrients, administered through the electrode wells and infiltration filters, are quickly decomposed and that they have a positive influence on the decomposition process of VOCs. The data show clearly that the concentration of these nutrients and electron donors increase, caused by the infiltration and dispersion of nutrients by the Electrokinetic Biofence.

Fig. 2 shows that the concentration of DOC decreases near the fence and increases downstream thereof. This can be explained by the increase of N and P near the fence and consequently an increase in

Table 1
Changes in the concentration of nutrients

| Concentration of nutrients | March 01 | July 02 | January 03 |
|----------------------------|----------|---------|------------|
| Nitrogen-Kjeldahl (mg/l) | 3.3 | 29 | 28 |
| Ortho-phosphate (mg/l) | 1.1 | 5.4 | 5.6 |
| DOC (mg/l) | 47 | 97 | 60 |

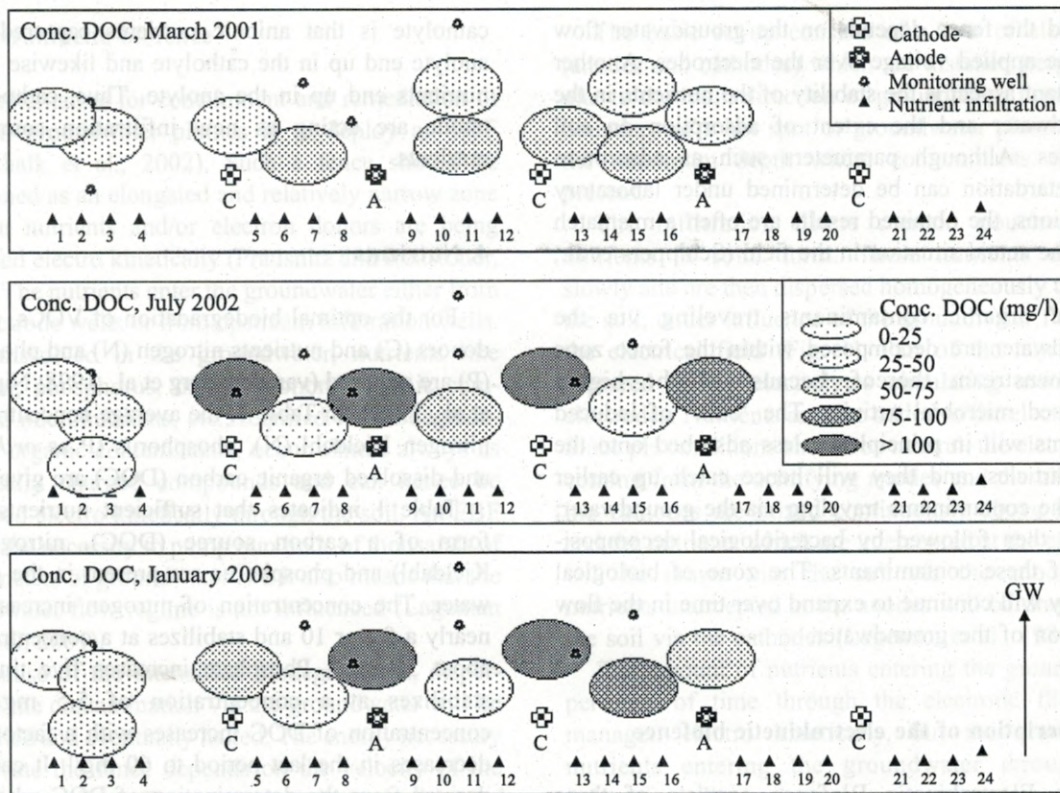


Fig. 2. Changes of DOC concentrations, during treatment with an Electrokinetic Biofence.

biological activity, which leads to a decrease in DOC as it is being used by the microorganisms.

5. VOCs

An Electrokinetic Biofence is designed to remove VOCs in a groundwater plume or to stop their downstream migration. The biofence will stimulate and create optimal conditions for biological activity to dechlorinate VOCs downstream of the fence. In Fig. 3 the development in concentrations of VOCs is represented. Note that the building of the chemical laundry starts just 1 m south of the nutrient infiltration wells.

From Fig. 3 (July 2002 and January 2003) it can be observed that there is an increase in concentrations of VOCs. This is caused by an inflow of VOCs from underneath the chemical laundry building, which still acts as a source area.

6. The chloride index

To monitor the dechlorination of VOCs, the chloride index (CI-index) is being used. By calculating this index an indication of biological activity can be obtained, based on the concentrations of VOC compounds. The CI-index has been adapted slightly and it is calculated as follows:

$$\text{CI-index} = \{4 \cdot [\text{PCE}] + 3 \cdot [\text{TCE}] + 2 \cdot [\text{C-DCE}] + 2 \cdot [\text{T-DCE}] + 1 \cdot [\text{VC}]\} \cdot \{[\text{PCE}] + [\text{TCE}] + [\text{C-DCE}] + [\text{T-DCE}] + [\text{VC}]\}^{-1},$$

wherein [PCE] = concentration of perchloroethylene in mol/l, [TCE] = concentration of trichloroethylene in mol/l, [C-DCE] = concentration of *cis*-dichloroethylene in mol/l, [T-DCE] = concentration of *trans*-dichloroethylene in mol/l, [VC] = concentration of vinyl chloride in mol/l.

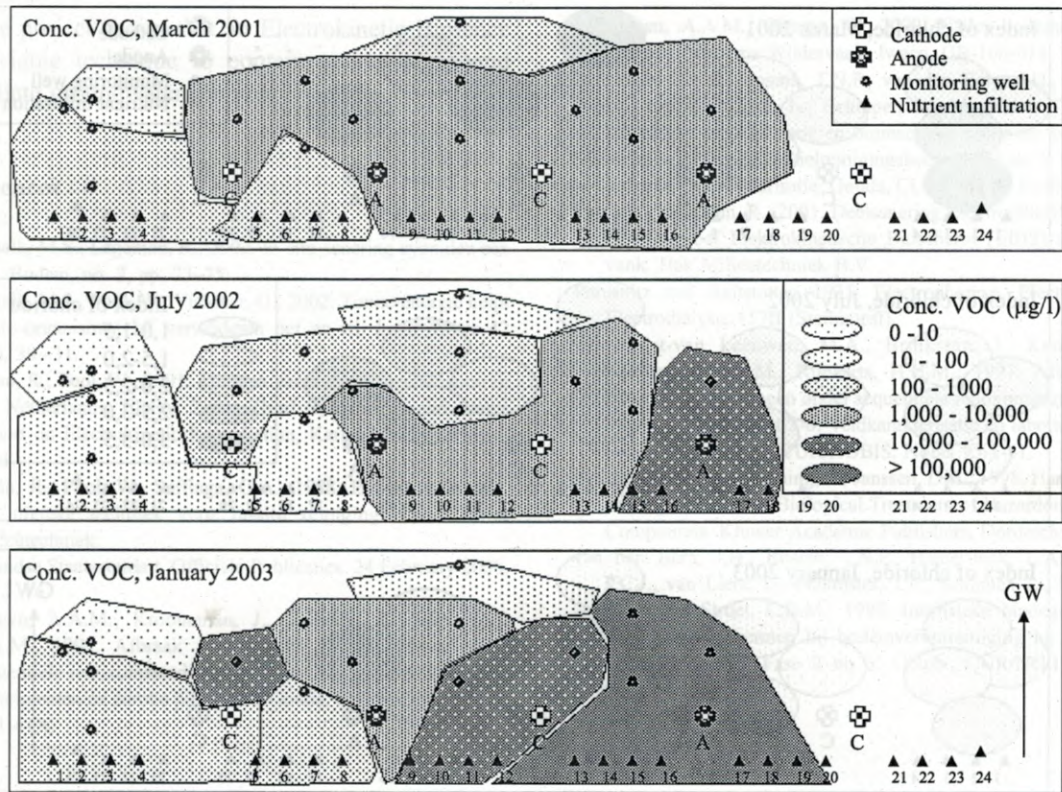
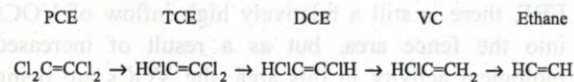


Fig. 3. Changes of the VOC concentrations, during treatment with an Electrokinetic Biofence.

loroethylene in mol/l, [VC]= concentration of vinyl chloride in mol/l.

When VOCs are present in the groundwater, the Cl-index may vary from 4 (only PCE dissolved) to 1 (only VC dissolved). Thus, during biodegradation of PCE to VC, the chloride index changes from 4 to 1. The biodegradation of PCE (dechlorinisation) via intermediate products to ethane can be described as follows (van Agteren et al., 1998; van Aalst-van Leeuwen et al., 1997):



The change of the Cl-index at the location is represented in Fig. 4.

From Fig. 4 it is obvious, that the average Cl-index is decreasing. Before the activation of the EBF, chloride indexes of more than 2.5 were observed. In

July 2002, all monitoring wells showed a Cl-index below 2.5. In January 2003 most of the monitoring wells showed Cl-indexes below 2.0. Some monitoring wells, however, have Cl-indexes above 3 again. The location of these monitoring wells coincides with the area where an inflow of VOCs was observed. In spite of these high concentrations, total Cl-index stays low, which indicates that the biological activity has been enhanced to such an extent that it can cope with high influxes of VOCs.

7. Energy requirements

The calculations for the electrical power requirements, needed to transport nutrients electrokinetically through the soil, are based on the velocity of the groundwater flow. If the voltage is too high, all nutrients will end up either at the cathode or anode. If the voltage is too low,

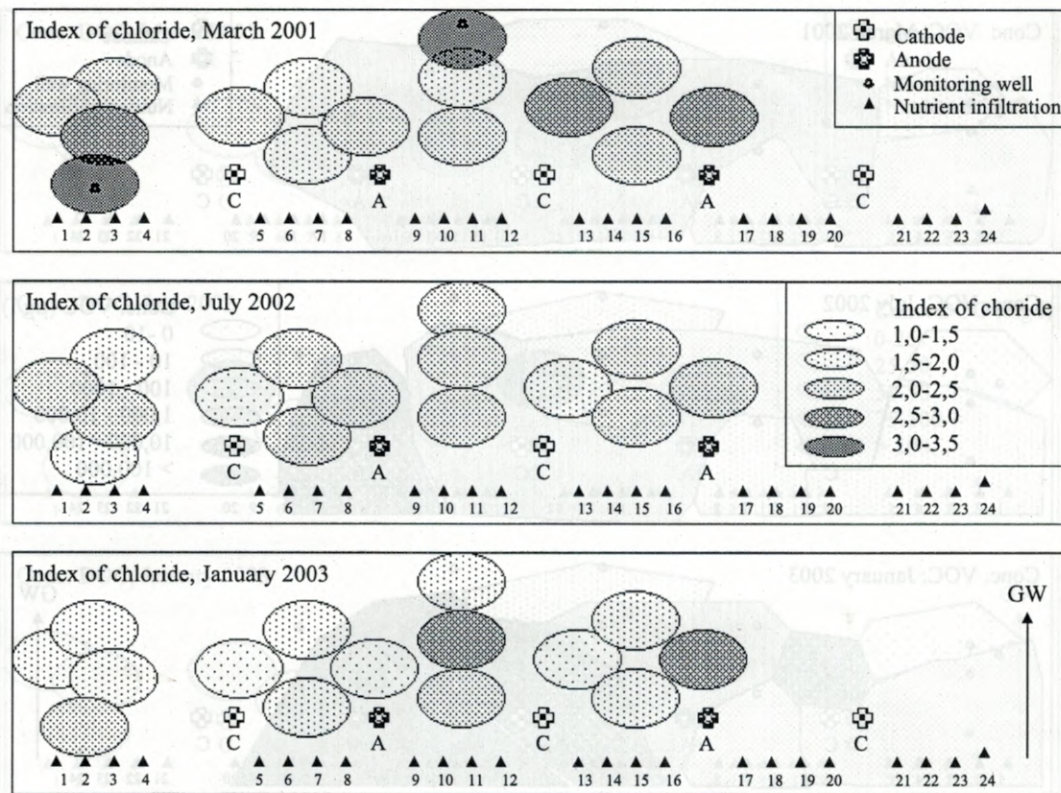


Fig. 4. Change of the chloride index, during the treatment with an Electrokinetic Biofence.

nutrients will not be dispersed. The optimal voltage, therefore is the voltage at which nutrients are dispersed homogeneously through the soil, as shown in Fig. 1.

The average groundwater velocity at the site amounts to some 3 m/year. Based on this velocity, the EBF needs an electrical power input of about 300 to 350 W (Pool and Lageman, 2001). This energy input can be supplied by solar panels. The solar panels installed at the site have a maximum output of 500 W. This is sufficient for sunny days. At night and on cloudy days the electricity is taken from the grid.

8. Conclusions

At the site of a chemical laundry at Wildervank in the Netherlands, a pollution with VOCs has extended into a large plume of about 250 m length.

The plume is being treated with an Electrokinetic Biofence (EBF), consisting of three cathodes, two anodes and 24 infiltration wells. The infiltration wells are being filled with a combination of nutrients and electron donors. These compounds dissolve in the groundwater and are homogeneously dispersed through the soil under the influence of the induced electrical field. Since the start of the EBF, concentrations of nutrients increase downstream of the electrodes, while the Cl-index is decreasing. From the source area upstream of the EBF, there is still a relatively high inflow of VOCs into the fence area, but as a result of increased biological activity in this area, the VOCs are being degraded efficiently, as shown by low Cl-index numbers.

The electrical power for the biofence is being generated by solar energy panels. At night and during cloudy days, electrical energy is taken from the grid.

The project shows that an Electrokinetic Biofence is a viable technique to contain source areas and remediate groundwater plumes.

References

- Godschalk, M.S., Lageman, R., 2002. In-situ-sanering cyaniden een feit. *Bodem*, no. 2, pp. 73–75.
- Godschalk, M.S., Pool, W., Visscher, G., 2002. Zonne-energie helpt micro-organismen bij verwijderen per en tri. *Land Water* 42 (11), 30–31.
- Lageman, R., Pool, W., 2001. Thirteen years electro-reclamation in the Netherlands. EREM 2001, Third Symposium and Status Report on Electrokinetic Remediation, Karlsruhe, 18–20 April 2001.
- Lageman, R., Pool, W., Seffinga, G.A., 1988. Electro-reclamatie, een nieuwe techniek voor in-situ reiniging. *Land Water Milieutechniek*.
- Nederlandse Staatscourant, Officiële Publicaties. 24 February 2000, pp. 7–16.
- Nipshagen, A.A.M., Krooneman, J., Tuinstra, A., Langehoff, A.A.M., 1999. Afbraak van per- en trichlooretheen onder sequentiële redoxomstandigheden; Fase 2: Aanvullende kolom-experimenten en aëroë pilorproef. Gouda, CUR/NOBIS. Nobis 95-1-41A.
- Nipshagen, A.A.M., Olsman, S., 2000. Nader bodemonderzoek Wasserij Moderna Wildervank. Iwaco, GR-106-018.
- Schippers, B.P.A., Bosma, T.N.P., van den Berg, J.H., te Stroet, C.B.M., van Liere, L., Schipper, L., Praamstra, T.F., 1997. Intrinsieke biodegradatie en bioreactieve schermen bij bodemverontreiniging bij textielreinigingsbedrijven: Fase 1. Probleemdefinitie en inventarisatie. Gouda, CUR/NOBIS. Nobis 96-2-01.
- Pool, W., Lageman, R., 2001. Deelsanering Elektro(Bio)Reclamatie en Pilotproef Elektrokinetische Bioscherm (EBIS) te Wildervank. Hak Milieutechniek B.V.
- Prausnitz and Reitstotter, 1931. Electrophorese, Electroosmose, Electrolyse, 157ff (Steinkopff).
- van Aalst-van Leeuwen, M.A., Brinkman, J., Keuning, S., Nipshagen, A.A.M., Rijnaarts, H.H.M., 1997. Afbraak van per- en trichlooretheen onder sequentiële redoxomstandigheden: Fase 1. Deelresultaat 2-6: Veldkarakterisatie en laboratoriumexperimenten. Gouda, CUR/NOBIS. Nobis 95-1-41.
- van Agteren, M.H., Keuning, S., Janssen, D.B., 1998. Handbook on Biodegradation and Biological Treatment of Hazardous Organic Compounds. Kluwer Academic Publishers, Dordrecht.
- van den Berg, J.H., Bosma, T.N.P., Hamerlinck, L.A., Leijten, P.C.J., van Liere, L., Praamstra, T.F., Schipper, L., Schippers, B.P.A., te Stroet, C.B.M., 1998. Intrinsieke biodegradatie en bioreactieve schermen bij bodemverontreiniging bij textielreinigingsbedrijven. Fase 2 en 3. Gouda, CUR/NOBIS. Nobis 96-2-01A.

1. Site characteristics

Previous investigations have indicated high grades (10–20 g/kg) of volatile chlorinated hydrocarbons (VCHs) underneath the building (Nipshagen and Olsman, 2000). In the groundwater in the front of

the building, concentrations of polychlorinated biphenyls (PCBs) of 100 µg/l indicate mass transport of these products up to the clay layer at approximately 10 m below ground surface (bgs).

The heavily contaminated soil underneath the ground the building and is still acting as a source for the down-slope groundwater containing line. In the groundwater plume, *o*-xylodichlorobenzene (OCDB) was found in concentrations above the Dutch intervention value of 25 µg/l from the building and at a depth of 1.2 m bgs (Nipshagen and Olsman, 2000).

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