Electrokinetic Biofence

Reinout Lageman, Lambda Consult

Wiebe Pool, Holland Environment

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1. Introduction

An Electrokinetic Biofence (EBF) is a derivative of an Electro-Kinetic Fence (EKF). In general, electrokinetic fences can be applied as a passive in-situ method to fence off, contain, and remediate polluted groundwater plumes. EKF is applied in the case of inorganic pollutants, such as heavy metals and other electrically charged contaminants, while EBF is used for pollution with organic contamination. Under the influence of the electrical DC field, metal ions, transported by the groundwater towards the fence are deflected towards the electrode filters and captured in the electrolyte solutions circulating the electrodes. Subsequently they are removed from the electrode solutions above ground. The efficiency or effectiveness of an electro-kinetic fence can be defined according equation 1.

$$Nd = \frac{\text{number of charged particles caught by the fence}}{\text{number of charged particles entering the fence area}}$$

or

$$Nd = \frac{C_b - C_e}{C_b} 100 \qquad [1]$$

Where:

Nd = efficiency (%)

Cb = concentration in front of the fence (µg/l)

Ce = concentration behind the fence (µg/l)

The yield can be determined by computer simulations that calculate the velocity of the charged particles coming toward the fence for each value of the relevant physical/chemical and geohydrological parameters. Important parameters in this respect are listed in table 1

Symbol	Parameter	Dimension
V_{gw}	Groundwater velocity	m/year
K_{ek}	Electro-kinetic mobility	m^2/Vs
φ	Electric potential	V
K_s	Specific electric conductivity of the soil	S/m
L	Length of the electrodes	m
D	Distance between the electrodes	m

Table 1. *Important parameters for an electrokinetic fence*

In the case of organic pollutants, the fence acts as an ElectroBioFence (EBF). Such a fence should be envisioned as a more or less elongated zone, wherein biodegradation is enhanced and/or from where downstream biodegradation is being optimized. Nutrients such as nitrogen, phosphorus, oxygen donors, organic compounds, spore elements etc. necessary for biodegradation of organic pollutants dissolved in water, appear almost always as electrically charged compounds and can be dispersed through the soil electrokinetically.

2. Applications in the field

The basic set-up consists of a row of electrodes bordering a high concentration area or polluted groundwater plume. The row of electrodes is set perpendicular to the prevailing groundwater flow direction, while the depth of the electrodes coincides with to the lowest depth where pollutants are found. Depending on the type of pollution (inorganic or organic), the following configurations are possible.

2.1. EKF

The electric current is induced into the ground by means of alternating anodes and cathodes. Anodes as well as cathodes are integrated into separate closed loop pump systems, wherein electrolytes are circulated. Via these electrolytes pH is controlled at a predetermined level and the pollutants, transported by the groundwater, are captured by the electrodes under the influence of the applied potential (Figure 1). Conditioning of the electrolytes as well as periodical removal of the contaminants from the electrolytes is effectuated in a special containerized installation. If necessary, electricity cables and extraction ducts and pipes can be installed underground.

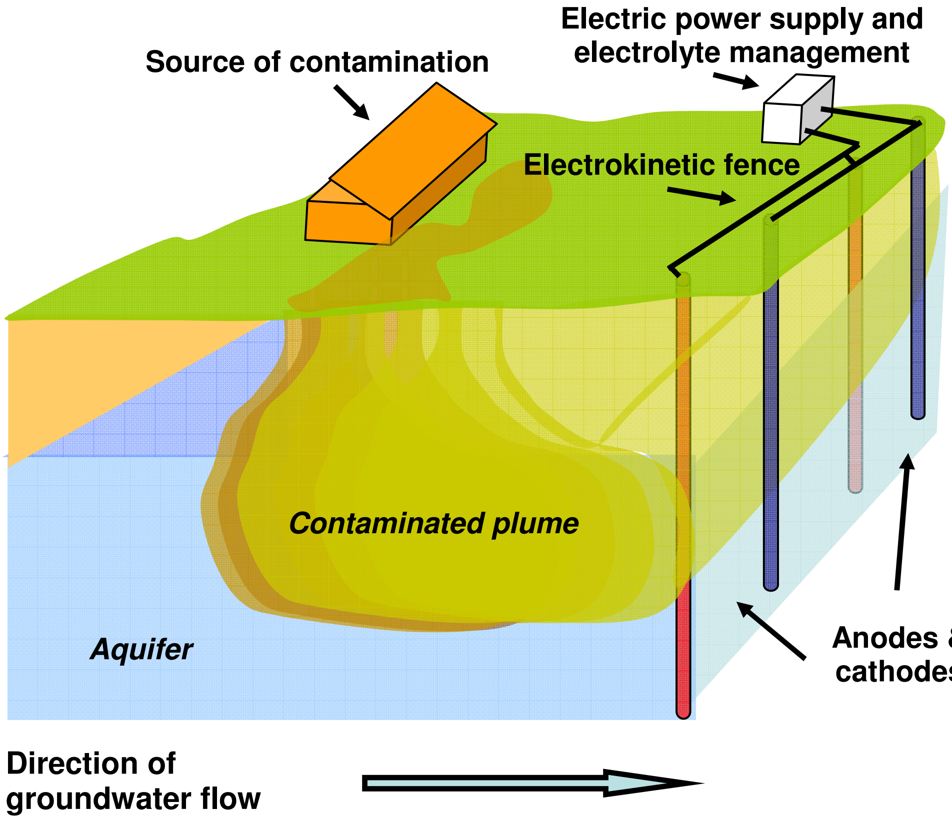

Figure 1. *Schematic representation of an Electrokinetic Fence*

- Heavy metals and other polar contaminants are captured in the electrolytes and periodically removed
- No contamination downstream of the fence area and no disturbance of the groundwater flow regime

2.2. EBF

Depending on site specific circumstances, an electrokinetic biofence is set up according to the following configuration:

- A row of alternating anode and cathode electrodes is installed perpendicular to the main groundwater flow direction. Anodes as well as cathodes are integrated into separate closed loop pump systems, wherein electrolytes are circulated. Via these electrolytes pH is controlled and kept neutral (pH=7), by mixing anolyte and catholyte above ground.
- A row of infiltration filters is installed several meters upstream from the electrodes (figure 2). The infiltration filters are used to bring a nutrient-rich aqueous solution into the ground. Direct current (DC) is applied by which electrically charged nutrients, transported by the groundwater, are deflected and dispersed homogeneously within the zone of the fence. A part of the nutrients is captured by either the anodes or the cathodes, depending on their electrical charge. The neutralized electrolyte mixture which is returned to the field induces anionic nutrients into the soil from the anodes and cationic nutrients from the cathodes.

The organic pollutants, transported by the groundwater are degraded by enhanced microbiological activity, either within or downstream of the zone. Electro-kinetic biofences can be installed at relatively great depths and over great distances, avoiding extraction of large volumes of groundwater.

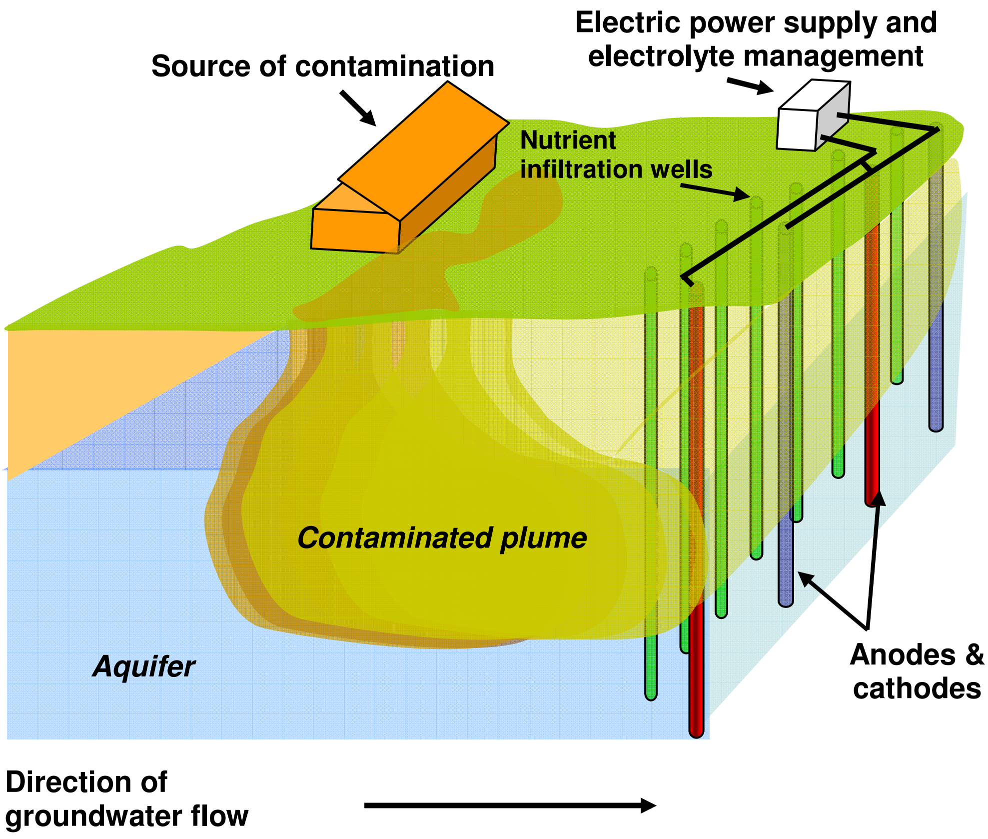

Figure 2. *Schematic representation of an Electrokinetic BioFence*

Biodegradation inside and downstream of the fence area is enhanced by:

- Inducement of nutrients
- Homogeneous dispersion of nutrients

3. Case Study

At the site of chemical laundry a project with an EBF started in April 2001. This fence has been installed to disperse nutrients in the ground and groundwater in order to enhance reductive dechlorinization of present perchloroethene (PCE), trichloroethene (TCE), Cis 1,2-dichloroethene (Cis-DCE) and vinylchloride (VC). The fence acts as a temporary safety measure to avoid further migration of the contamination from the source area underneath the building to the plume area.

3.1. Background information

Previous investigations indicated high grades (10 g/kg) of VOCs underneath the building. In the groundwater at the front of the building, concentrations of PCE of 180 mg/l in the ground indicated mass transport of free product through the upper aquifer. It consisted of fine to medium fine sand down 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-DCE and VC were found in concentrations above the Dutch intervention value at a distance of 300 m from the laundry and at a depth of 11 m bgs.

3.2. Electrokinetic Biofence

An alternative for containment of source areas and remediation of polluted groundwater plumes is to deploy an EBF. An EBF avoids the necessity to pump and treat hundreds of thousands of cubic meters of groundwater, which is only slightly contaminated. It also means that the groundwater flow regime is not influenced.

Because of the enhanced biodegradation, downstream migration of the contamination 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 (volatile organic compounds) in the groundwater and on the nutrients already present in the groundwater.

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.

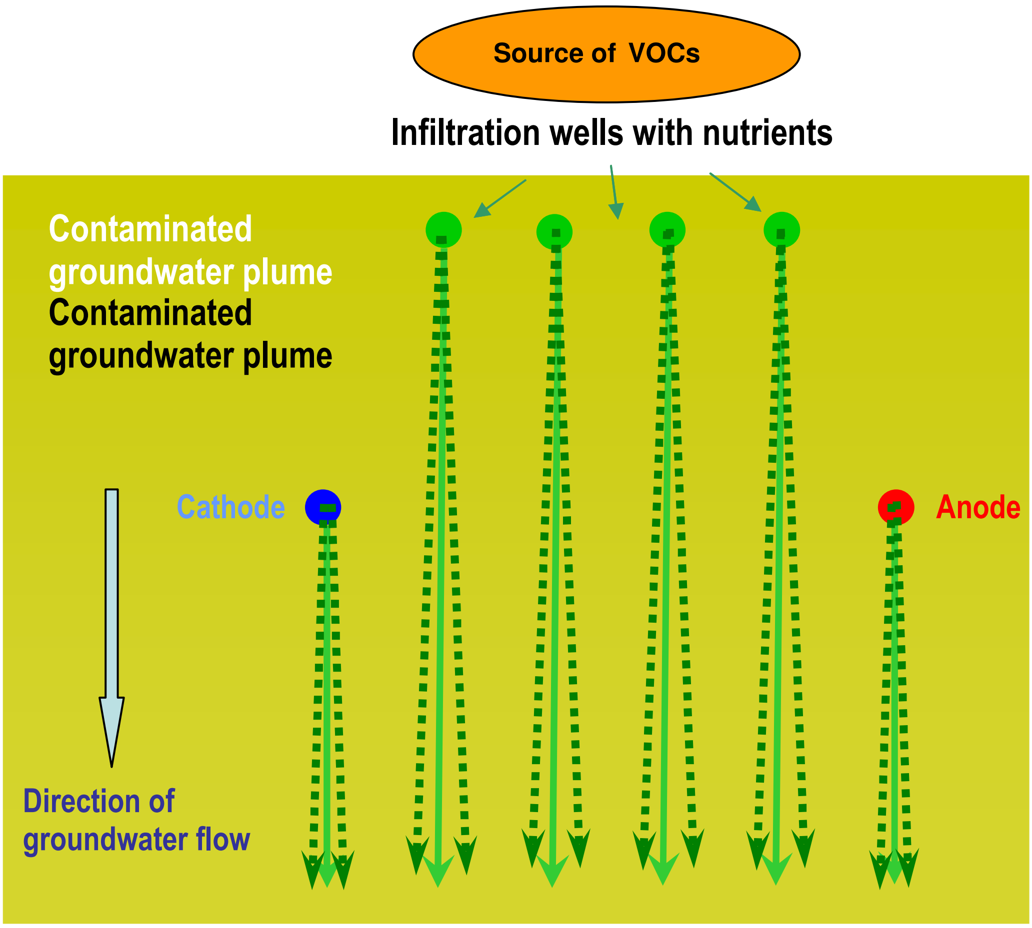

Figure 3. *Flow paths of nutrients without an electrical DC-field*

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.

The amount of nutrients entering the groundwater per unit of time through the electrode filters, is managed electrokinetically, 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 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.

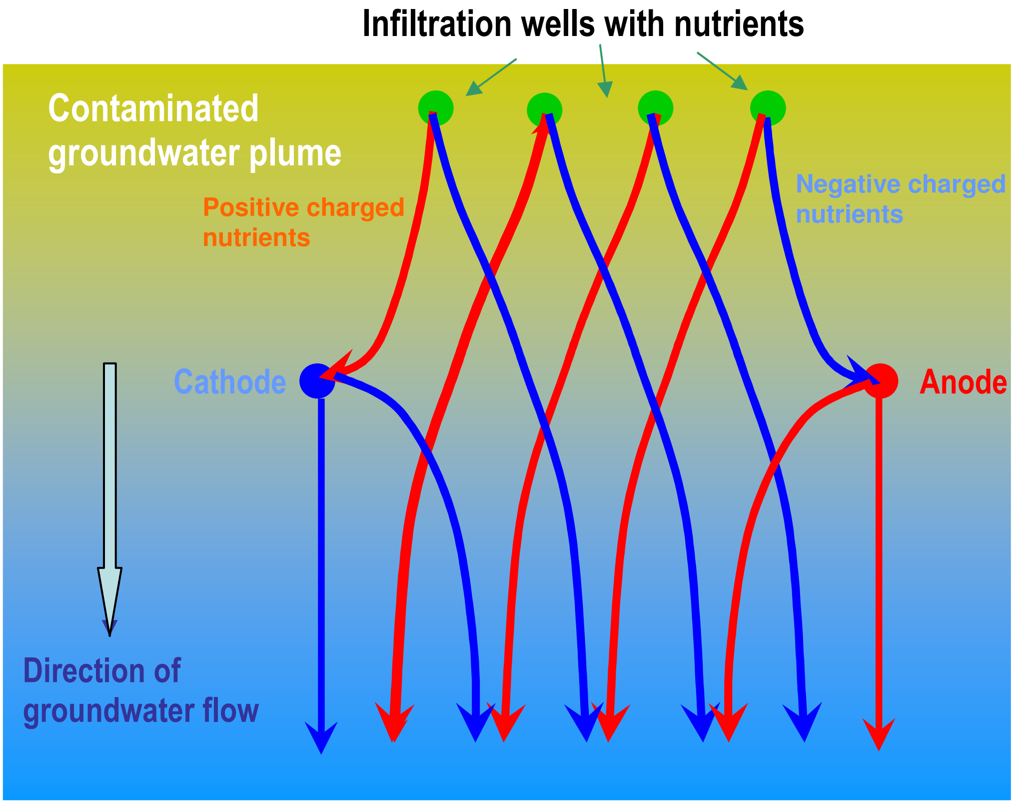

Figure 4. *Flow paths of nutrients with an electrical DC-field*

The organic contaminants migrating 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 travelling 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.

3.3. Field set-up

The Electrokinetic Biofence consists of 3 cathodes and 2 anodes. 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. At a distance of approximately 2 m upstream of the electrode wells, 24 infiltration wells have been installed, 19 of which are in use so far. These infiltration filters consist of PE filter tubes with a diameter of 50 mm, length of 10 m, and perforation from 1 m 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 form the 24 filters located directly upstream of the 5 electrodes wells, 7 reference wells have been placed adjacent to, but outside of the zone with the electrode wells. Downstream 18 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 alkalinisation at the cathodes and acidification at the anodes by mixing anolyte and catholyte and thus neutralizing both electrolytes to pH=7. 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. Figure 5 gives an overview of the site with the location of electrodes, nutrient infiltration wells and monitoring wells.

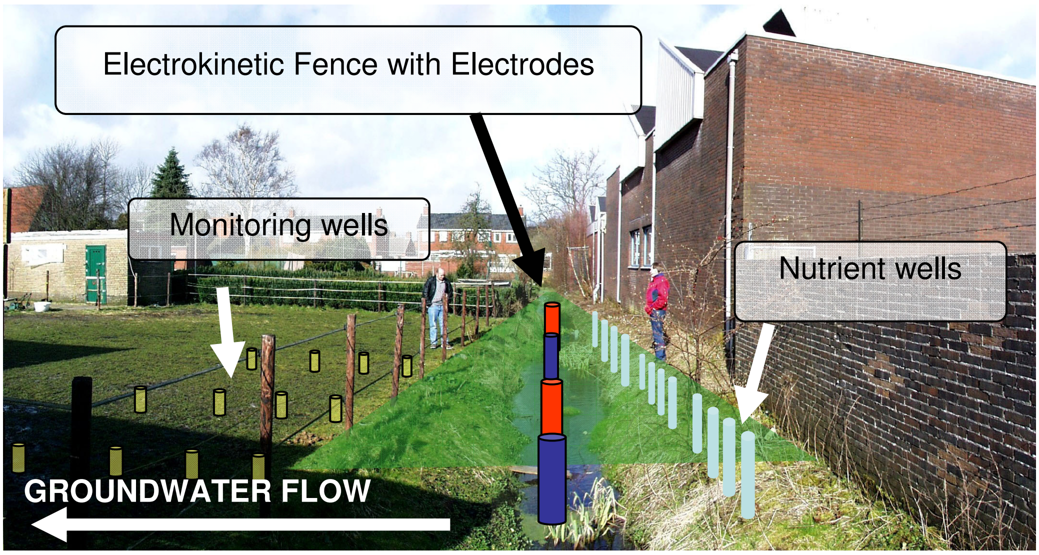

Figure 5. *View of Electrokinetic Biofence*

3.4. Project results

Nutrients

For the optimal biodegradation of VOCs, electron donors (C) and nutrients nitrogen (N) + phosphorus (P) are required. In table 1 the average concentration of nitrogen Kjeldahl (N), phosphorus (P as ortho-PO_4^{3-}) and dissolved organic carbon (DOC) are given.

Table 2 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 increased with nearly a factor 10 during measurement in July 2003 and decreased to a concentration of about 6 mg/l at the end of last year. Phosphate increased 5 times in July 2003 15 and 15 times at the end of 2005. The concentration of DOC first increased with a factor 2, but decreased in the last period to 52 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.

Concentration of nutrients	March 01	December 04
Nitrogen-Kjeldahl (mg/l)	3.3	5.7
Ortho-phosphate (mg/l)	1.1	17
DOC (mg/l)	47	52

Table 2. *Changes in the concentration of nutrients*

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 figures 6 and 7 the development in concentrations of PCE+TCE and Cis-DCE+VC is represented. Note that the building of the chemical laundry is situated just 1 m south of the nutrient infiltration

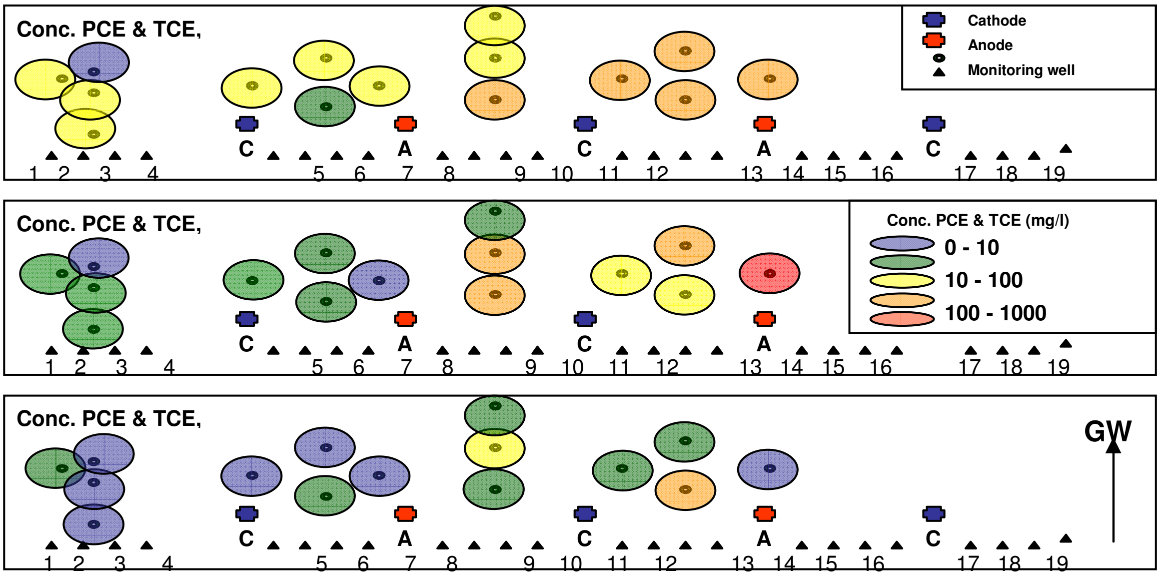

Figure 6. *Changes in concentration of PCE and TCE*

From figure 6 it can be observed that there is a decrease of PCE and TCE as these compounds are being dechlorinated and their degradation products Cis-DCE and VC are formed. This effect is shown in figure 7 which depicts the concentration of Cis-DCE and VC. In January 2003 the highest concentrations are reached, where after a period of decrease starts.

Chloride index

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

$$\mathrm{Cl-index} = \frac{\{4*[\mathrm{PCE}]+3*[\mathrm{TCE}]+2*[\mathrm{C\text{-}DCE}]+2*[\mathrm{T\text{-}DCE}]+1*[\mathrm{VC}]\}}{\{[\mathrm{PCE}]+[\mathrm{TCE}]+[\mathrm{C\text{-}DCE}]+[\mathrm{T\text{-}DCE}]+[\mathrm{VC}]\}} \quad [2]$$

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-dicholoroethylene in mol/l
[VC]	= concentration of vinyl chloride in mol/l.

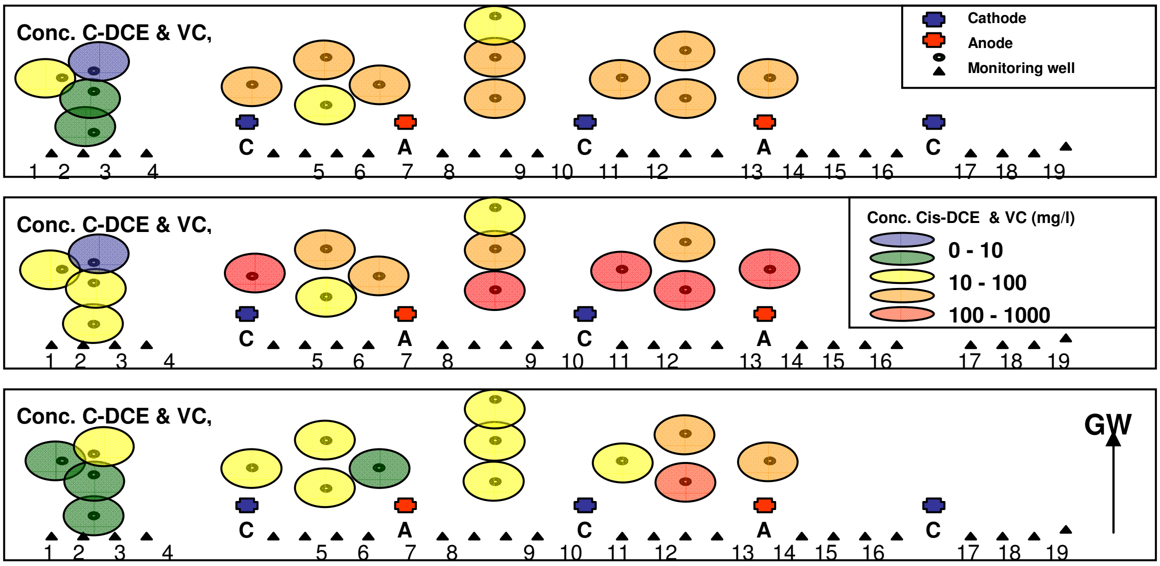

Figure 7. *Changes in concentration of Cis-DCE and VC*

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 Cl-index at the fence changed from an average of 2.9 to 2.0. Some monitoring wells, however, have Cl-indexes > 3. The location of these monitoring wells coincides with the area where an inflow of VOCs was observed from the original soured area underneath the building. 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.

3.5. Energy requirements and energy consumption

The calculations for the electrical power requirements, needed to transport nutrients electro-kinetically 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, nutrients will not be dispersed. The optimal voltage therefore is the voltage at which nutrients are dispersed homogeneously through the soil, as shown in figure 3.

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 Watt. This energy input can be supplied by solar panels. The solar panels installed at the site have a maximum output of 500 Watt. This is sufficient for sunny days. At night and on cloudy days the electricity is taken from the grid.

4. Summary

Electro-reclamation in the form of an Electro-Kinetic Fence can be applied as a passive In-situ method to fence off, contain, and remediate groundwater plumes polluted with inorganic species like heavy metals, arsenic and cyanide. In the case of organic pollutants, the fence acts as an ElectroBioFence. Such a fence should be envisioned as a more or less elongated zone, wherein biodegradation is enhanced and/or from where downstream biodegradation is being optimized by the inducement of nutrients. Nutrients such as nitrogen, phosphorus, oxygen donors, organic compounds, spore elements etc. necessary for biodegradation of organic pollutants dissolved in water, appear as electrically charged compounds and can be dispersed homogeneously through the soil electrokinetically.

A pilot project with an Electrokinetic Biofence has been carried out at the beginning of the 2000s at the site of a chemical laundry. The aim of the was to enhance biodegradation of the VOCs in the groundwater at the zone of the fence by electrokinetic dispersion of nutrients dissolved in the groundwater upstream of the fence. After a three years test period, clear and positive results have been observed. The concentration of nutrients in the zone has increased, the chloride index has decreased, and VOCs were being dechlorinated by bio-activity. The electrical energy for the EBF is being supplied by solar panels in combination with electricity from the grid.

Reference

Agteren van MH, Keuning S, Janssen DB (1998). Handbook on Biodegradation and Biological Treatment of Hazardous Organic Compounds. Dordrecht, The Netherlands: Kluwer Academic Publishers.