In situ bioremediation technologies – experiences in the Netherlands and future European challenges

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EURODEMO
European Co-ordination Action for Demonstration of
Efficient Soil and Groundwater Remediation

Contents

1 Introduction

In-situ bioremediation relies on micro organisms to biologically degrade groundwater contaminants through a process called biodegradation. This process can occur naturally (Natural Attenuation), or can be enhanced through various methods (Enhanced Natural Attenuation or Enhanced Bioremediation). Both processes will be discussed below.

In-situ bioremediation avoids the costs associated with bringing water to the surface for treatment; instead, the main costs associated with bioremediation include delivery of the amendments to the subsurface (which varies depending on the depth of contamination), the cost of the amendments themselves, and monitoring of the treatment.

The bioremediation technology of contaminated sites depends on the type of contaminant. Since chlorinated solvents are one of the most common groundwater contaminants, numerous laboratory studies as well as pilot and field applications have been or are being conducted with chlorinated solvent, such as chlorinated ethylenes and ethanes.

2 Monitored Natural Attenuation (MNA)

2.1 Background

The term **Natural Attenuation (NA)** refers to "naturally occurring processes in soil and groundwater environments that act without human intervention to reduce the mass, toxicity, risk, mobility, volume and/or concentration of contaminants in these media" (Environmental Protection Agency, 1998).

The most important destructive process during Natural Attenuation is microbial degradation; the contaminants are broken down ultimately into harmless compounds such as water and carbon dioxide, and also chloride in the case of chlorinated compounds. With other processes such as dispersion, volatilisation, and adsorption, the contaminants remain in the environment; concentrations in the groundwater and associated risks decrease, but the total amount of contaminants in the environment remain the same. Inorganic compounds like heavy metals and arsenic can be attenuated by chemical and physical processes, but can not be degraded.

Monitored Natural Attenuation (MNA) is the monitoring and evaluation of these processes. When migration of contaminants is stopped and acceptable concentration levels are reached, MNA is sufficient as long as the pollution causes no unacceptable risks, see figure 2.1.

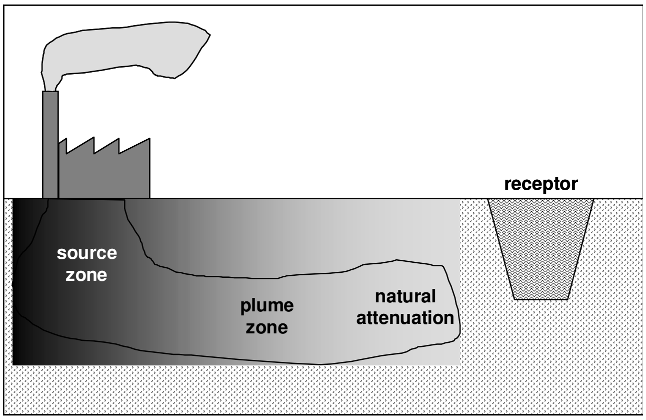

Figure 2.1 *Schematic overview of a typical industrially polluted site and the different zones, which determine the type of bioremediation technique.*

Although the occurrence of NA has been demonstrated in the US and in Europe, the actual use of these processes as remedial strategy is a new phenomenon in Europe. Furthermore, in several European countries (for instance the Netherlands) MNA is only accepted by authorities when the contaminants are actually degraded by biological processes. All other processes that reduce the concentration of contaminants e.g. dilution, dispersion, volatilisation are not regarded as Natural Attenuation.

Biodegradation can occur under both aerobic and anaerobic conditions. Under aerobic conditions organic contaminants are generally used by micro-organisms for "nourishment": i.e. as energy (metabolism) and carbon source (for growth). This is called oxidative degradation.

Organic contaminants can also be degraded under anaerobic conditions. Alternative electron acceptors are used instead of oxygen, e.g. nitrate, iron (III), sulphate and carbon dioxide (in order of decreasing energy yield to oxidise the contaminant. Alternatively, organic contaminants can be degraded via a reductive pathway. In this process the contaminant is used as electron acceptor and naturally available organic carbon or other contaminants may serve as electron donor. This reductive degradation is called reductive dechlorination in the case of chlorinated contaminants.

Highly chlorinated compounds (e.g. hexachlorobenzene, tetrachloroethylene) are essentially not degradable at high redox potentials. Such compounds can be dechlorinated to lower chlorinated analogues under methanogenic and sulphate-reducing conditions. Therefore, to achieve total mineralisation of these compounds, sequential anaerobic and aerobic conditions are required.

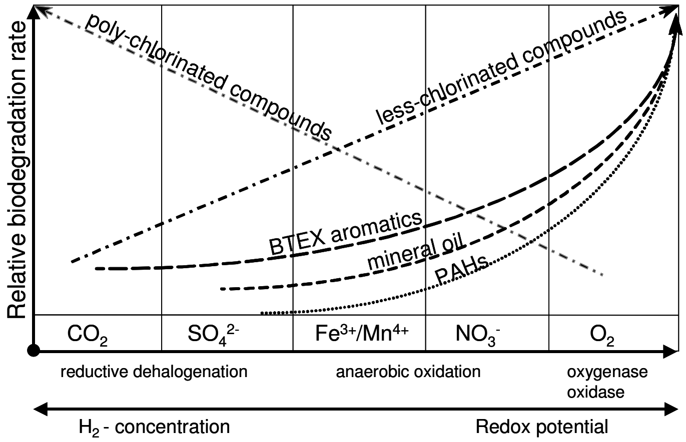

Figure 2.2 Biodegradation rates and processes for different classes of pollutants under various redox conditions.

To demonstrate the efficacy of MNA, three lines of evidence can be used:

1. Documented loss of contaminant mass in the field,
2. Geochemical and biochemical indicators demonstrating that processes occur resulting in a reduction of contaminant mass,
3. Confirmation of NA in microcosm studies or laboratory experiments.

(Environmental Protection Agency, 1998).

To implement MNA the following aspects have to be considered:

- Protection of potential receptors during attenuation,
- Sustainable favourable geological and geochemical conditions
- Reduction of contaminant mass in a reasonable time frame.
- Monitoring plan
- Contingency plan

Taking MNA into consideration usually requires modelling and evaluation of contaminant degradation rates and pathways. Also predicting contaminant concentrations at down-gradient receptor points is required, especially when the plume is still expanding/migrating. The primary objective of site modelling is to demonstrate that natural processes of contaminant degradation will reduce contaminant concentrations below regulatory standards or risk-based levels in an appropriate time frame. In addition, sampling and sample analysis must be conducted during the process to confirm that clean up is proceeding at rates consistent with the objectives. Monitored Natural Attenuation is not the same as "no action," although it is often perceived as such. In all cases, extensive site characterization and continued monitoring are required.

2.2 Implementation

NA is principally used in the saturated zone of the soil, although oxidative biological degradation also takes place in the unsaturated zone. Oxidative degradation occurs usually in permeable layers, since oxygen or other electron acceptors have to be transported to the contaminant by groundwater flow. Reductive degradation, for which the absence of competing electron acceptors is needed, can also occur in less permeable clay and peat layers. Natural attenuation is possible for almost all organic compounds, although degradation rates may be too low for the required time frame. Even when reactions rates are considered fast, complete remediation can take decades. Natural attenuation as a remedial strategy is especially effective in contaminant plume areas (fig. 2.1). In contaminant source areas, concentrations are usually too high to be removed without active intervention.

2.3 Considerations

- The legal framework might not allow MNA as remedial technique in some countries.
- Many organics are not or only very slowly degraded under the conditions (anaerobic or low oxygen concentrations) that prevail in the soil.
- The degradation can stagnate at an intermediate product that is more harmful than the initial contaminant, e.g. the reductively dechlorination of perchloroethylene (PCE) can yield the more toxic intermediate vinylchloride.
- To keep the process going, favourable conditions for biodegradation have to be maintained for a long period. When the necessary conditions in the soil have to be actively applied or restored, this is called Enhanced Bioremediation or Enhanced Natural Attenuation (see chapter 3).

3 Enhanced Bioremediation/Enhanced Natural Attenuation

3.1 Background

When Natural Attenuation is not sufficient to either stop migration or to lower concentrations to acceptable levels within a given time frame, E**nhanced Biodegradation/Bioremediation** can be considered. This is also referred to as Enhanced Natural Attenuation (ENA). ENA involves the addition of specific compounds to the soil or groundwater to create conditions that are favourable for the desired degradation of the present contaminants. The added compounds are often dissolved in infiltrated water, for which extracted groundwater from the site can be used.

Various compounds can be used to stimulate degradation processes under both aerobic and anaerobic condition e.g. nutrients, electron acceptors, electron donors or even bacteria. The latter process is called bioaugmentation (see chapter 4).

Nutrients are necessary for all biological processes. When high concentrations of contaminants are present, the availability of nitrogen and phosphate can be the limiting factor for the growth of bacteria that perform the degradation processes. These nutrients have to be supplied in a molar ratio of C:N:P of roughly 100:10:1.

Many organic contaminants can be degraded aerobically with oxygen (see also MNA). **Aerobic bioremediation** is based on this fact. Oxygen can be introduced in the soil in either in the gas phase (see Biosparging for the saturated zone and Bioventing for the unsaturated zone) or the water phase by saturation of groundwater with air or oxygen. Furtermore it is possible to use oxygen release compounds or fluids like magnesium (per)oxide powder or hydrogen peroxide.

Anaerobic bioremediation can be used for both oxidative as well as reductive conversions of the contaminants, see the explanation under MNA. For anaerobic oxidative degradation, electron acceptors are needed, such as nitrate, iron (III), sulphate or carbon dioxide (in order of decreasing energy yield). These compounds can be added to extracted groundwater before re-infiltration or directly infiltrated into the soil. High chlorinated ethylenes, ethanes and aromatics can be degraded reductively. The necessary low redox conditions and required quantities of electron donor can be administered by introducing an organic compound into the soil, e.g methanol, ethanol, molasses, sugar, fatty acids, oil, chitin, or hydrogen. These compounds generate hydrogen, which generally acts as the ultimate electron donor in reductive degradation reactions.

3.2 Implementation

Enhanced Bioremediation is a technique that is mainly used in the saturated zone of the soil (for application in the unsaturated zone see Bioventing). For the introduction of the necessary compounds, it is imperative that permeable soil layers are present.

Aerobic degradation is possible for many organic compounds, such as non-chlorinated and low-chlorinated compounds.
Anaerobic oxidative degradation of mineral oil and aromatics is possible when the correct conditions are applied. However, not all of these compounds can be degraded under anaerobic conditions.

Anaerobic reductive dechlorination is possible for, e.g. chlorinated ethylenes en ethanes. Bioremediation is most effective in contaminant plume areas. In contaminant source areas, concentrations may sometimes be too high for removal by biological processes only. Remediation times can vary from a few years to decades, depending on the soil characteristics (groundwater flow, properties of the contaminants etc.).

3.3 Considerations

- The legal framework might not allow introducing certain substances in the soil. Electron donors and acceptors can be regarded as contaminants in some countries.
- In a complex heterogeneous soil with for instance the presence of silt, clay or peat layers, the remediation may last for decades because these layers are not well permeated by the introduced water.
- Infiltration installations may get clogging problems because of precipitation of e.g. iron oxides that are formed when extracted anaerobic groundwater becomes aerobic.

3.4 Case 1: Reductive dechlorination of PCE at a contaminated site in the Netherlands

Mixed redox conditions control the intrinsic biodegradation processes at a location in the centre of a Dutch city, which is contaminated with perchloroethylene (PCE) and trichloroethylene (TCE). Intrinsic degradation had taken place at this site, which was demonstrated by the detection of degradation products *cis*-dichloroethylene (*cis*-DCE) and vinyl chloride (VC), see figure 3.1.

Figure 3.1 Degradation pathway of perchloroethylene (PCE)

This intrinsic reductive dechlorination may have been enhanced by a leakage from an sewage system, providing the electron donors that are needed for the dechlorination processes. However, the natural transformation rates of *cis*-DCE and VC at the site were too low to prevent migration of these hazardous compounds from the source zone to areas that must be protected. The low levels of DOC in the groundwater (< 10 mg/l) indicated a lack of naturally present electron donor and addition of electron donor was needed to achieve a complete degradation of the chlorinated ethylenes at the site.

Stimulation of the degradation process was first demonstrated in laboratory experiments in both batch and column experiments. These experiments demonstrated a successful degradation of PCE to the harmless compound ethylene. Based on these laboratory experiments a full scale experiment was designed for the site, focussing on reductive dechlorination with a mixture of methanol and compost-leachate as electron donor. An infiltration and recirculation system was designed and implemented at the site to add the electron donor to the system with the recirculated groundwater.

The pilot system (65 x 20 m) consisted of 10 infiltration wells on one side and 5 extraction wells at the other side of the source zone at a depth of 5 to 8 m bgs. Part of the extracted groundwater was re-infiltrated via the infiltration wells. By recirculating part of the extracted groundwater without purification, the soil was used as a ‘bioreactor’. A mixture of electron donor and nutrients (methanol, compost leachate and ammonium chloride) was added to the untreated re-infiltrated groundwater. The pilot test lasted for 35 weeks, and was continued afterwards due to its success.

A few months after start up, nitrate was depleted, sulphate concentrations decreased significantly, and methane concentrations increased. This indicates that the soil had become more reduced (sulphate reducing or methanogenic conditions), which is beneficial for the reductive dechlorination process. Increased levels of H_2 in the groundwater and decreasing redox-potentials confirm these results.

The percentage of dechlorination was calculated from the monthly monitoring of chloroethylene concentrations, and is expressed as the amount of chlorine that is eliminated from the source compound PCE.

$$Dechlorination\% = \frac{\frac{1}{4}[TCE] + \frac{2}{4}\left[\sum DCEs\right] + \frac{3}{4}[VC] + [Ethene] + [Ethane]}{[PCE] + [TCE] + \left[\sum DCEs\right] + [VC] + [Ethene] + [Ethane]} * 100$$

Dechlorination was established in most of the stimulated area. Starting at an average of 35%, the dechlorination increased to 50 - 95% in the different monitoring wells. A high degree of dechlorination (> 75%) was found primarily in the northern part of the stimulated area and in close proximity to the infiltration wells in the southern part. The concentrations of PCE and TCE decreased over time, and completely dechlorinated products like ethylene and ethane were formed. Figure 3.2 shows an example of a monitoring well in which the sequence of dechlorination products was evident, and the dechlorinated end products, ethylene and ethane, were produced.

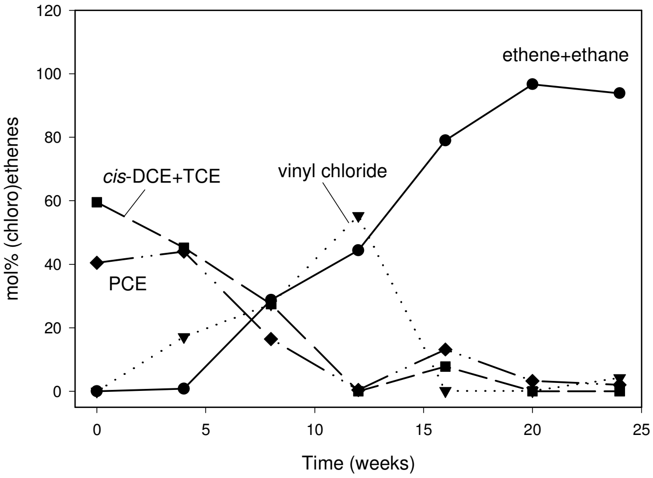

Figure 3.2 Mol% of (chloro)ethylene concentrations in a monitoring well. The total concentration of chloroethylenes was around 10 μM.

Detection of chloroethylene-dechlorinating *Desulfitobacterium* species at the site indicated increased numbers during the infiltration processes. Another site in the Netherlands has shown increased numbers of *Dehalococcoides* species that are responsible for the dechlorination of *cis*-DCE (Ballerstedt and Gerritse, 2002)).

The successful bioremediation process has been monitored over 3 years by measuring changes through a combination of parameters. The central part of the plume showed less degradation, as the added electron donor was not able to reach this area. This was caused by malfunctioning infiltration filters: changes in infiltration strategy will solve this problem in the future.

3.5 Case 2: Reductive dechlorination of *cis*-DCE at a contaminated site in the Netherlands

In the south of the Netherlands the site of a metal workshop was contaminated with DCE, VC and dichloroethanes (DCA). A biologically activated zone or bioscreen was studied near a contaminant source, as well as Natural Attenuation (NA) in the accompanying contaminant plume downstream. The top soil layers consist of a complex sequence of sand, peat, silt and clay. The source of the contaminants is located underneath a large production facility, which makes source removal impossible. Contaminants have reached the underlying aquifer at a depth of 30 m-bgs. The contaminant plume in the aquifer has a length of 1000 m, at a depth of 40 and 60 m-bgs (see fig.3.3).

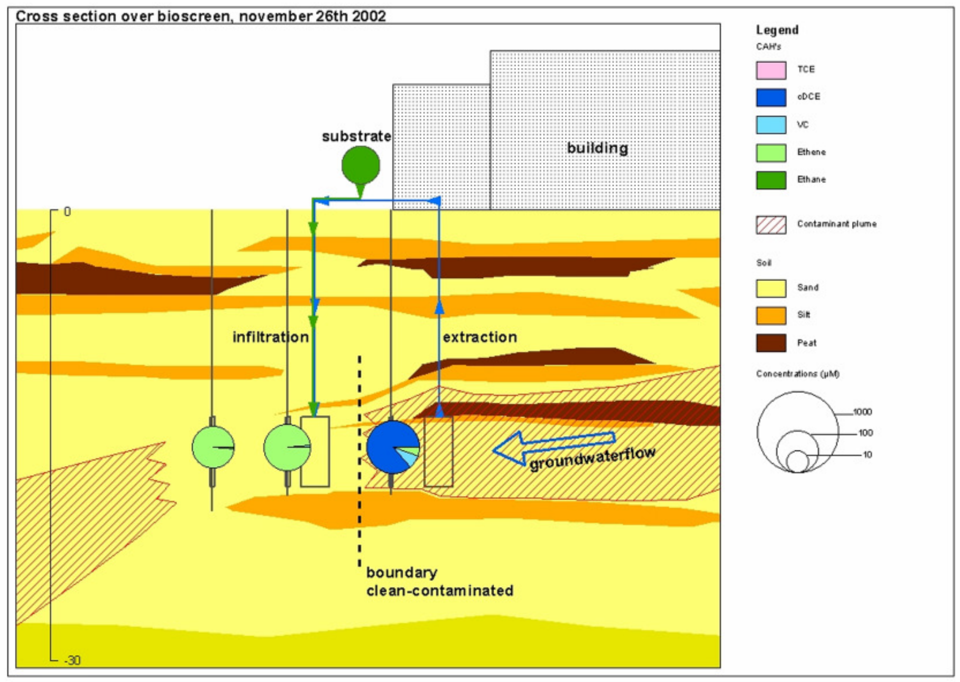

Figure 3.3 Bioscreen operation schematics

Natural degradation stagnates between 10 and 20 m-bgs as a result of unsuitable redox- and nutrient conditions. Modelling shows that the plume will become stable in 60 years and will remain present over hundreds of years. It is predicted that with the use of a bioscreen the plume will vanish in 60-80 years. S a result, a bioscreen or biologically activated zone (infiltration of electron donor) was created to stop the outflow of contaminants to the plume.

A full-scale biological treatment zone with infiltration and extraction screens was created just outside the main production facility at a depth of 10-20 m (fig. 3.3). Extended research was performed on redox conditions, hydrogen concentrations and optimal system operation (amount and composition of electron donor). The electron donor is a molasses like complex organic matter. Several bioscreen options were evaluated, and a system was chosen with minimal flow of groundwater and electron donor. The amount of groundwater was extracted once a week (during 4-8 hours) and equals the natural groundwater flow passing through the bioscreen.

Elaborate monitoring of contaminants (including degradation products, hydrogen, sulphate and fatty acids) was essential to adjust the operation of the bioscreen and the electron donor infiltration regime. The results show that both chloroethylenes and chloroethanes are degraded in the bioscreen. Concentrations of *cis*-DCE dropped from 15,000 µg/l to 10 µg/l after 2 years of operation. VC concentrations initially increased from 1,500 to 3,300 µg/l, followed by a decrease to less then 1 µg/l. Concentrations of 1,1-DCA and 1,2-DCA dropped from 1000 µg/l to 100 µg/l and 10 µg/l, respectively.

The bioscreen focussed on the degradation of the contaminants in the source and the prevention of further flow of contaminants into the plume. Monitoring showed the degradation in the source zone, but also showed that natural attenuation occurred in the plume as well.

3.6 Case 3: Reductive dechlorination of an HCH contaminated site in the Netherlands

At an industrial site in The Netherlands, high concentrations of different HCH isomers have been found in the groundwater. A large HCH containing groundwater plume was moving towards an adjacent canal. To prevent contamination of the canal, HCH had to be removed from the groundwater before the plume reached the canal. In contrast to other HCH isomers, β-HCH is known to be recalcitrant to biodegradation under aerobic conditions. However under anaerobic conditions, all isomers, including β-HCH, can be microbiologically transformed to the intermediates monochlorobenzene (CB) and benzene (Middeldorp et al, 1996; van Eekert et al, 1998). As these intermediates can be further degraded under aerobic conditions, complete mineralisation of all HCH isomers is possible (fig 3.4).

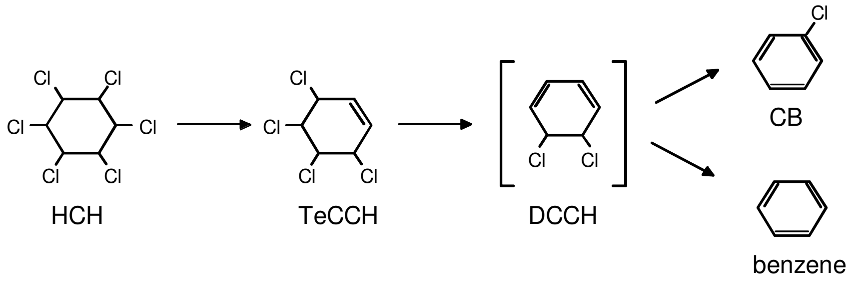

Figure 3.4 Anaerobic biodegradation pathway of HCH. HCH is reductively dechlorinated to tetrachlorocyclohexene (TeCCH), dichlorocyclohexadiene (DCCH) to form the end products benzene and chlorobenzene (CB). Scheme from Middeldorp et al. 1996).

Characterisation of the industrial site indicated that natural attenuation occurred, but that the degradation rate was too low to prevent infiltration of HCH into the canal. Batch experiments with material from the site showed the possibility to stimulate the degradation of HCH into chlorobenzene and benzene.

Based on these laboratory experiments a full scale experiment was designed for the site to treat an area of 150m * 80 m up to a depth of 8 m-bgs. As part of the redevelopment of the site, infiltration facilities have been installed to create an anaerobic electron donor infiltration zone in which HCH transformation into benzene and chlorobenzene is stimulated. Since aerobic conditions are required for the subsequent degradation of benzene and chlorobenzene, the anaerobic infiltration zone is followed by an aerobic zone. Due to the redevelopments of the site into a container terminal, realisation of an aerobic *in situ* system was not possible, and an above ground aerobic on site wastewater treatment system was installed. The groundwater withdrawn from the site is treated in this plant, prior to discharging in the sewage system of the factory. The specific design of the system has been determined by the combination of a bioremediation system, and the redevelopment of the site into a container terminal control (fig. 3.5).

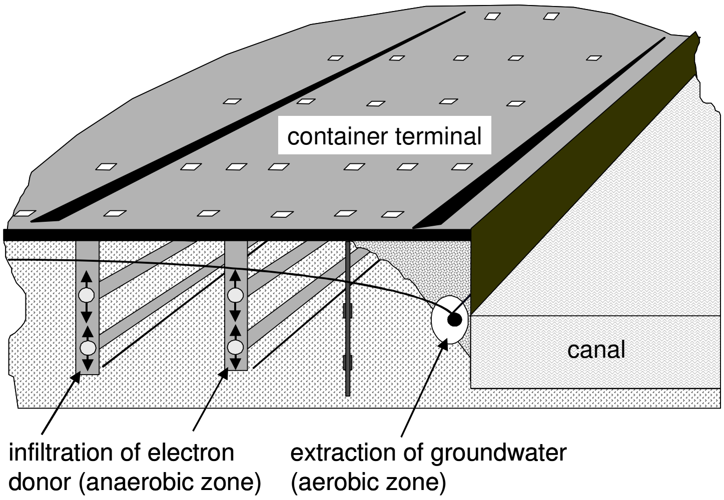

Figure 3.5 Cross-section of a sequential anaerobic-aerobic biological screen with electron donor infiltration and extraction drain facilities to treat the HCH plume.

The system for the infiltration of electron donor has been in use since 2001 and its applicability was evaluated at the end of 2003. During the first year, 4 infiltrations with electron donor, nutrients and tracer were performed. The tracer study indicated a groundwater flow velocity of 15 to 30 m/yr in the first aquifer.

After start-up of the infiltration system, the HCH concentration in the groundwater from a monitoring well, located behind the second infiltration drain, decreased quickly to values below the detection limit (0.05 µg/l). Simultaneously, increasing concentrations of the intermediates benzene and chlorobenzene were produced (fig. 3.6). This indicated biological transformation of HCH into benzene and chlorobenzene.

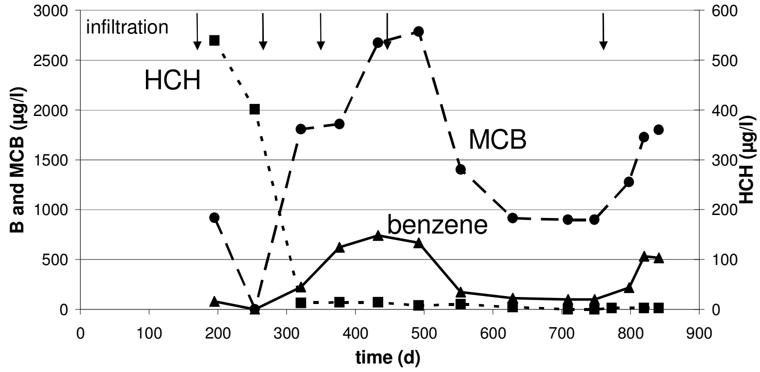

Figure 3.6 Measured concentration profile in a monitoring well, located behind the second infiltration drain. HCH concentration is the sum of the different isomers. The arrows indicate infiltration of electron donor

No electron donor was infiltrated from day 500 to 800. This resulted in a decrease in benzene and chlorobenzene concentrations, indicating that less HCH was transformed due to the lack of electron donor. When electron donor was infiltrated again at day 800, the concentration benzene and chlorobenzene increased again. This clearly demonstrates the stimulating effect of the added electron donor on the degradation of HCH.

The groundwater of the site was collected in an extraction drain and pumped to an aerobic wastewater treatment plant in which benzene and chlorobenzene were quickly degraded to H_2O and CO_2.

As a result a complete removal of HCH is achieved at this site, due to the stimulation of HCH degradation by the addition of an electron donor, followed by complete aerobic degradation of the intermediates benzene and chlorobenzene. After 3 years of operation, only limited amounts of methanol are needed to keep the system active.

3.7 Case 4: Anaerobic oxidation of BTEX at a contaminated site in the Netherlands

A site was contaminated with aromatic compounds like BTEX, with benzene as the most dominant contaminant. The degradation was stimulated by the addition of nitrate, as tested and demonstrated in batch experiments. Nitrate-dependent enhanced benzene degradation was observed under anaerobic conditions after a lag-phase of more than 80 days. Using ^{14}C-labelled benzene it was proven that benzene was oxidised to $^{14}CO_2$ in the presence of nitrate. No loss of benzene was found in sterile controls and in parallel incubations with sulphate. These results were translated to a field study.

An area of 10 m x 10 m was studied in a pilot. Six infiltration wells and one extraction well were installed to infiltrate nitrate at the site. High amounts of nitrate were added (> 500 mg/l), as compounds in the soil and groundwater used a lot of nitrate as well. Measurements of the benzene concentration indicate a stimulated degradation of benzene (fig 3.7).

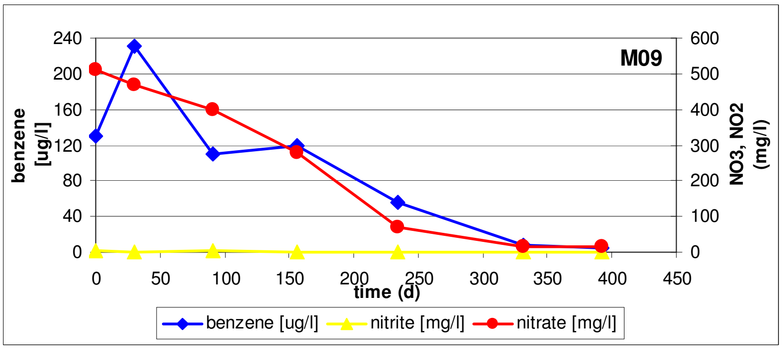

Figure 3.7 Benzene concentrations in a monitoring well

The nitrate and benzene concentration were measured for more than one year and benzene concentrations decreased from 250 µg/l to below detection limit (< 0.5 µg/l).

These data demonstrate that enhanced natural attenuation (e.g. addition of nitrate) may have great potential for remediation of sites contaminated with aromatic hydrocarbons.

4 Bioaugmentation

4.1 Background

Providing pregrown micro organisms to a contaminated site that can degrade the contaminants to augment naturally occurring micro organisms is called **bioaugmentation**. This can be performed under both aerobic and anaerobic conditions.

The addition of nutrients, electron acceptors, or electron donors might also be necessary.

4.2 Implementation

Bioaugmentation is a technique that is mainly used in the saturated zone of the soil. For the introduction of the bacteria, it is imperative that permeable soil layers are present.

The bacteria are added to the soil when it is demonstrated that the needed bacteria are not present at the contaminated site. The range of influence of the added bacteria depends on the infiltration technology, and on the bacteria. They might stick to the infiltration well, or do they have the tendency to migrate away from the infiltration well.

4.3 Considerations

- The legal framework might not allow introducing bacteria in the soil.
- Bacteria that are cultivated in a lab might not survive in the environment.

5 Biosparging

5.1 Background

Biosparging is a technology that stimulates the natural in situ biodegradation of any aerobically degradable compounds in soil by providing oxygen to soil micro-organisms. Oxygen is delivered to the contaminated saturated soil zone by injection of air to increase oxygen concentrations and stimulate biodegradation (see fig. 5.1).

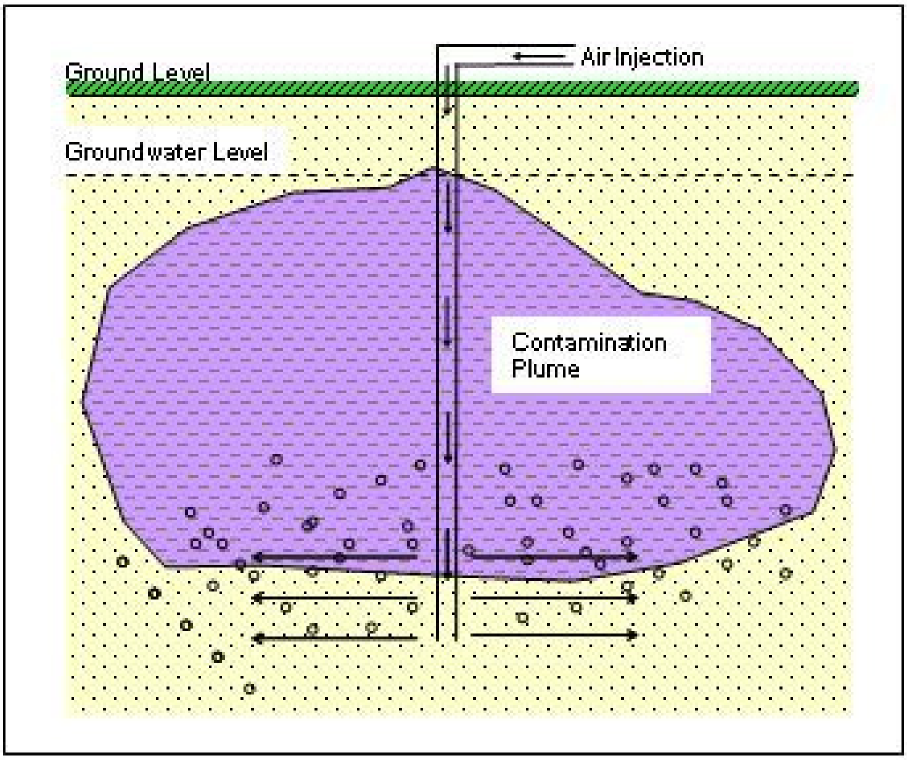

Figure 5.1 Schematic overview of a biosparging system

The pollutants are degraded to harmless compounds within the soil, and extraction and treatment of air is not needed. Biosparging uses low airflow rates in order to provide enough oxygen to sustain microbial activity.

5.2 Implementation

Biosparging is an established and frequently applied technique for the remediation of aerobically degradable organic compounds, such as fuel residuals in the saturated zone of the soil. The effectiveness of the technique increases with the permeability of the soil. Biosparging is less effective in heterogeneous soils, since contaminants remain in the less permeable layers. Oxidation of organic matter in the soil competes with the oxidation of the pollutants. As a result, biosparging is less efficient for very heterogeneous soils or soils with high organic matter and iron contents.

5.3 Considerations

- The sphere of influence is considerably smaller in heterogeneous soils, compared to homogeneous soils.

- In a heterogeneous soil with for instance the presence of silt, clay or peat layers, the remediation may last for decades because the layers are not permeated by the air and contaminant and oxygen have to come in contact as a result of diffusion.
- Competition for the oxygen by organic matter or iron in the soil will increase remediation times considerably.
- In soils with high organic matter contents, desorption of contaminants may be slow, leading to very long remediation times and high remaining concentrations.
- The air injection could oxidize iron, manganese and arsenic, followed by precipitation, possibly causing clogging of filters.
- The soil matrix may be disrupted, especially when peat is present, which could be oxidized.
- This technique removes both volatile and non-volatile organic degradable compounds from the soil. As a result of the induced airflow also non-degradable volatile (organic) compounds (when present) are removed. These travel to the unsaturated zone, where they may have to be removed. Non-degradable non-volatile organic compounds, such as long aliphatic components of mineral oil, will stay behind in the soil. Usually these compounds do not cause risks.

5.4 Case 5: Aerobic oxidation of mineral oil and BTEX at a harbour site in the Netherlands

In a harbour area in The Netherlands, a contaminated groundwater run-off towards the harbour surface water had to be prevented. The contaminants consisted mainly of BTEX and mineral oil. Therefore, a specific pilot site was selected for the construction of three aerobic biological fences. The pilots are based on air injection in soil at a depth of 4 m-bgs. Two fences consisted of horizontal infiltration drains in either the original soil material (fence 1) or in gravel (fence 2). The third fence had vertical infiltration filters that were installed in the original soil for the injection of air. The fences were tested for their capacity to remove aromatic compounds and mineral oil from the groundwater.

The biological fences were operated for two years. Oxygen was found in the monitoring wells, and a moderate increase in the redox potential in the monitoring wells was found. This indicates that more oxidised conditions (favourable for hydrocarbon degradation) were present.

Analysis of the contaminants demonstrated that the fences were biologically active, and that the concentrations of hydrocarbons in the fences decreased over time. The concentrations of total hydrocarbons decreased in fence 1 from 17,000 to 9,000 µg/l, in fence 2 from 3,500 to 1,600 µg/l and in fence 3 from 2,000 to 1,000 µg/l (fig. 5.2).

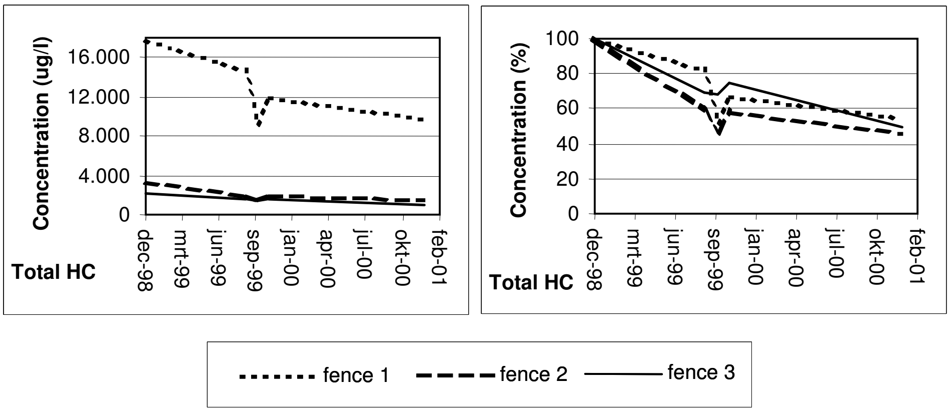

Figure 5.2 Performance of the aerobic fences

Based on the performance, fence 1 (horizontal infiltration drain) showed the largest decrease in concentration, but this was also the fence with the highest initial contaminant concentration. When calculating the decrease in percentage, the three fences acted similar and showed 50 % reduction of the contaminants. The flexibility with respect to construction and air injection is high at fences with vertical filters. The flexibility of fences with horizontal injection drains is low. Based on the technical comparison, the fence with vertical filters is the most cost-effective technique for air injection, both from construction and operation point of view. However, in the presence of buildings and infrastructure, horizontal drains are the only alternative. The costs of biological fences are comparable to conventional systems at the site. However, biological fences have less environmental drawbacks than conventional techniques.

6 Bioventing

6.1 Background

Bioventing is a technology that stimulates the natural *in situ* biodegradation of any aerobically degradable compounds in soil by providing oxygen and possibly heat to existing soil micro-organisms. Oxygen is delivered to contaminated unsaturated soil zones by forced air movement trough either injection or extraction of air to increase oxygen concentrations and stimulate biodegradation (see fig. 6.1).

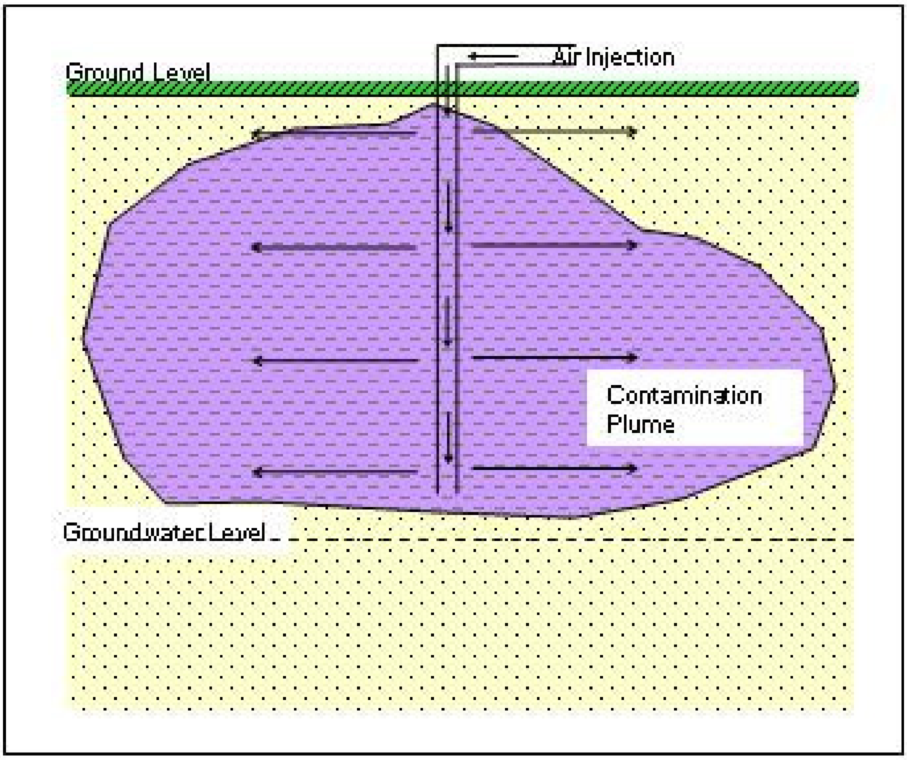

Figure 6.1 Schematic overview of a bioventing system

Oxygen can also be supplied through direct air injection into residual contamination in soil. In addition to degradation of adsorbed pollutants, volatile compounds are biodegraded as vapours move slowly through biologically active soil.

6.2 Implementation

Bioventing is a frequently applied technique for the remediation of aerobically degradable organic compounds, such as fuel residuals, in the unsaturated zone of the soil. The effectiveness of the technique increases with the permeability of the soil. In heterogeneous soils, bioventing is less effective since contaminants remain in the less permeable layers. Oxidation of organic matter or iron, present in the soil, is a process that competes with the oxidation of the pollutants. Therefore, bioventing is less effective for very heterogeneous soils and for soils with high contents of organic matter and iron. Remediation times are considerably longer compared to SVE and vary from a few years in homogeneous sandy soils up to several decades in heterogeneous soils.

6.3 Considerations

- In heterogeneous soils the sphere of influence can be unpredictable, compared to homogeneous soils.
- Competition for the oxygen by organic matter or iron in the soil will increase remediation times considerably.
- Infiltration of air can cause risks caused by resulting emissions from the soil.
- This technique removes both volatile and non-volatile organic degradable compounds from the soil. As a result of the induced air flow also non-degradable volatile (organic) compounds (when present) are removed, for which treatment aboveground may be necessary. Non-degradable non-volatile organic compounds, such as long aliphatic components of mineral oil, will stay behind in the soil. Usually these compounds do not cause risks.

7 Concluding remarks

In this report we have shown that *in situ* bioremediation is a valuable tool to deal with soil and groundwater pollution, which can be applied both in source and plume zones. If the environmental conditions are suitable, monitored natural attenuation is a responsible and cost-effective plume management approach. Whether or not a biodegradation process has to be stimulated, the key issue remains to understand the biological and physical-chemical processes that take place in the soil aquifer. The occurrence of these processes can be measured with various tools; chemical and biological parameters but also the detection of *in situ* microbial activity by revealing the presence of messenger RNA of specific key-enzymes of biodegradation processes. DNA probes have already been used successfully for detection of aromatic dioxygenases and reductive dehalogenases in laboratory cultures. Improved procedures to extract mRNA from groundwater and soil will make it possible to reveal specific in situ activities.

Different guidelines and quick-scans are available to evaluate natural attenuation of BTEX and chlorinated solvents for a range of scenarios. Still, there is a great need for a toolbox with robust long-term tools for the forecasting of natural attenuation. More accurate tools can be established when there is a greater understanding of the underlying processes of natural attenuation such as biodegradation, chemical reactions, sorption, volatilisation and dispersion.

Besides a refinement of the *in situ* remediation methods, our highly industrialised societies and concomitant integrated environmental legislation have forced us to look at soil and groundwater pollution at a different abstraction level. Throughout the world, large areas and regions exist with a high density of industry and polluted sites (megasites). Examples are seaports, (former) complexes of chemical industry, and mining and military areas. Integrated, large-scale application of natural attenuation and *in situ* biotechnology is an important means to meet such legislative requirements throughout the world and provide a safe and sustainable quality of life and of our environment.

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