



evaluation

of three executed
soil remediation
reports at
CAH-polluted sites
in Flanders



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This report presents a study concerning three sites contaminated with CAHs (Chlorinated Aliphatic Hydrocarbons). Goal of this study is to define and critically evaluate bottlenecks that have been encountered during the remediation. Particular attention was devoted to evaluating conclusions formulated in remediation interim reports.

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SAMENVATTING

CityChlor is een Europees project dat een geïntegreerde benadering uitwerkt voor de aanpak van verontreiniging met gechloreerde solventen in stedelijke omgeving. Het project wordt uitgevoerd door een partnerschap tussen Vlaamse, Franse, Nederlandse en Duitse overheden, onderzoeksinstituten en steden binnen het INTERREG IV B programma voor Noordwest Europa. Voor meer informatie zie www.citychlor.eu.

In voorliggende studie zijn drie VOCl-verontreinigde terreinen bestudeerd waar bodemsaneringswerken in uitvoering zijn of zijn geweest in opdracht van de OVAM. De bodemsaneringswerken werden uitgevoerd door een bodemsaneringsaannemer, en begeleid door een erkend bodemsaneringsdeskundige (EBSO). Doel van de studie is om knelpunten die tijdens de uitvoering van de sanering zijn opgedoken, te analyseren en kritisch te evalueren. Daarbij werd speciale aandacht besteed aan de besluiten geformuleerd in de door de EBSO opgestelde tussentijdse verslagen. Er worden tevens aanbevelingen gegeven voor de verdere aanpak van onderzoek en /of sanering. De studie vormt een onderdeel van het voortraject van het CityChlor project en heeft als doel vaak-voorkomende knelpunten bij de sanering van verontreinigingen met gechloreerde solventen te inventariseren. De studie heeft betrekking op volgende dossiers:

1. *“Moens”, Ninove*. Dit betreft een voormalige droogkuis in woongebied. Het grondwater is sterk verontreinigd met PCE en partiële dechloreringsproducten (TCE, DCE, VC). Een sanering werd uitgevoerd met behulp van tweefasenextractie en persluchtinjectie.
2. *“Kling Immo”, Wervik*. Dit betreft een voormalige machinefabriek in industriegebied. Het grondwater is sterk verontreinigd met PCE, TCE en TCA en partiële dechloreringsproducten (DCE, VC, DCA). Gedurende meerdere jaren werd pump&reat uitgevoerd. Nadien werd een pilootproef uitgevoerd om de haalbaarheid van in-situ chemische oxidatie te evalueren.
3. *“Afriglas”, Kortrijk*. Dit betreft een voormalige productiefaciliteit voor schoonmaakproducten in een industriële/landelijke omgeving. Het grondwater is voornamelijk verontreinigd met TCE en partiële dechloreringsproducten (DCE, VC). De uitgevoerde saneringswerken omvatten tweefasenextractie, persluchtinjectie en pump&reat.

Volgende hoofdconclusies kunnen worden geformuleerd:

- o Alle saneringen werden aangevat vóórdat voldoende inzicht was verkregen in de verontreinigingssituatie (bronzones, vuilvracht,...). De effectiviteit van uitgevoerde saneringsacties kan enkel goed worden beoordeeld indien verwijderde vuilvracht kan worden vergeleken met de oorspronkelijk aanwezige vuilvracht. Een realistische schatting daarvan is dus noodzakelijk en daarvoor is een uitgebreid bodemonderzoek nodig.
- o In cases 2 en 3 werd de totale aanwezige VOCl-vracht aanwezig in de bodem onderschat. In alle gevallen werd de benodigde saneringsduur onderschat. In alle gevallen werden onrealistische saneringsdoelstellingen geformuleerd (BSN voor grondwater). Aanbevolen wordt om bij VOCl-saneringen niet zozeer te streven naar het behalen van bepaalde (lage) grondwaterconcentraties, maar naar risicoverwijdering en het bereiken van een “stabiele” situatie waarbij concentraties een dalende trend vertonen en/of het verontreinigd bodemvolume niet langer in omvang toeneemt. Deze benadering is opgenomen in de richtlijnen opgesteld in het kader van het Vlabotex bodemsaneringsfonds voor de droogkuissector.
- o Pump & treat is geen geschikte vrachtverwijderingstechniek voor VOCl-verontreinigingen met nog aanwezige kern(en) van (residuele) DNAPL. Grondwater oppompen op onoordeelkundig gekozen locaties kan zelfs tot versnelde verdere verspreiding van de verontreiniging leiden. Anderzijds kan een pumping op welgekozen locaties in de VOCl-pluimzone(s) wel nuttig zijn in saneringsvarianten bedoeld ter voorkoming van een verdere verspreiding van de grondwaterverontreiniging naar een stroomafwaarts gelegen receptor. Tweefasenextractie, al

dan niet gecombineerd met persluchtinjectie, is een geschikte vrachtverwijderingstechniek in VOCl-bronzones. Het juist kwantificeren van verwijderde vuilvracht via de gasfase is echter moeilijk. Mogelijk kan on-line influent monitoring en/of het bemonsteren en analyseren van verbruikte (verzadigde) actief kool worden toegepast om de verwijderde vrachten beter te kunnen inschatten. Tweefasenextractie moet enkel in de VOCl-kernen (DNAPL zones) worden toegepast en niet in de pluim. Tijdens plaatsing van de extractiefilters dient tegelijkertijd te worden beoordeeld of men zich effectief in dergelijke kern bevindt. Dit kan o.a. met PID-metingen, ondersteund door chemische analyses van grondstalen. Het aantal filters en hun exacte plaatsen kan mede afhankelijk worden gesteld van deze aanvullend verkregen informatie. De aanwezigheid van de EBSD tijdens de plaatsing van de filters is daarom aangeraden. In de meeste gevallen zal een combinatie van meerdere technieken nodig zijn om de sanering met succes uit te kunnen voeren. Na afloop van tweefasenextractie kunnen de extractiefilters worden benut voor verdere saneringsacties (b.v. injectie van een organisch substraat t.b.v. anaërobe bioremediatie). Diepe DNAPL-zones zijn niet goed aan te pakken met tweefasenextractie. In dergelijke gevallen kan men ISCO of surfactant/cosolventspoeling overwegen.

SUMMARY

CityChlor is a European project that develops an integrated approach for the tackling of pollution with chlorinated solvents in urban environments. The project is carried out by a partnership between Flemish, French, Dutch and German authorities, research institutes and cities within the INTERREG IV B programme for Northwest Europa. For more information, see www.citychlor.eu.

This report presents a study concerning three sites contaminated with CAHs (Chlorinated Aliphatic Hydrocarbons). Soil and groundwater are being remediated by order of OVAM (Public Flemish Waste Agency). Soil remediation activities are being conducted by contractors, under supervision of a certified soil remediation consultant. Goal of this study is to define and critically evaluate bottlenecks that have been encountered during the remediation. Particular attention was devoted to evaluating conclusions formulated in remediation interim reports. Also recommendations are given for future additional soil and groundwater remediation activities and/or investigations. The study forms a part of the CityChlor project and aims at surveying frequent problems in the remediation of pollutions with chlorinated solvents. The following sites were subject in the study:

1. “Moens” in Ninove: a former drycleaning facility in a residential environment. The groundwater is contaminated by primarily PCE and partial dechlorination products (TCE, DCE, VC). Remediation efforts included dual phase extraction and air sparging.
2. “Kling Immo” in Wervik: a former machine factory situated in an industrial area. The groundwater at the site is polluted with PCE, TCE and TCA, and partial dechlorination products (DCE, VC, DCA). Remediation was attempted by pump&treat. Later in-situ chemical oxidation was evaluated (pilot).
3. “Afriglas” in Kortrijk: a former production facility for cleaning products in an industrial/rural environment. The groundwater is contaminated by primarily TCE and partial dechlorination products (DCE, VC). Remediation efforts included dual phase extraction, air sparging and pump&treat.

The following main conclusions were obtained:

- All remediations were started prematurely (a better characterization of source zone concentrations and dimensions should have been available). When evaluating remediation success, the pollutant mass removal realized must be compared to estimated total pollutant mass initially present. A realistic estimate of the latter must be obtained by adequate site characterization before starting remedial actions.
- In cases 2 and 3, total subsoil CAH mass present was underestimated. In all cases remediation time scales needed were underestimated. All remediation plans had unrealistic target concentrations set. It is recommended NOT to focus on reaching certain target concentration levels, but to focus on risk-removal and obtaining a “stable” situation in which concentrations are declining and/or the contaminated soil volume is no longer expanding. This approach was also adopted in the guidelines of Vlabotex, the soil remediation fund for the drycleaning sector.
- Pump & treat is not an efficient remediation technology for CAH-mass removal; pumping at inappropriate depths and locations may, instead, lead to increased horizontal migration of dissolved CAHs. Groundwater pumping is only useful as a chosen strategy to provide hydrological containment of CAH plumes. Dual phase extraction - either combined with air sparging or not – is an efficient mass removal strategy for shallow CAH source zones. Quantifying pollutant recovery via the gas phase is difficult. We propose to evaluate possible on-line influent monitoring and/or analysis of spent (saturated) activated carbon filters to better quantify CAH mass recovery. Dual phase extraction should be focussed to the CAH source zones only. When installing extraction wells, it is recommended to use that opportunity to also additionally evaluate soil quality. The presence of the soil remediation consultant during extraction well installment is therefore recommended. The number of extraction wells and their planned locations may be changed based on additional results. In most cases a combination of techniques will be required to realize remediation successfully. After completion of dual-phase source zone treatment, the extraction wells may be used for secondary plume treatment (e.g. as injection wells for an organic substrate to stimulate further biological reductive dechlorination).

Deep DNAPL-zones cannot be efficiently treated by dual phase recovery. In such cases, ISCO or detergent/co-solvent flushing may be applicable.

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LIST OF ABBREVIATIONS

(c)DCE	(cis)Dichloroethene
CAHs	Chlorinated Aliphatic Hydrocarbons
CGP	Code of Good Practice
DCA	1,1-Dichloroethane
dm	Dry matter
DNAPL	Dense Non-Aqueous Phase Liquid
ISCO	In Situ Chemical Attenuation
m bgl	Metres below ground level
MIP	Membrane Interphase Probe
MNA	Monitored Natural Attenuation
MW	Monitoring well
NAPL	Non-Aqueous Phase Liquid
OM	Organic Matter
OVAM	Public Flemish Waste Agency
P&T	Pump & Treat
PCE	Tetrachloroethene
PID	Photo Ionization Detector
TCA	1,1,1-Trichloroethane
TCE	Trichloroethene
VC	Vinyl chloride

1.1 Descriptive site investigation

This first study site covers 15a 62ca and is situated in a residential area. From 1968 until 1995 it was used for drycleaning activities. A descriptive site investigation was executed¹ involving 22 soil borings, in which monitoring wells were installed (figure 1).

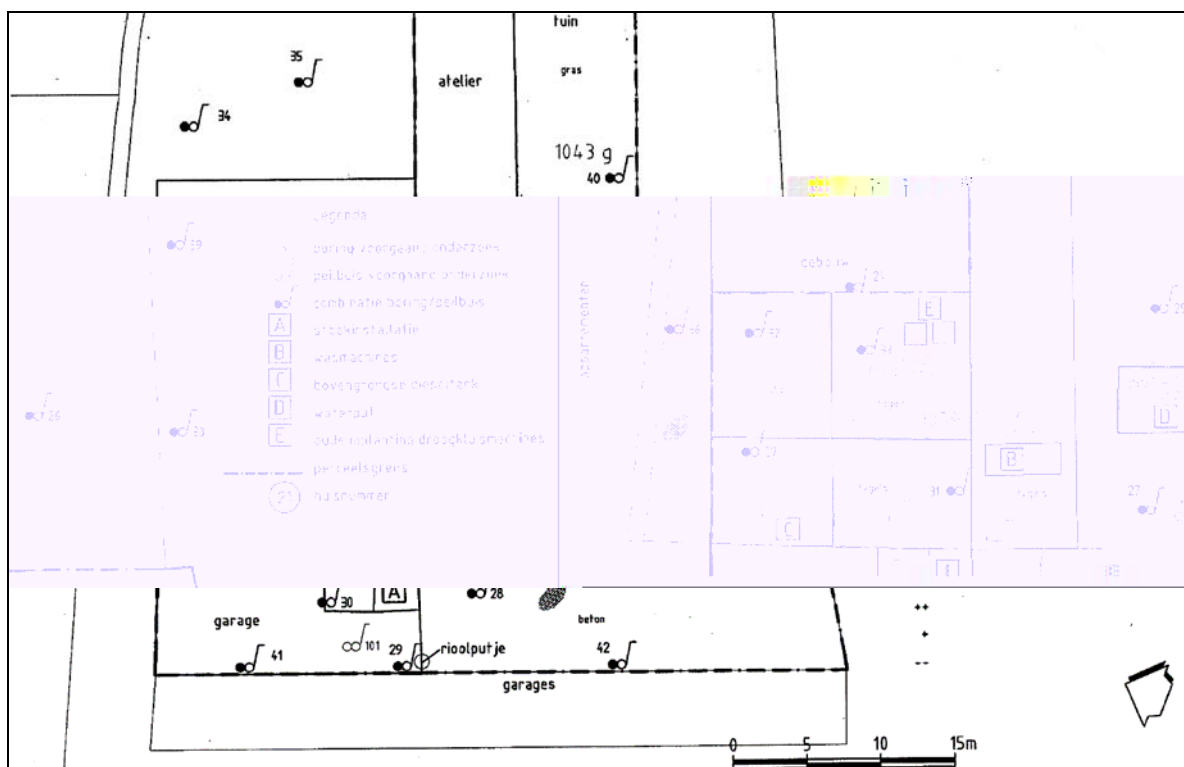


Figure 1. Schematic overview on the site (source: descriptive site investigation, 1999)

Primary conclusions were:

The groundwater level is at approximately 1.5 m bgl (m below ground level) and flows in South-Eastern direction towards the river Dender (estimated velocity: 3.4 m/y). Soil permeability was estimated to be 0.23 m/d. To a depth of 6.5 m bgl the soil is silty/clayey. Beneath 3.5 m bgl also sand and peat are present.

¹ "Beschrijvend bodemonderzoek voormalige droogkuis te Ninove". report nr. R9502028.001/NBA, July 1999.

The groundwater at the site is polluted with chlorinated ethenes. PCE and TCE are present to a depth of 6 m bgl, the estimated volume of it was 745 m³ (volume of groundwater containing PCE or TCE in concentrations exceeding legal limit values). The volume of groundwater polluted with reductive dechlorination products VC and DCE was estimated to equal about 1600 m³. Delineation for these parameters had not yet been fully accomplished.

Highest concentrations observed were near the former location of the drycleaning machine (monitoring well 24, screened at 0.7-2.7 m bgl): PCE: 190 mg/L; TCE: 56 mg/L; cDCE: 63 mg/L; VC: 1.9 mg/L. Estimated horizontal migration velocities for these CAHs were 0.07 – 0.21 – 0.3 and 0.4 m/y, respectively.

In the descriptive site investigation, most of the efforts were focused on the groundwater. Taking the silty soil type into account, as well as the presence of a continuous peat layer at certain depth, in this case *a thorough delineation of the CAH source zones should have been executed as well*. It might have been recognized – even at that time – that most of the pollutant mass was present adsorbed to the soil solid phase and/or present as a (residual) NAPL-phase in the 0 - 5 m bgl subsurface zone. Especially peat layers, as a consequence of the high organic matter content, possess large CAH sorption capacities.

1.2 Pilot test

As a preparation for designing a remediation project, the consultant and specialized contractor involved, designed a pilot test “air sparging and soil vapour extraction”. Prior to the execution of this test, an additional soil investigation was performed (March 2001), in which 4 new borings (n^os. 201-204) were placed inside the polluted area. During execution of these borings, it was observed that, in the CAH source zone area, the peat layer is continuously present and has a thickness of several dm (all four borings showed the peat layer starting at depths of about 3.9 to 4.2 m bgl). One of the profiles recorded is presented in Fig. 2. The peat layer as well as the sandy layer above it were sampled separately. Chemical analysis of the samples showed high total CAH levels in the peat layer: **286 mg/kg** (just downstream of the expected source area) and **409 mg/kg** (in the source area). The sample taken from the sandy/silty soil on top of the peat layer contained total CAH concentrations of 11 to 36 mg/kg.

These analysis results allowed to obtain a first estimate of pollutant mass present. Per area of 10x10 m within the contours of the CAH source zone (with still unknown overall dimensions!):

Peat layer: $10 \times 10 \times 0.4 = 40 \text{ m}^3$ or 60 tonnes. Assuming that a CAH concentration of 400 mg/kg is representative for this volume, the total estimated pollutant mass in that volume equals 24 kg.

Superficial sandy/silty layer: $10 \times 10 \times 3.5 = 350 \text{ m}^3$ or 600 tonnes. Assuming that a CAH concentration of 20 mg/kg is representative for this volume, the total estimated pollutant mass in that volume equals 12 kg.

Diepte (m-Mv)	Profiel	Beschrijving grondsoort
0		cementtegel,
		zeer fijn zand, weinig leemhoudend, veel steenfragmenten (tot 20 mm), roodgrijs, weinig vochtig,
1		leem, kleihoudend, steenfragmenten (tot 20 mm), plastisch, grijs, vochtig,
		klei, weinig steenfragmenten (tot 15 mm), plastisch, grijs, vochtig/verzadigd,
2		klei, weinig zeer fijn zandhoudend, steenfragmenten (tot 20 mm), slap/plastisch, grijs, verzadigd,
		klei, weinig zeer fijn zandhoudend, plastisch, bruingrijs, verzadigd,
		klei, roestconcreties (tot 5 mm), plastisch, bruingrijs, verzadigd,
3		klei, veenhoudend, plastisch, donkerbruingrijs, verzadigd,
		veen, sterk kleihoudend, donkergrijsbruin, verzadigd,
4		leem, weinig zeer fijn zandhoudend, plastisch, lichtgrijsgroen, verzadigd,
		leem, weinig zeer fijn zandhoudend, plastisch, lichtgrijsgroen, verzadigd,
5		zeer fijn zand, zeer sterk leemhoudend, grijs, verzadigd,
		zeer fijn zand, sterk leemhoudend, grijs, verzadigd,
6		fijn zand, leemhoudend, grijs, verzadigd,
		fijn zand, weinig leemhoudend/leemhoudend, groengrijs/grijs, verzadigd,
7		zeer fijn tot fijn zand, leemhoudend, grijs, verzadigd,
		fijn zand, zeer weinig leemhoudend, groengrijs/grijs, verzadigd,
8		fijn zand, grijs, verzadigd,
		fijn zand, grijs, verzadigd,
9		fijn zand, zeer weinig kleihoudend, groengrijs/grijs, verzadigd,
		fijn zand, kleihoudend, grindhoudend (tot 30 mm), groengrijs/grijs, verzadigd,
10		klei, matig vast, groengrijs/grijs, verzadigd,

Figure 2. Soil profile

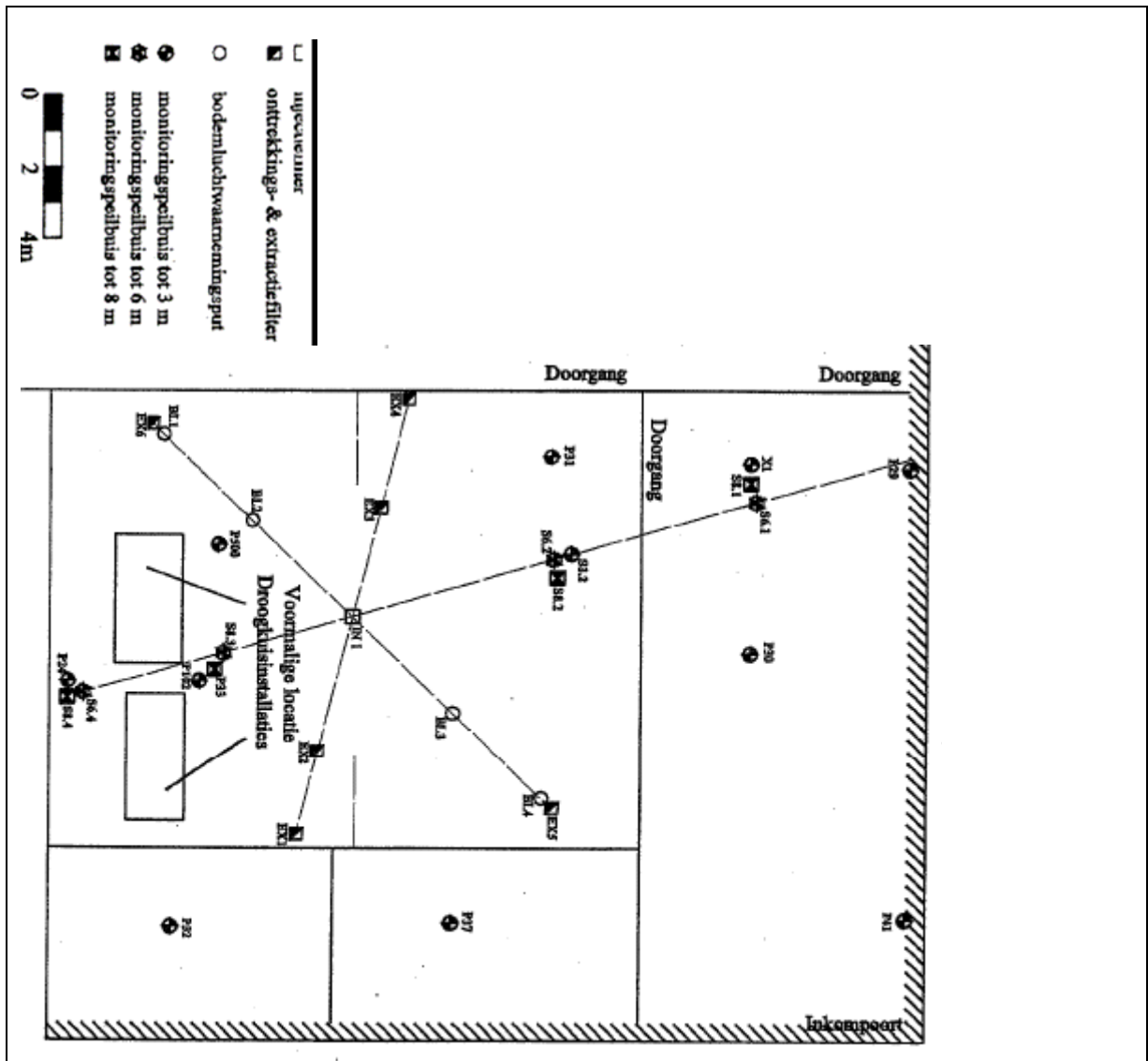


Figure 3. Pilot test set-up plan, indicating former drycleaning machines, central air injection filter (IN1), dual phase extraction wells (EX), soil gas monitoring wells (BL) and groundwater monitoring wells (P; screened at 3, 6 and 8 m bgl)

The pilot test included 1 air injection well, 6 dual-phase extraction wells and a number of monitoring wells (Fig. 3). The test was started on 2 May 2001. A first report describing the pilot testing results dates from 2001². VITO was involved as well to follow the test by order of OVAM³.

Table 1 summarizes pollutant mass removal established during the test. A constant vapour extraction flow rate of 76 m³/h was assumed. Concentrations in the gas phase were estimated using Dräger detection tubes.

² "Pilotproef persluchtinjectie (PLI) en bodemluchtextractie (BLE) Ninove" (01/4814/av), June 2001

³ "Opvolgingsverslag airsparging/bodemlucht-extractie pilotproef te Ninove". VITO report n° 2001/MIT/R/112, August 2001.

Table 1. Pollutant mass removal calculations during the pilot test

date	N° days extr.	PCE ppm	VC ppm	PCE mg/m ³	VC mg/m ³	Extr. Volum. m ³	PCE mass kg	PCE cumul. kg	VC mass kg	VC cumul. kg
04/jun	0	50	0.2	370	0.557	0	0	0	0	0
05/jun	1	100	5	740	13.9	1824	1.35	1.35	0.025	0.025
06/jun	2	100	5	740	13.9	1824	1.35	2.70	0.025	0.051
07/jun	3	100	5	740	13.9	1824	1.35	4.05	0.0254	0.076
08/jun	4	50	5	370	13.9	1824	0.67	4.72	0.0254	0.102
11/jun	7	60	1	444	2.79	5472	2.43	7.15	0.0152	0.117
12/jun	8	60	1	444	2.79	1824	0.81	7.96	0.0051	0.122
13/jun	9	50	1	370	2.79	1824	0.67	8.63	0.0051	0.127
14/jun	10	50	2	370	5.57	1824	0.67	9.31	0.0102	0.137

Calculations “ppm to mg/m³” can be done using the formula $\text{ppm} = (\text{MW}/22.42) \text{ mg/m}^3$, with MW the molecular weight of the compound (165.8 g/mole for PCE and 62.45 g/mole for VC).

The results show that, during the soil vapour extraction test⁴, a total of about 9 kg PCE and 140 g VC were removed from the soil. It can be expected that a few kg DCE and TCE were removed by the system as well. The total pollutant mass removal during the pilot therefore was in the order of magnitude of 10 to 15 kg CAHs (i.e. 150 g CAH per extraction well per day).

The quantity of activated carbon required for CAH gas phase removal during the first month of a full-scale remediation (assuming (i) a maximum loading capacity of 10 to 20%, (ii) 10 kg CAH removal per day during the first week and 2 kg/day during the next three weeks) can thus be calculated to equal about 500 to 1000 kg.

Based on these results some alterations to the original soil remediation plan were suggested as well as a number of points of particular interest. Generally, remediation using dual-phase extraction combined with air sparging was evaluated as being feasible, when taking the following points into close consideration:

- The full-scale remediation should be correctly dimensioned with special attention to the CAH source zone (adequate well density with screens at multiple depths). The peat layer in particular, containing high CAH levels, should be treated in the best way possible. If this can not be realized, this layer will remain a continuous source for future groundwater pollution. Apart from that, the exact amounts of pollution present below the peat layer were still unknown at that moment.
- The dual-phase extraction should be executed using a high vacuum system (optimized to realize a large vapour flow rate but minimum groundwater pumping). The type of pump to be used should be suited to pump both water and vapour, and vapour alone.
- The remediation plan proposed will more than likely NOT improve groundwater quality to concentration levels below legal remediation standards (let alone “background levels”). This was concluded at that time, based on published results from other ongoing or finalized remediations of similar pollutions elsewhere. VITO therefore advised NOT to impose strict target groundwater concentrations but to formulate a more general remediation goal (“to realize a significant pollution mass reduction in the soil, in order to be able to switch to a more passive remediation approach in a later stadium: natural attenuation or bioremediation”).
- It was suggested to install extraction wells screened at 1.5-2.5 bgl and 3.5-4.5 bgl. The distance between wells should be kept small in the source zone area (i.e. about 2 m), increasing linearly towards the borders of the pollution (to inter-well distances of 3 to 4 m). A phased instalment of the extraction wells was also recommended. The dimensions of the CAH source zone may be

⁴ The mass removal realized by the simultaneously extracted groundwater could not be calculated because of unknown amounts (failing flow meter). However, it may be assumed that it is low relative to the mass removed by the soil vapour extraction.

additionally assessed during installation (drilling) of the remediation wells: local higher well density should be used for all heavily polluted (source) zone coordinates. PID-screening methods and other field techniques were proposed as useful tools to determine CAH-pollution severity in collected soil samples during remediation well installation.

- Further recommendations were:
 - Flow rates should be adjustable per extraction well and the blower must be equipped with a timer to allow intermitted extraction regimes.
 - Air injection at depths of 8 m bgl should be started only when pollutant mass removal via the dual phase extraction has decreased to low levels. Air injection should be performed discontinuously, with an on-off frequency to be determined experimentally.
 - Regarding safety issues, indoor air should be monitored (CAH analyses) as soon as air sparging is switched on. This should be done in the building at the remediation site itself as well as in directly neighbouring buildings. Passive samplers and active measurements can be used during the first week after air sparging start-up.
 - When removal rates have dropped to low levels, improved remediation efficiency may be obtained by switching to in-situ biodegradation (e.g. injecting an organic substrate to induce anaerobic dechlorination) or improve volatilization (increase temperatures e.g. by steam injection instead of air).
 - *The most important factor for success is an effective removal of CAHs present in the peaty soil layer. If this cannot be achieved in a sufficient manner, the groundwater will remain heavily polluted.*

Once mass removal with the dual-phase/air sparging system becomes marginal, the active remediation can be suspended and the secondary (more passive) phase commenced.

1.3 Soil remediation plan and additional pilot test phase

In May 2001 a full-scale soil remediation plan was developed⁵. The design involved the installation of 70 dual phase extraction wells screened at 0.5-4 m bgl and 30 air injection wells screened at 8 and 4 m bgl (Fig. 4). *Total estimated duration of the full-scale remediation was 2 years.*

As discussed in paragraph 1.2, it was recommended to determine the exact number and coordinates of wells required, using additional measurements (on-site PID-screening during the drilling activities). The locations of extraction and injection wells as indicated in Fig. 4 were therefore not final.

In the plan, the following remediation targets were proposed (despite the recommendations as presented in par. 1.2): PCE-TCE –DCE –VC in soil phase 1.4 / 1.4 / 0.7 and 0.02 mg/kg respectively; in the groundwater 10 / 70 / 50 and 5 µg/L, respectively. These target values were too ambitious.

⁵ "Bodemsaneringsproject site te Ninove". rapport n°. 00/4007; May 2001



Figure 4. Full-scale design (proposed in soil remediation plan)

1.4 Additional investigation regarding the presence of a confining clay layer

Prior to full-scale remediation, additional borings were performed⁶ to investigate the presence (or absence) of a confining clay layer below approximately 9 m bgl, as suggested by the bore log presented in Fig. 2. Two deeper borings were executed up to depths of 16 and 15 m bgl. Both were equipped with monitoring wells, screened at 14-16 m bgl. and 8-10 m bgl. No confining clay layer was observed. The soil profile becomes more clayey, however, below 12 to 13 m bgl. Permeability measurements in both wells yielded estimated hydraulic conductivities of 0.08 m/d for the deepest well and 0.23 m/d for the more shallow well.

⁶ "Verslag bijkomend onderzoek m.b.t. de aanwezigheid van een afdichtende kleilaag op 9 m-mv.", 30 October 2002.

1.5 Full-scale remediation: implementation phase

1.5.1 First interim report

The injection and extraction wells were put in place in September and October 2002. The presence of the peat layer was confirmed at almost all boring locations, at a depth of 3.5 to 4.5 m bgl. During the installation – according to the interim report – field measurements using PID and/or Dräger detection tubes were performed. However, these were either incomplete or incorrect since hardly any elevated values were detected.

Thirty-three extraction wells to 2.5 m bgl and 34 wells to 4 m bgl were installed as well as 40 air injection wells screened at 8 m bgl. (Fig. 5). Connective pipe work and the groundwater purification unit were installed in November and December 2002. The deep and shallow extraction wells were connected to individual vacuum vessels equipped with a compressor. Extracted soil air/ CAH vapours were purified by activated carbon. Extracted groundwater was purified by a sand filter, stripper and activated carbon.

The full-scale remediation was started on **5 December 2002** (extraction) and 13 May 2003 (air injection). In total 5 interim reports were produced⁷. On 13 September 2004 an additional monitoring campaign was reported⁸.

7

- o “Tussentijds verslag 1 – Ninove – Moens – Voormalige droogkuis – Ambtshalve saneringswerken van VOCI’s in de bodem en het grondwater”, 12 August 2003
- o “Tussentijds verslag 2 – Ninove – Moens – Voormalige droogkuis – Ambtshalve saneringswerken van VOCI’s in de bodem en het grondwater”, 15 March 2004
- o “Tussentijds verslag 3 – Ninove – Moens – Voormalige droogkuis – Ambtshalve saneringswerken van VOCI’s in de bodem en het grondwater”, 27 July 2005
- o “Tussentijds verslag 4 – Ninove – Moens – Voormalige droogkuis – Ambtshalve saneringswerken van VOCI’s in de bodem en het grondwater”, 14 September 2006
- o “Tussentijds verslag 5 – Restverontreiniging na stopzetting actieve fase - Ninove – Moens – Voormalige droogkuis – Ambtshalve saneringswerken van VOCI’s in de bodem en het grondwater”, 3 April 2007

⁸ “Verslag bemonsteringscampagne – Ninove – Moens – Voormalige droogkuis – Ambtshalve saneringswerken van VOCI’s in de bodem en het grondwater”, 13 September 2004

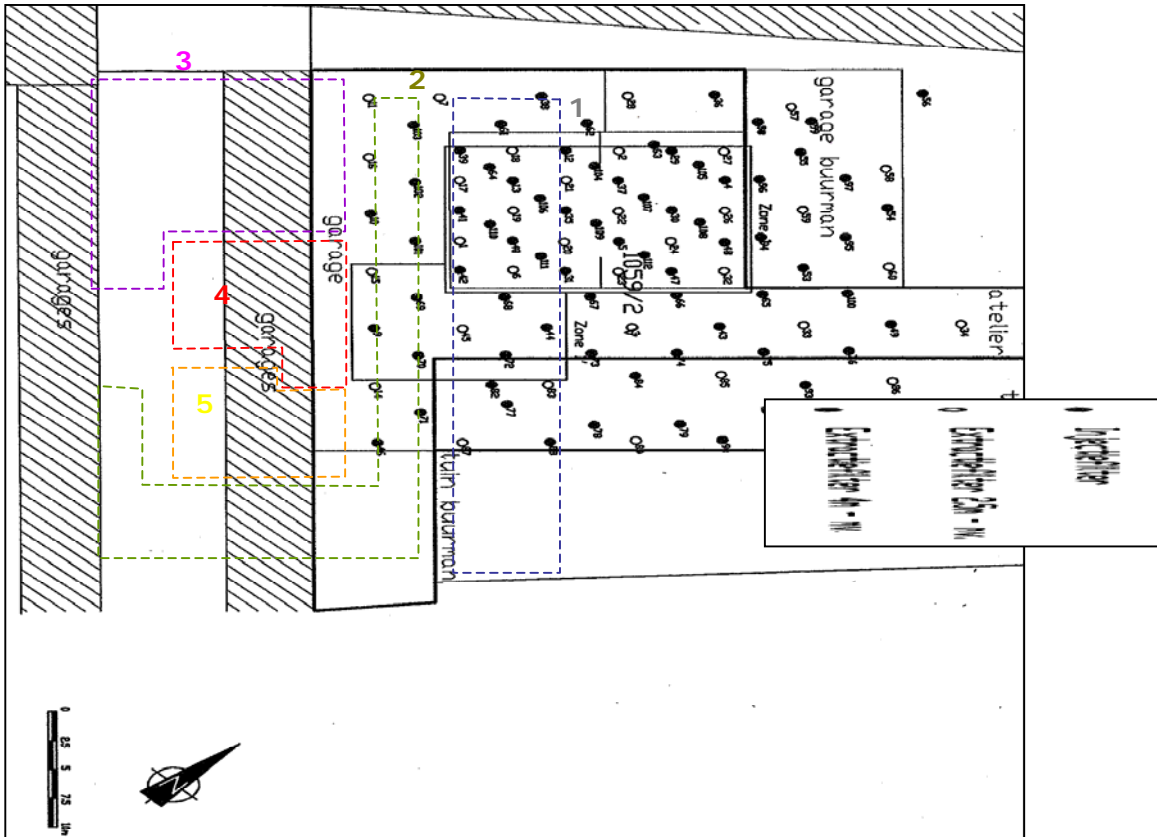


Figure 5. Overview of installed injection and extraction wells. Coloured lines indicate different zones (m-mv. = m bgl). (source: interim reports)

An average air extraction rate of approximately 50 m³/h was reported. Based on gas phase concentration measurements, 108.8 kg CAHs were removed from the subsoil, between start-up and 23 February 2003. Pollutant mass removal via the water phase was marginal as compared to the gas phase mass removal (agreeing to the general consensus that P&T (pumping groundwater) is not an adequate mass removal technique for CAHs present in subsurface source zones).

In interim report n°1 the total pollutant mass present in the subsoil was calculated using measured CAH groundwater concentrations in monitoring wells, and some analyses of organic matter (OM) contents in the 0 – 1.5 m bgl soil layer (an average OM content of 4.5 % was adopted for that soil layer). For the peaty soil layer, an OM content of 20% was *estimated*. For the soil volume beneath the peat layer, an average OM content of 4.5 % was assumed. Adsorbed CAHs were then calculated using Koc values for PCE, TCE, DCE, VC of respectively 87.2, 81, 50 en 29,5. The pollutant mass thus calculated in interim report n°1 was 6291 kg CAHs (of which 168 kg dissolved in the groundwater).

The consultant concluded mistakenly that the removal efficiency realized by the remediation installation was marginal as compared to the total pollutant mass present (because the latter was overestimated, see further) and that for that reason, air sparging should be directly commenced.

1.5.2 Second interim report

Air injection in the sparging wells was initiated on 13 May. Injection wells were grouped in 7 clusters of 5 wells each (Fig. 6), connected to a compressor by automatically operated valves.

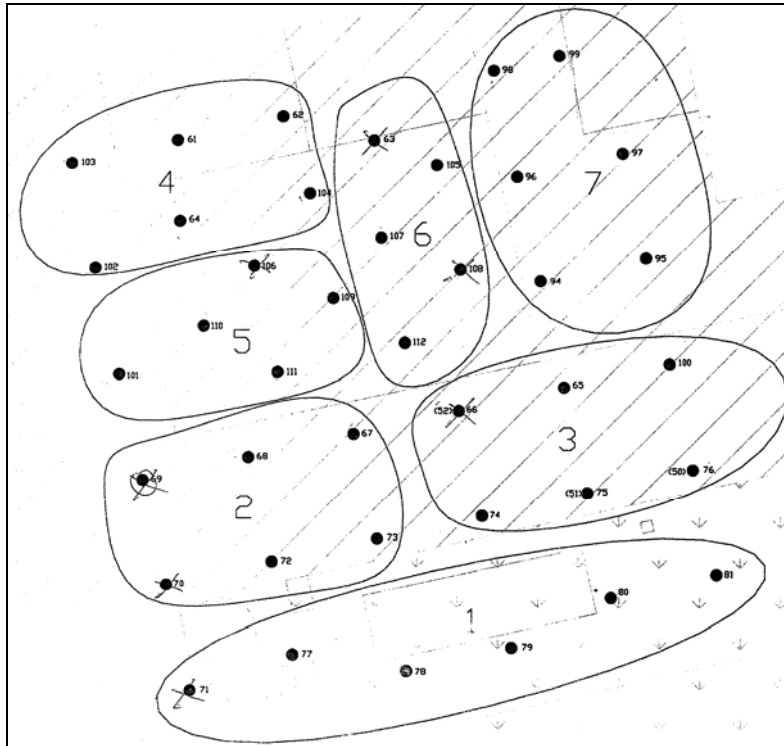


Figure 6. Clustered distribution and operation of air sparging filters at the site (figure taken from 2nd interim report)

Air injection was at 1.2 bar at a reported rate between 5.22 and 20.5 m³/h. After several days the injection pressure was reduced to 1 bar and some wells closed because of detection of air leaking from the clay seal of these particular wells. Gas phase concentration measurements in extracted air in each of the specified zones were conducted on 23 May, 31 October and 9 December 2003. The recovered pollutant mass in the period after air sparging start-up was estimated to be 37.31 kg. Total calculated pollutant mass recovery since remediation commenced (12 months in total at that time) was 154 kg (of which >99% via the vapour phase).

Remark: during sample collection on 31 October, very high concentrations were measured in the extracted soil vapour phase (overall influent). These values were excluded from the pollutant mass recovery calculations (they were discarded as being “unrealistically high”). This may have led to underestimation of the mass recovery. Indeed, when employing air sparging in subsurface CAH source zones, highly variable influent concentrations are likely to occur. Concerning influent concentrations per cluster, only results for (source zone) clusters 4 and 5 were reported. It could however be that the air injection may have caused lateral displacement of part of the pollutant mass to the more outwardly situated zones 1, 2 and 3 (Fig. 5).

Another pollutant mass calculation (remaining CAH mass in the subsoil) was performed and reported in interim report n°2. The same calculation method was used as the one described in interim report n°1. This time, the calculated pollutant mass present in the subsoil was 1379 kg, of which 175 kg reported to be dissolved in the groundwater.

1.5.3 Third interim report

Remaining pollutant mass in the subsoil was calculated for a third time (in identical way as was done in interim reports n°1 and 2: groundwater CAH concentrations in monitoring wells were measured and adsorbed CAH mass calculated using Koc’s and soil OM content). The calculated value now was 1879 kg, of which 111 kg dissolved in the groundwater.

Remark: these calculations probably were not accurate, which is proven when looking at the ratio's between calculated adsorbed and dissolved pollutant mass. These ratio's vary in each subsurface pollutant mass calculation while it should be more or less constant, since the OM and Koc's are constants. In the calculations this is obviously not the case (Table 2).

Table 2. Calculated subsurface pollutant mass (source: remediation interim reports n° 1 to 3)

	CAH mass (kg) dissolved in groundwater phase	CAH mass adsorbed to solid phase	(kg) Total (kg)
Interim report n° 1	168	6123	6291
Interim report n° 1	175	1204	1379
Interim report n° 1	111	1768	1879

1.5.4 Fourth interim report

From 25 February 2005 onwards, the remediation was focused on the 'source zone' of the CAH pollution. The extraction was sustained continuously, removing an estimated average pollutant mass of 0.13 kg/d. In July-August 2006 the extraction was limited to the deep extraction wells in the source area. Groundwater samples were taken in this zone (MW p28 and extraction filter 2). In monitoring well p28, concentrations were measured of 14000 - 18000 µg/L PCE, 9200 – 16000 µg/L TCE, 21000 – 25000 µg/L DCE en 500 – 1200 µg/L VC. In the groundwater sample taken from extraction well 2 the analysis result was 700 – 2400 µg/L PCE, 3000 – 8900 µg/L TCE, 17000 – 53000 µg/L DCE en 680 – 3700 µg/L VC. No further pollutant mass calculations were reported in this fourth interim report.

1.5.5 Fifth interim report

The remediation was suspended on 28 September 2006. The above-ground equipment was removed on 8 February 2007. When removing the activated carbon units from the site, no samples were taken from it. Such samples could have given additional information about the pollutant mass removed (in general no activated carbon samples were analysed at any instance during the remediation).

Five new borings and soil sampling were executed to estimate remaining subsurface pollutant mass. Five soil samples were taken from the soil above the peat layer; 5 samples from within the peat layer and 3 samples from the soil beneath the peat layer. They were analysed to determine their CAHs content. Results of these analyses are presented in Figs. 7 to 9. Also the groundwater was sampled and analysed for CAHs (Fig. 10).

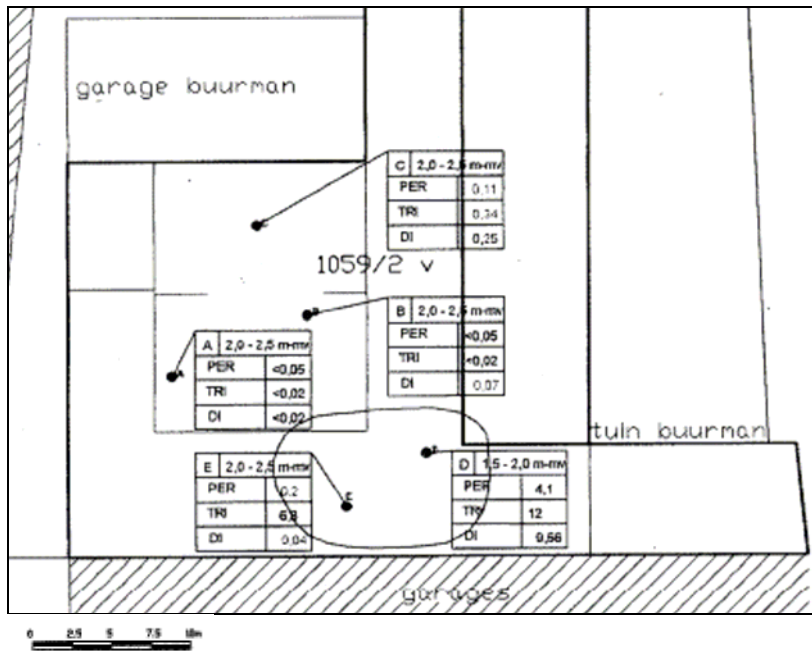


Figure 7. Overview of CAH analysis results for soil samples taken from above the peat layer. Units are mg/kg dry matter (source: interim report 5). PER=PCE; TRI=TCE; DI=DCE). Soil depth at which the samples were taken is indicated (m-mv = m bgl).

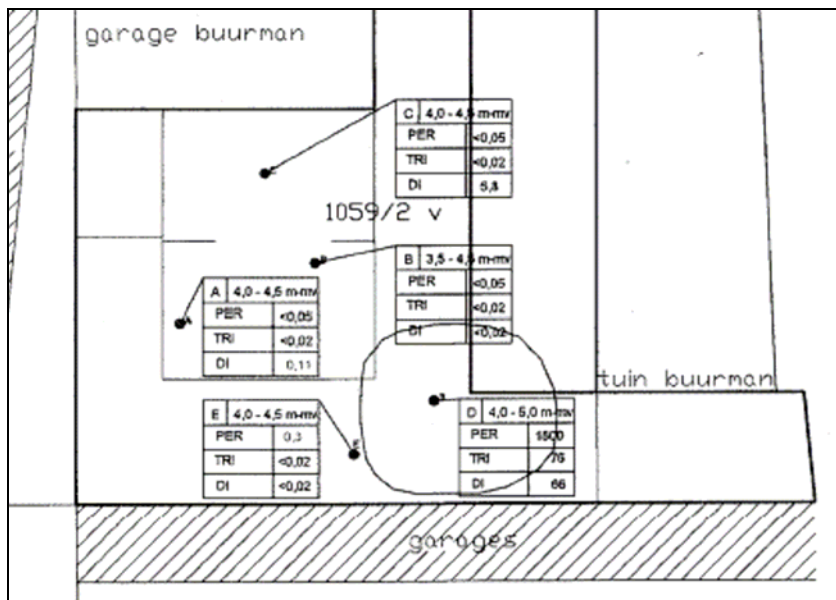


Figure 8. Overview of CAH analysis results for soil samples taken from within the peat layer. (source: interim report 5)

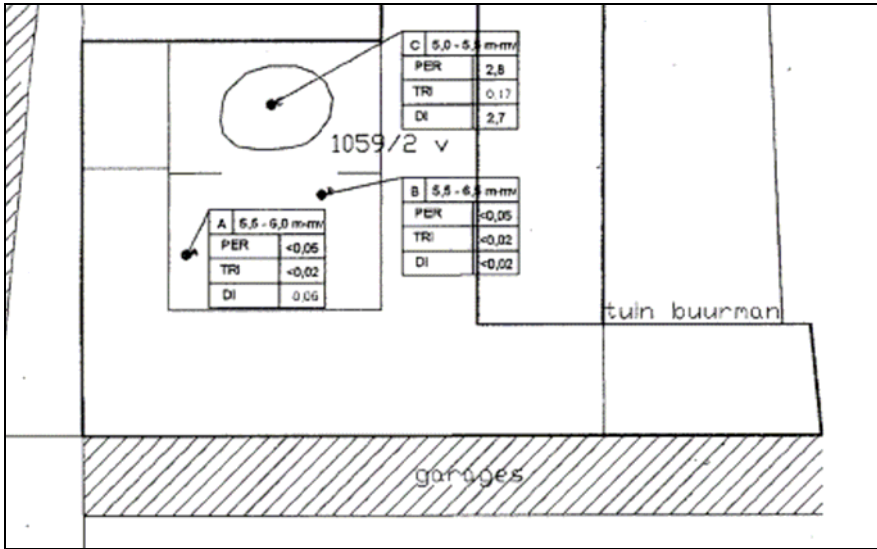


Figure 9. Overview of CAH analysis results for soil samples taken from below the peat layer. (source: interim report 5)

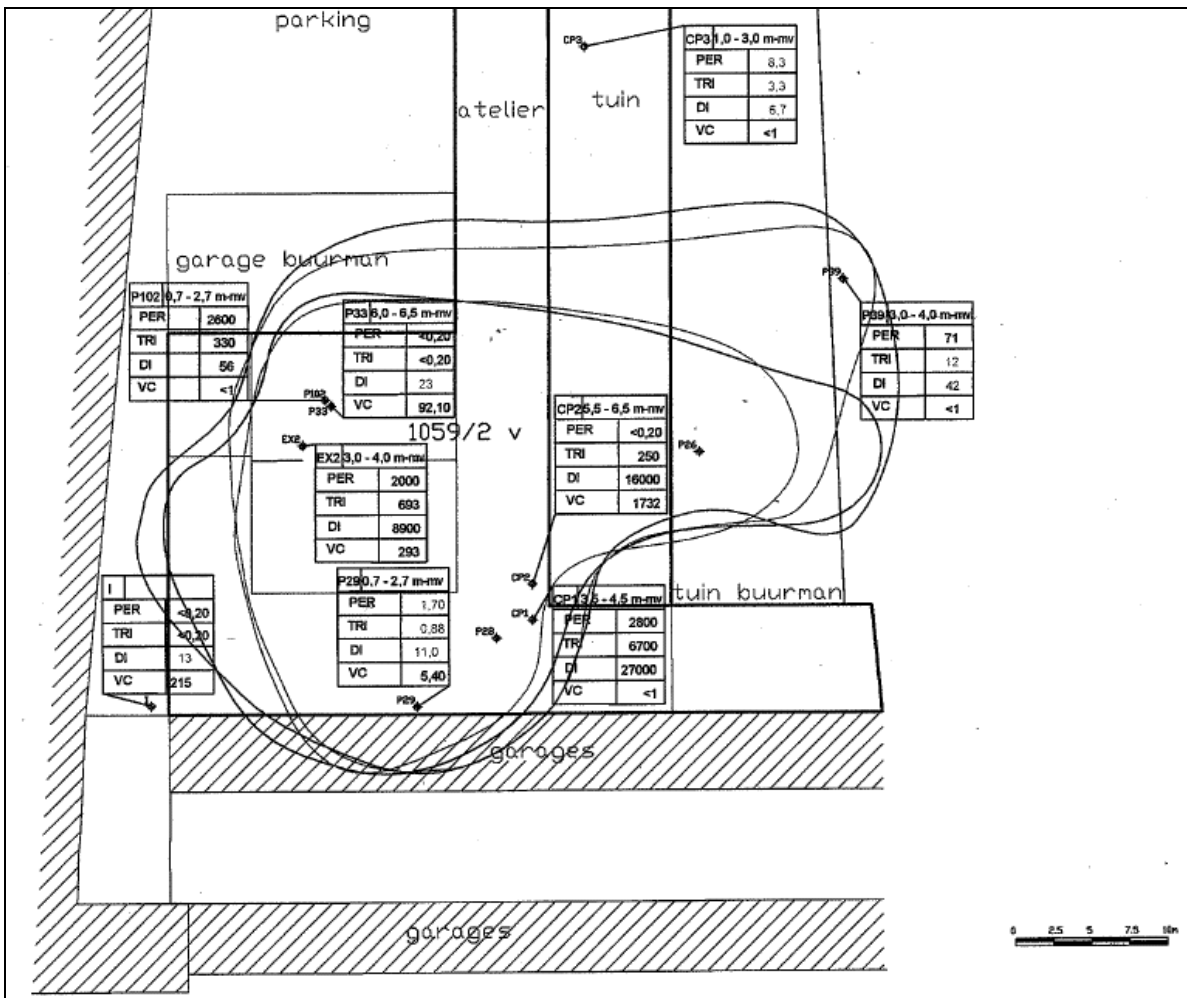


Figure 10. Overview of CAH groundwater analyses and estimated pollution contours of the individual CAHs. (source: interim report 5)

In this fifth interim report, an alternative pollutant mass calculation method was used, i.e. multiplying the estimated total polluted soil mass to average CAH concentrations measured in the soil (separately calculated for the three distinguished soil layers: above, in and beneath the peat layer). The following estimates were used in this calculation:

- Volume of polluted soil above peat layer: 250 m³ / assumed average concentration of 2.15 mg/kg PCE and 1.88 mg/kg TCE;
- Volume of polluted soil in peat layer: 120 m³ / assumed average concentration of 1800 mg/kg PCE and 76 mg/kg TCE;
- Volume of polluted soil beneath the peat layer: 100 m³ / assumed average concentration of 2.8 mg/kg PCE and 0.15 mg/kg TCE;

With these values, a more realistic remaining pollutant mass of 231 kg is calculated (DCE and VC not included). It should be mentioned, however, that the largest part in this calculation (the mass present in the peat layer), is based on only one analysis result (i.e. 1800 mg/kg PCE in sample D: 4-5 m bgl). The correctness of this pollutant mass calculation is strongly dependent on the question if this single value is valid as a good estimate for the average concentration in the peat layer as a whole. Of course, the value of the estimate of the total polluted soil volume and mass will also be of significant importance.

In order to get a better estimate, much more soil analyses are required.

Remarks:

- it may not be a coincidence that the one high CAH concentration detected in the peaty soil layer was measured outside the area having the higher remediation well density. In the other analysed soil samples taken from the peat layer, located inside this intensively remediated area (samples A, B and C), no strongly elevated PCE contents were present. If this is confirmed by additional soil sampling, it may be concluded that the remediation has effectively led to a significant pollutant mass removal in that area.
- In interim report 5 it is suggested to switch to a more passive remediation technique (monitored natural attenuation: MNA). This is indeed an option. However, switching to bioremediation may be preferable (injection of an organic substrate to stimulate reductive dechlorination). In any case, it is recommended to first perform additional sampling to obtain a better impression of the pollutant mass still remaining in the subsoil, with special attention to the potentially remaining CAH source near boring "D". This requires additional borings, PID-screening and soil analyses. If such additional investigation would reveal a substantial remaining pollutant mass, an additional dual phase/air sparging phase (involving additional wells) may be appropriate prior to switching to bioremediation or natural attenuation. When switching to reductive dechlorination, relevant additional analysis parameters should be included (e.g. final dechlorination products ethene and ethane)⁹.

1.6 General conclusions

1. The remediation plan *a priori* excluded the possibility to excavate the pollution. Some obvious practical reasons limited that possibility (closeness of surrounding buildings, lack of space and disapproval for demolition). A targeted CAH source excavation would have been the most convenient technical solution (although at higher initial costs). The peaty soil layer at about 4 m bgl – containing most of the pollutant mass, could then have been removed quickly and effectively. Remaining groundwater pollution could have been treated separately afterwards, using MNA or bioremediation.
2. A physical in-situ removal by dual phase extraction, aiming to recover the spilled CAHs primarily via the vapour phase (high vacuum extraction, in this case combined with air sparging), is a suitable remediation strategy. In this case however, a very substantial part of the total pollutant mass was present in a peaty soil layer. Such layers are very difficult to remediate using an in-situ approach.

⁹ Code of Good Practice "In-situ anaërobie bioremediatie van VOCl's" (www.ovam.be/jahia/Jahia/pid/637).

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3. Prior to remediation start-up, VITO recommended not to impose strict soil and groundwater concentration target levels, because these were unrealistic under the given conditions and using the selected remediation techniques, especially within the specified remediation schedule of only two years. It may have been a better option to formulate the remediation goals more qualitatively: "realisation of a substantial pollutant mass reduction in the subsoil". Afterwards a further, more passive, reduction of the contamination can then be intended, leading to decreasing concentrations in the long term. Either natural attenuation or bioremediation are applicable. In any case, any potential hazard (that the pollution may reach potential receptors) must be excluded.
 4. The remediation wells were not optimally localized: a significant number of wells were installed too far away from the CAH source zone, while the well density in part of the source area itself was too low. This can be concluded from the analysis results of the influent air per zone: in zones O/D 1 to 3 a clearly lower CAH mass was extracted than in zones O/D 4 and 5. The location of extraction wells may have been more optimal if their coordinates had been selected based on PID/Dräger measurements and sensorial observations during installation. According to the reports this had been attempted but obviously had not resulted in an optimal choice of well locations (according to the report, no CAH odours nor elevated PID values were observed, suggesting that these field observations may not have been optimally conducted. Earlier PID screening by VITO did yield strongly elevated PID readings in the CAH source zone). In zone D5, very high pollutant concentrations were detected in the extracted vapour on 7 January 2003: 188 µg/L PCE. Remarkably, high DCE and VC concentration levels in the extracted air were also measured: 172 µg/L and 100 µg/L, respectively. This indicates that reductive dechlorination processes were active in the peaty soil layer. This was confirmed by later groundwater analyses.
 5. CAH mass removal realized during the remediation has not been correctly appreciated. Concluded was that it was "rather limited", because of an overestimation of total pollutant mass present prior to remediation start-up. *The efficiency of the ongoing remediation was evaluated too negatively for that reason.* Moreover, the extracted CAH mass itself may have been underestimated, by discarding one set of measurements (October 2003) that revealed very high CAH concentrations in the extracted vapour phase. The remediation system did lead to a significant pollutant mass removal: after 100 days more than 100 kg CAHs had been removed by the dual phase system (prior to air sparging start-up). Also, after air sparging start-up, significant additional mass recovery was accomplished. Total CAH mass recovered should therefore be estimated in the order of several hundreds of kg, where total pollutant mass initially present in the subsoil was expected to be of the same order of magnitude¹⁰. In the most intensively treated subsoil zones 4 and 5 (source zone with high remediation well density) three soil samples from the treated peat layer contained relatively low remaining CAH levels. On the other hand, one soil sample taken from a treated zone with the lower extraction well density, still contained a very high CAH concentration of 1800 mg/kg dm PCE.
 6. A potentially interesting method, that has not been used in this case, is to assess pollutant mass removal by a regular follow-up of the activated carbon used for purification of the extracted subsoil vapour phases (if the loading capacity for CAHs of the activated carbon is known, the amount of pollutant mass can be easily assessed by counting the number of activated carbon replacements necessary). This can be measured on-line, using PID. Replacement of the activated carbon is necessary when effluent concentrations increase. This would drastically reduce the needed amount of analyses of influent vapour phase. Also, the option exists to sample the spent activated carbon for exact adsorbed CAH mass determination.
 7. Remediation duration required had been estimated to be 2 years. In reality, the remediation was sustained twice that time. After this period, the planned target concentration levels were still far from being realized: the groundwater still contained CAH concentrations in the order of several tens of thousands micrograms per litre. Although these concentrations were still high, they have decreased by more than one order of magnitude in comparison to concentration levels measured prior to remediation start-up (local PCE-levels then were close to theoretical maximum solubility, i.e. 160,000 µg/L). It has been recognized that only after near-complete

¹⁰ CAH mass in the saturated subsoil above and in the peat layer was estimated, based on analyses of soil samples prior to remediation start-up, to be in the order of 36 kg per 100 m² "source zone". Total mass present could not be assessed accurately because the dimensions of the source zone were not yet properly established. It had been suggested to additionally evaluate this important aspect while installing the remediation wells. This seems to have been unsuccessful.

PCE-DNAPL removal (>90%) groundwater levels will significantly decrease. This is caused by the fact that groundwater concentrations are being buffered by continuous dissolution of DNAPL¹¹. After the remediation actions taken, still high levels of partial reductive dechlorination products are observed (DCE and VC). This suggests that switching to bioremediation or natural attenuation may be an option for further groundwater quality restoration in the long run.

8. This remediation project clearly reaffirms the need for a thorough site investigation prior to starting remedial actions. An estimate of the total pollutant mass (by collecting an appropriate number of samples, and combining quick field screening by PID with chemical analyses) is necessary to be able to correctly evaluate remediation efficiency.

¹¹ "Studie betreffende de bodemsanering van stedelijke VOCl verontreinigingen" (www.ovam.be/jahia/Jahia/pid/915).

2.1 Descriptive site investigation

Study site 2 covers about 0.9 ha and is situated in an industrial area. Since the sixties, a machine factory was present (producing metal components, using processes of degreasing, surface treatment and coating). Until 1982 TCE and PCE were used for degreasing. In the rear of the site, waste materials were stored since the '80. A number of soil investigation studies were executed^{12,13}. The groundwater at the site was found to be polluted with PCE, TCE and TCA, and with partial dechlorination products (DCE, VC, DCA). The pollution status of the groundwater as described in the reports is given in Figure 11.

The 1999-2000 soil investigations concluded:

The soil is sandy with local clay layers.

The groundwater is located at approximately 2 m bgl., with seasonal variations. Based on an estimated permeability of 5 m/d, an effective horizontal groundwater flow velocity of 12 m/y was calculated in Northerly direction. Remark: a Southern flow direction towards the river Leie (800 m downstream of the site) seems more plausible. This confusion may have been due to the 180° erroneously drawn North arrow on the plans enclosed in the soil remediation plan.

Measured CAH concentrations in the groundwater are locally very high: in the 1999 investigation, levels of up to 44000 µg/L (PCE); 43000 µg/L (TCE) and 5770 µg/L (TCA) were reported. Partial dechlorination product concentrations were lower at that time: up to 4000 µg/L cDCE and 144 µg/L DCA. The established vertical boundaries of the CAH pollution were 13 m bgl. During the additional investigation of 2001, a locally elevated TCA level was measured (69000 µg/L) as well as cDCE (41000 µg/L). Vinylchloride levels were generally small (max. 34 µg/L). The largest groundwater concentrations were measured near monitoring well MW11. The estimated surface area of the pollution was 3400 m². In the rear end of the site, according to the investigation, a second – smaller – CAH pollution source area was situated (estimated 400 m²). At that location a partially overlapping heating oil pollution was also present.

¹² "Beschrijvend bodemonderzoek (eindverslag)", report nr. E012289, February 1999.

¹³ Actualisatie OBO Terreinen N.V. Kling Immo, report nr. EB0012/039, January 2001.

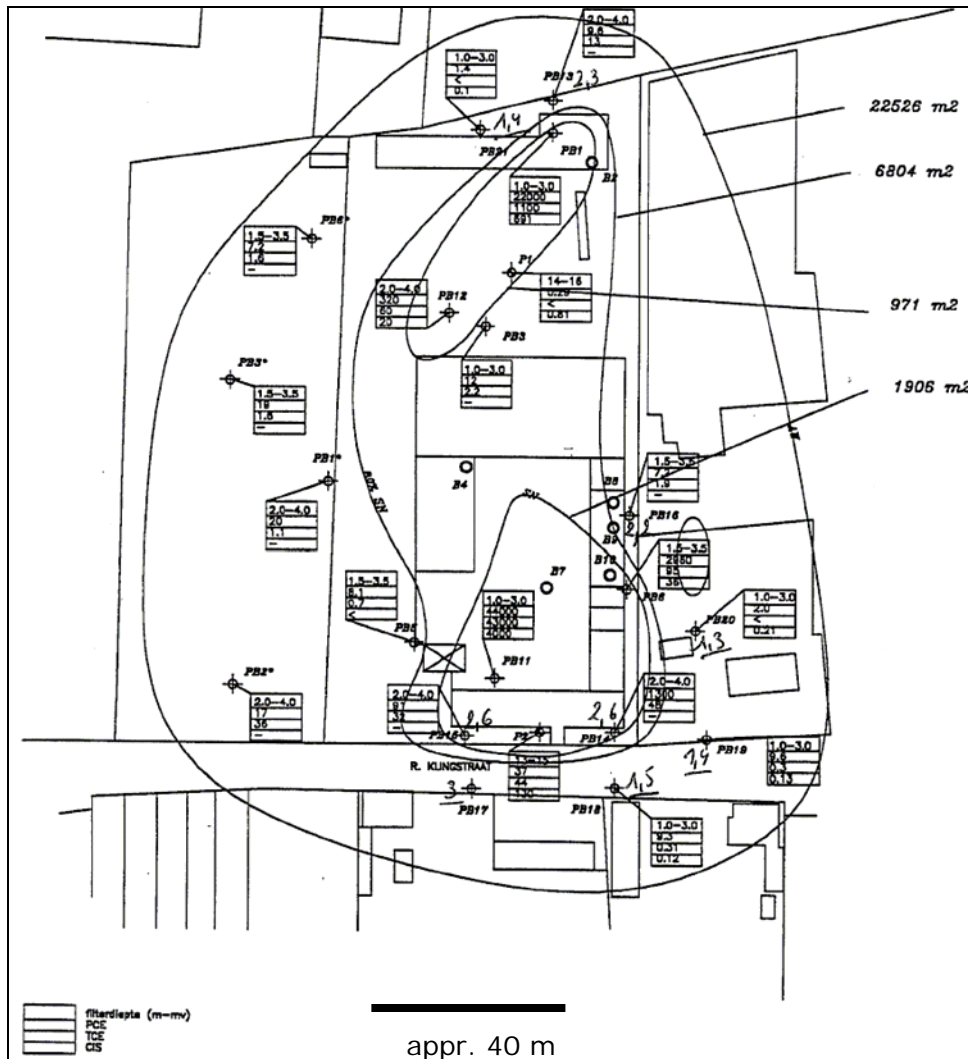


Figure 11. Schematic plan of the site and CAH groundwater pollution (with measured concentrations in µg/L and estimated surface areas in m² indicated) as reported in 1999 (Envirotox, 1999)

In soil samples analysed, rather small CAH levels were determined. At one location only, a sample from the top soil contained a concentration exceeding limit values (boring B31(0-0.5 m bgl): 2.2 mg/kg dm).

Remark: relatively few samples were taken from the most suspicious zones at the site. A potentially DNAPL-containing area inside the building was not sufficiently assessed by borings (inside the area formed by the triangle B4 - B7 - B5. Later (2007, see further), a pilot test ISCO was executed in that area, in which presence of DNAPL was established). During the additional investigation in 2001 this area again was not assessed. At that time, no elevated CAH concentrations had yet been observed in soil samples, which may explain the (incorrect) assumption of the consultant involved, that CAHs were primarily present dissolved in the groundwater. Additional remark: analysing soil samples for CAHs can best be done in combination with PID measurements¹⁴. Samples for chemical analyses can be selected based on PID read-outs. In this way more borings and measurements can be realized at reasonable costs, thus lowering the risk to "miss" pollution sources. Also soil gas measurements using a hand-driven probe in combination with PID can help delineating CAH source zones. These measurements require smaller diameter holes drilled through (concrete) floors in buildings and are thus

¹⁴ E.g. by collecting a soil sample by hand and placing it in a gas-tight bag with some air inclusion. After shaking, CAHs in the soil will volatilize and can be measured by PID in the gas phase of the bag.

less expensive than normal drillings for hand auguring and/or monitoring well installation.

2.2 Soil remediation plan

The soil remediation plan for the site¹⁵ proposed a pump&treat as best available remediation technology. This was obviously based on the assumption that the pollution was only present in the groundwater, not involving (residual) DNAPL. The remediation design included 5 extraction wells to a depth of 6 m bgl for the smaller pollution hot-spot in the rear, and 15 wells to 10 m bgl in the more centrally located larger polluted area (Figure 12). Two deep wells were also installed (at 16 and 17 m depth). Considering an estimated total extraction rate of 10 m³/h and a postulated flushing factor needed of 54, the consultant expected a total volume of 470.000 m³ needed to be pumped and treated and a total project duration of 5 years. In the remediation plan it is also mentioned that, if the infrastructure would be removed at the rear end of the site, an excavation should also be considered, during which the heating oil pollution could also be removed.

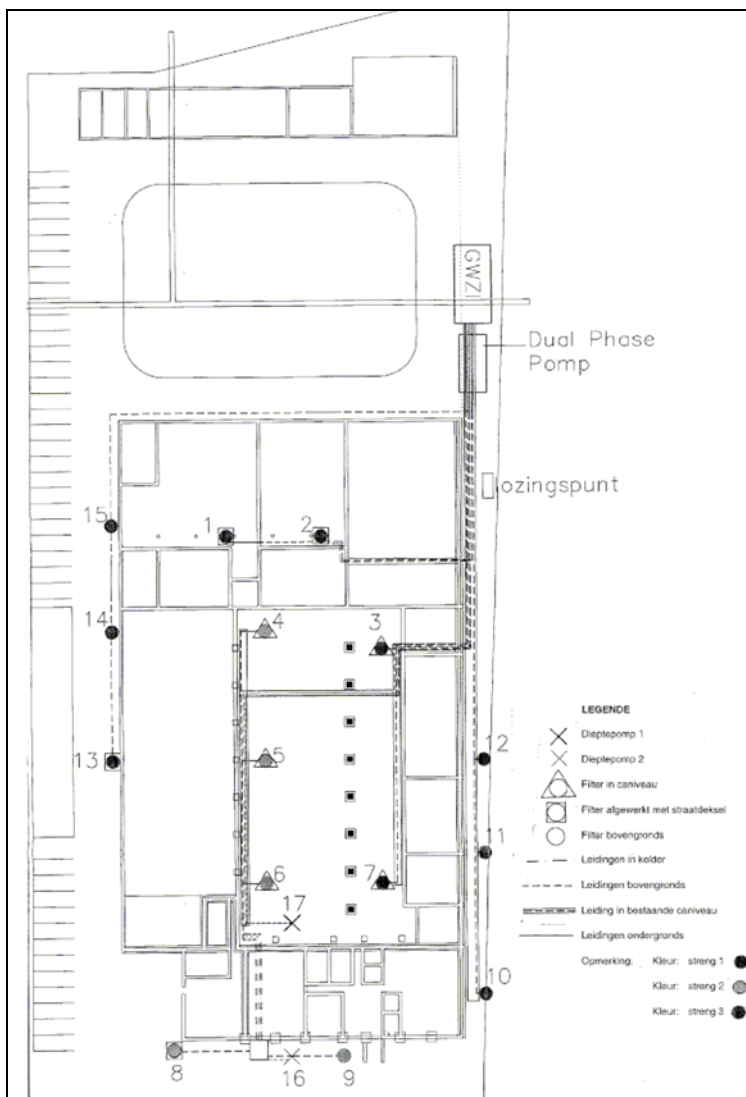


Figure 12. Full-scale design of P&T system employed. Wells 1 – 15 are 10 m deep. Wells 16 and 17 are deepwells placed at 16 to 17 m bgl)

¹⁵ "Bodemsaneringsproject", report nr. EB0102/021; January 2002.

The remediation plan proposed groundwater concentration target levels for PCE, TCE, cDCE, VC of 32, 56, 40 and 4 µg/L and for TCA and DCA 400 and 264 µg/L, respectively.

2.3 Full-scale remediation: execution phase

2.3.1 Interim reports

On 2 September 2003 an excavation was started at the rear side of the site. In four separate phases, in total 500 tonnes of soil was removed and transported for off-site treatment. Before refilling with clean soil, a drain was placed in a shallow trench at the bottom of the excavation pit, for potential later use for groundwater extraction. Remark: the excavation was limited to 2.5 m bgl instead of 4 m bgl as initially planned. Later groundwater monitoring showed that a residual DNAPL-containing source zone is still present underneath the excavated layer. The drain was installed relatively shallow, in clayey soil. Later sampling of groundwater extracted from the drain yielded relatively low concentrations, not representative for the groundwater quality in the deeper subsoil (see further).

After the excavation, the vertical pumping wells were installed as indicated in Fig. 12 and connected to a pump and a purification system. The latter consisted of an oil-water separator, stripper and activated carbon filter. Purified groundwater was discharged into the public sewer (Klingestraat).

The groundwater extraction from the wells was started on 30 October 2003. The consultant involved produced 7 interim reports describing the remediation results¹⁶. On 17 November 2006 a laboratory investigation was reported evaluating ISCO as potential additional remediation technology¹⁷. In April 2007, finally, a report of a pilot test using ISCO with Fenton's reagent, was submitted to OVAM¹⁸.

2.3.2 First interim report

Shortly after start-up, the over-all groundwater extraction rate was about 30 m³/d. After a few months, this had decreased to 21 m³/d. The remediation plan reported an expected realizable extraction rate of 10 m³/h. During the first 2.5 months of operation, 575 m³ groundwater was pumped up. Influent concentrations (total CAHs) varied between 27 to 44 mg/L. PCE was the primary pollutant. The report states that after 2.5 months of pumping, in total about 40 kg of CAHs had been removed from the subsoil by the remediation system.

On 23 January 2004, also groundwater collected from the drain was analysed. This sample contained mostly cDCE (800 µg/L) and VC (900 µg/L). The relatively higher concentrations of these partial dechlorination products than observed elsewhere at the site, were also observed during the

¹⁶

- o "Tussentijds rapport eerste fase saneringswerkzaamheden", 4 December 2003
- o "Tussentijdse rapportering bodemsaneringswerken (rapport 1) – periode december 2003 tot januari 2004" (nr. 04/A0158), 18 February 2004
- o "Tussentijdse rapportering bodemsaneringswerken (rapport 2) – periode februari 2004", (nr. 04/A0635), 4 March 2004
- o "Tussentijdse rapportering bodemsaneringswerken (rapport 3) – periode maart 2004", (nr. 04/A1166), 5 April 2004
- o "Tussentijdse rapportering bodemsaneringswerken (rapport 4) – periode maart 2004 tot februari 2005" (nr. 05/A0441), 8 March 2005
- o "Tussentijdse rapportering bodemsaneringswerken (rapport 5) – periode maart 2005 tot september 2005" (nr. 05/A2201), 3 November 2005
- o "Tussentijdse rapportering bodemsaneringswerken (rapport 6) – periode oktober 2005 tot februari 2006" (nr. 05/A5119), 10 March 2006
- o "Tussentijdse rapportering bodemsaneringswerken (rapport 7) – periode maart 2006 tot november 2006" (nr. 06/R0146), 30 November 2006

¹⁷ "Tussentijdse rapportering bijkomende onderzoeken en labotesten" (nr. 06/R0508), 17 November 2006

¹⁸ "OVAM, Robert Klingestraat 19, Wervik" (nr. 06/R0617), 27 April 2007

excavation, and are likely a result of the co-presence of petroleum hydrocarbons here, acting as an organic substrate (inducing reductive microbial dechlorination).

2.3.3 Second and third interim reports

Groundwater pumping rates slightly further decreased in the period January – March 2004, reaching 19 m³/d on average. Average CAH levels in the influent remained more or less constant (23 - 31 mg/L). After 5 months of pumping, an estimated amount of 62 kg of CAHs were removed through the groundwater extraction. The third interim report mentions that the drain present in the excavated zone was also connected to the groundwater purification system.

2.3.4 Fourth interim report

The counter registering pumped volumes indicated 7808 m³ on 21 September 2004. The average extraction rate in the period March-April 2004 was 16.3 – 26.1 m³/d. Reported influent concentrations were 5.5 mg/L in June 2004 and 24 mg/L in August. After 327 days of groundwater pumping, the estimated total CAH mass removed from the subsoil was 138 kg. After 21 September 2004, pumping rate data reporting was temporarily suspended but CAH concentration measurements were continued. In November 2004 the total CAH concentration in the influent was 15.7 mg/L (of which 9.7 mg/L PCE). In January and February 2005, total CAH concentrations were 26 and 22 mg/L, of which 19 and 15 mg/L PCE.

The drain was resampled in February 2005; again, the drain water showed rather low levels of CAHs (28 µg/L PCE; 17 µg/L TCE; 33 µg/L cDCE; <5 µg/L VC; 9.2 µg/L TCA and 5.3 µg/L DCA).

The report concludes: “we propose to continue the ongoing remediation, since pure product is still being pumped up”. Remark: this conclusion was not correct; no DNAPL (‘pure product’) has been pumped up but dissolved CAHs only. The mass removal realized by the groundwater pumping has been relatively small when considering the total pollutant mass present in the subsoil. This mass had never been calculated by the consultant. Even at present, it is difficult to get a realistic estimate of the amount of pollutant mass present because little is known about the source zone dimensions (subsoil volume containing residual DNAPL). Increasing the pumping rate, as proposed in the interim report, would not have improved remediation effectiveness. As long as substantial amounts of DNAPL persist in the subsoil, it will continue to slowly dissolve into the groundwater, buffering the groundwater CAH concentrations at high levels.

2.3.5 Fifth interim report

From April to September 2004 the average pumping rate was 29 - 34 m³/d. After 678 days of pumping, 13700 m³ of groundwater had been removed according to the report. An estimated total mass of 385 kg CAHs was removed with it. Remark: the report leads to some confusion regarding the total pumping rate. Wells 16 and 17, both deep wells, have separate counters. The sum of reported rates of these wells is larger than the reported influent rate of the purification plant. Another Point of attention was that pumping on the deep screens of wells 16 and 17 leads to undesired vertical migration of the groundwater pollution.

The drain was resampled in June 2006 and did not contain CAH levels exceeding detection limits anymore. In September 2006, however, another sampling of the drain showed CAH concentrations (sum) of 240 µg/L.

The fifth interim report for the first time contains individual pumping well concentration measurements (12 January 2006). Wells F1, F11, F5 and F14 were sampled. These wells showed groundwater concentrations of the same order of magnitude as measured at the beginning of the remediation (October 2003). The wells primarily contained PCE (10 - 40 mg/L). The report proposed to sample the three pumping strains individually in order to evaluate which strains yield the highest CAH concentrations.

The individual pumping well sampling revealed that highest measured CAH-levels were measured in the rear (excavated area): 42 PCE mg/L in F5.

This interim report (n°5) mentions (for the first time) – correctly – that the pollutant mass present in the subsoil had been underestimated, and that a significant portion of it is associated with the solid soil phase (adsorbed/residual DNAPL).

Furthermore, it is suggested to conduct further soil investigation. Obviously, it would have been far better to have conducted such investigations *before* starting remedial actions.

2.3.6 Sixth interim report

This report covers the period October 2005 - February 2006. The average groundwater extraction rate had been increased to 35 - 37 m³/d. On 20 February 2006 a total volume of 21730 m³ of groundwater had been pumped. The reported estimated pollutant mass removed was 540 kg CAHs.

This amount of removed mass seems considerable, but when it is compared to roughly estimated total mass present in the subsoil, it is clear that this is not so. The total mass can be approximated based on (1) the total water-saturated polluted soil volume; (2) the average CAH groundwater concentrations within that volume; (3) the average organic matter content of the soil and (4) Koc's of the CAHs; (5) soil bulk density.

For PCE alone, the following mass estimate may be obtained:

Estimated impacted soil volume (m ³)	Assumed average groundwater concentration (mg/L)	Assumed average OM (%)	logKoc	Calculated mass dissolved in the groundwater (kg)	Calculated mass adsorbed to the solid phase (kg)
31500	20	1	3.2	220	10400

This estimate does not include (residual) DNAPL potentially present as a separate liquid phase in the soil pores in the pollution source areas.

2.3.7 Seventh interim report

This report covers the period March - November 2006. Continued groundwater pumping yielded an estimated average mass removal rate of 0.3 kg CAHs per day. In the conclusions formulated in the report, this is still being defined as "good mass removal rate". However, observing no decrease of CAH concentrations, neither in the influent nor in groundwater samples taken from monitoring wells, the report proposes to switch to another soil remediation technology. By the end of December 2006 the pump & treat therefore was terminated.

2.3.8 Feasibility study and pilot test ISCO

The reported ISCO lab-tests indicated that:

- o "the pH buffer capacity of the soil is elevated";
- o the soil permanganate demand of the soil is 1.4 to 11.2 g/kg. At larger depths the oxidant consumption is larger than at smaller depths.
- o It is proposed to use Fenton's reagent in the source zone areas, followed by anaerobic bioremediation through organic substrate injection.

In the ISCO pilot using Fenton's reagent, executed inside the building in an expected source zone area, 8 injectors (4 shallow: screened 2-3 m bgl and 4 deep: 8-9 m bgl) were used, installed in an area of 6x6 m near the existing monitoring well MW303. Also a set of vapour extraction wells were installed (Figure 13). Two additional MIP probings had revealed that the CAH pollution primarily resides at a depth of 8 - 9 m bgl, just above a less-permeable soil layer. At 6 – 7.2 m bgl, a soil sample collected during these MIP-probings, had a PCE concentration of 35 mg/kg dm.

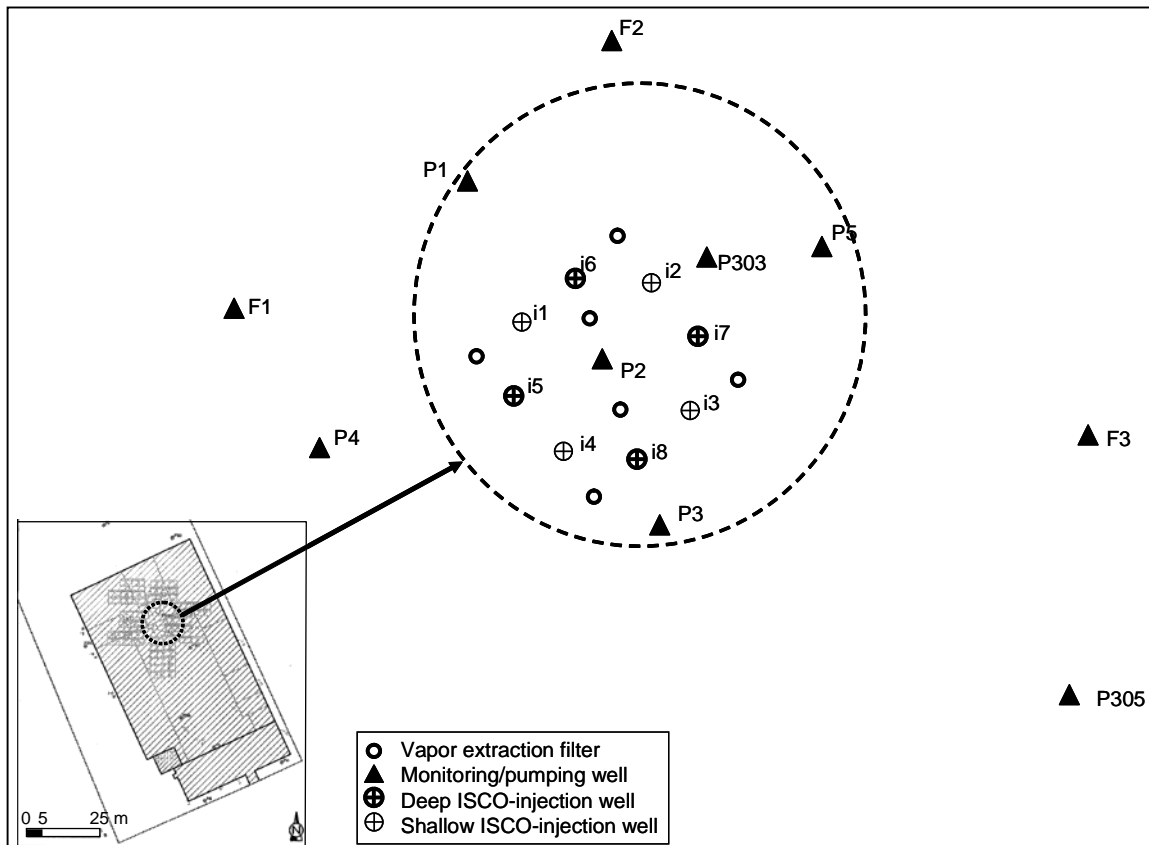


Figure 13. ISCO pilot test set-up (source: report 2007)

On 27 September 2007 approximately 1330 L of 12.5% Fenton's reagent was injected within 3 hours. The surrounding wells were sampled every 30 minutes and presence of peroxide tested (indicator strips). Peroxide was detected in these wells, and it was concluded that the peroxide had effectively reached the complete pilot area. Remark: it has not been proven that the full saturated soil volume has been homogeneously treated; the migration of the peroxide may have been limited to some more narrow soil layers with higher permeability.

From 28 September 2007 to 3 October 2007, about 18 m³ of hydrogen peroxide with catalyst was injected at 0-0.7 bar. H₂O₂-concentrations in the pilot zone were reported to have reached 10 to 12%. In the deep injection wells, somewhat larger amounts could on average be dosed than in the shallow injection wells. This agrees to the somewhat larger permeabilities observed at the larger depth, with respect to the more shallow soil:

- in the deep wells I5 - I8 (8-9 m bgl) resp. 2.1; 3.6; 4.1 and 2.1 m³ of oxidant was injected;
- in the shallow wells I1 - I4 (2-3 m bgl) resp. 0.4; 2.7; 2.3 and 0.6 m³ of oxidant was injected.

The pH in the monitoring wells was in the range 4.5-6.1. In the injection wells the pH remained low after application (3.7), rising to pH 5 after 34 days after application. This indicates that the pH can be adequately lowered to values that allow application of Fenton's reagent.

Peroxide and iron concentrations in the monitoring wells reached their maxima on 1 October (average values 70 and 84 mg/L, respectively). In the vapour extraction wells elevated CO₂ and O₂ levels were detected with respect to pre-test measurements. This may be due to oxidation of organic material in the subsoil and partial autolysis of the peroxide (unwanted loss of peroxide that is transformed to water and O₂). This reaction is significant when pH's are not sufficiently low.

Three monitoring campaigns were performed during the test. During the second sampling, 8 days after peroxide injection, smaller CAH concentrations were measured than during the first sampling (prior to the test: 'T0') and last monitoring round (34 days after peroxide injection). This was interpreted as observed destruction of CAHs. Remark: *temporary dilution effects may also explain this* (since a large CAH-free aqueous solution was injected). During monitoring round three, even higher CAH levels were measured than at T0: prior to ISCO the average CAH-concentration in the pilot area was about 100 mg/L; 8 days after ISCO this was about 20 mg/L and 34 days after ISCO about 125 mg/L. This 'rebound', to even higher concentrations than at T0, can be partially explained by the increased temperature (as a result of the exothermic Fenton's treatment) and the destruction of OM with adsorbed CAHs (releasing more CAHs into the groundwater phase).

The increase of chloride concentrations in the pilot zone groundwater was believed to confirm that substantial destruction of CAHs had occurred. However, it is also a possibility that chloride has been co-injected together with the Fenton's reagent (chloride-content of the injected liquid was not reported). The fact that the soil volume treated during the pilot test is not 'closed', complicates an accurate estimation of the CAH-destruction realized within that volume. It is recommended to continue the Fenton's treatment using the existing pilot system in order to answer remaining questions regarding the efficacy of the ISCO and evaluate potential larger-scale use of it at the site.

2.4 General conclusions

1. The soil remediation that has been executed at this site involved a pump&treat, aimed at removing the CAH groundwater pollution and attain low concentration targets. Earlier research has already demonstrated that P&T is not an optimal method to reach such goals¹⁹. Due to their limited water solubility but large volatility, a multi-phase extraction technology focussed on mass removal via the vapour phase leads to better CAH mass reduction in the treated subsoil. In the case studied here, the source zone area dimensions (e.g. near monitoring wells MW303 and 306, and the zone at the back of the site) should have been better characterized *before* remediation start-up. More borings should have been executed, combining PID screening and chemical analyses, as well as active and/or passive soil gas measurements (unsaturated zone) in order to locate the "hot-spots" of the pollution.
2. The source zone in the rear of the site had been recognized as such, and partially excavated. Owing to the absence of infrastructure here (after demolition), this was an effective CAH mass-removal method. However, the excavation had been limited to 2.5 m bgl, while DNAPL was also present deeper. It would have been technically feasible to excavate to larger depth, although it is still uncertain how deep exactly the DNAPL is present.
3. The frequency of CAH groundwater monitoring during the on-going remediation was too large. From 27 October 2003 to 7 December 2004 the monitoring wells were sampled and analysed five times. Taking into account travel times and distances between wells, it may have been recognized that no significant change could have occurred within that short time frame. At no instance groundwater and pollutant travel times were assessed/reported in the interim reports.
4. The CAH-target concentrations proposed in the remediation plan were far too ambitious (and in fact unrealistic). The same was true for the estimated total remediation duration.
5. The groundwater extraction rates as foreseen in the remediation plan (10 m³/h) were too optimistic; in practice hardly 1.6 m³/h was attained with the installed system. The mass removal realized by the pump&treat system was incorrectly interpreted in the first number of interim reports: they were described as being "substantial". If the mass removal is compared to realistic estimates of total CAH mass present however, it can be concluded that the mass removal realized by the pump and treat was in fact only marginal. Not earlier than in the 6th interim

¹⁹ Evaluatie bodemsaneringswerken en bodemsaneringsprojecten (www.ovam.be/jahia/Jahia/pid/635).

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- report, a correct conclusion was formulated (that P&T had been ineffective in removing CAHs from the subsoil). By the end of 2006 the P&T was subsequently halted.
6. The total time required to reach target concentrations had been set to 5 years (remediation plan). In practice, the P&T was ceased after about 3 years (by then 40600 m³ of groundwater had been pumped from the subsoil). CAH groundwater concentrations as observed in monitoring wells had not decreased in any significant way during that time. Only after a drastic PCE-DNAPL removal (>90%) significant groundwater concentration reductions may be expected, since PCE concentrations are being buffered by continuous dissolution of PCE from (residual) DNAPL²⁰.
 7. During the pumping, realized capture zones nor travel times were assessed, although this should have been done if the CGP for P&T (available at that time at www.ovam.be) had been followed. A regular measurement of water levels in groundwater monitoring and extraction wells would have allowed an evaluation of the hydraulic captation zones and travel times inside the contaminated soil/groundwater volume. After P&T was shut down, no further groundwater flow direction measurements were executed. The flow direction had been incorrectly determined during previous investigations; it was claimed to be Northerly, while a Southerly direction is expected. The CAH-plume might therefore exceed site boundaries in that direction. It is recommended to perform further measurements with this respect.
 8. Another observation in this remediation project is the negative effect caused by pumping of groundwater in two deep wells (screened to 16 and 17 m bgl). Goal of this pumping was “to remove the DCE-pollution present at those depths”. The actual result was an increase of CAH concentrations at those larger depths due to an induced vertical migration of polluted groundwater by the pumping.
 9. This case reconfirms the unsuitability of P&T as a mass removal technology for subsurface CAH pollutions. A thorough characterization of the pollutant mass present (using an adequate number of borings and representative sampling) is a prerequisite to correctly evaluate in-situ remediation efficiency.
 10. The reported ISCO pilot using Fenton’s reagent has been well conducted, but results obtained are still insufficient to be able to decisively determine if ISCO is suitable for full-scale use (leading to efficient CAH mass removal at reasonable costs). The consultant recommends a full-scale ISCO treatment in the DNAPL-source zones, followed by reductive dechlorination by organic substrate injection. Studies are indeed available acknowledging this possibility²¹. An important factor of success however may lie in the redox-buffering capacity of the aquifer material (which could be very high considering the large amounts of iron present in the subsoil in this case). If redox buffering is significant, much oxidant will be required to first oxidize the subsoil to a degree that a substantial amount of the CAHs are destroyed. Afterwards, much organic substrate will be needed to adequately reduce the subsurface again, in order to obtain conditions suitable for reductive dechlorination²². Considering the scale of this CAH pollution, we highly recommend to first assess such remediation strategy on a lab and pilot scale. First the ISCO pilot should be continued until its efficiency can be proven and rebound is no longer observed in the pilot zone. It is also recommended to monitor extracted vapour phases by PID measurements and chemical analyses.

²⁰ “Studie betreffende de bodemsanering van stedelijke VOCl verontreinigingen” (www.ovam.be/jahia/Jahia/pid/915).

²¹ E.g.: Hrapovic L, Sleep BE, Major DJ, et al., 2005. Laboratory study of treatment of trichloroethene by chemical oxidation followed by bioremediation. *Environmental Science & Technology* 39 (8): 2888-2897

²² E.g.: Chapelle FH, Bradley PM, Casey CC, 2005. Behavior of a chlorinated ethene plume following source-area treatment with Fenton’s reagent. *Ground Water Monitoring and Remediation* 25 (2): 131-141

3.1 Site investigation and soil remediation plan

The observed CAH-groundwater pollution at this site is described in a soil remediation plan developed in 1999²³. Since 1984 a production facility for cleaning products was present at the site. Groundwater analyses in 1997 had demonstrated a CAH pollution in the groundwater, primarily consisting of TCE. In 1998 and 1999 a phased soil and groundwater investigation was conducted. The final report concluded that the pollution had been completely delineated, and that the major part of the pollution resided at depths of about 3.5 m bgl., to a maximum depth of about 10 m bgl. The overall polluted area was estimated to be around 5000 m².

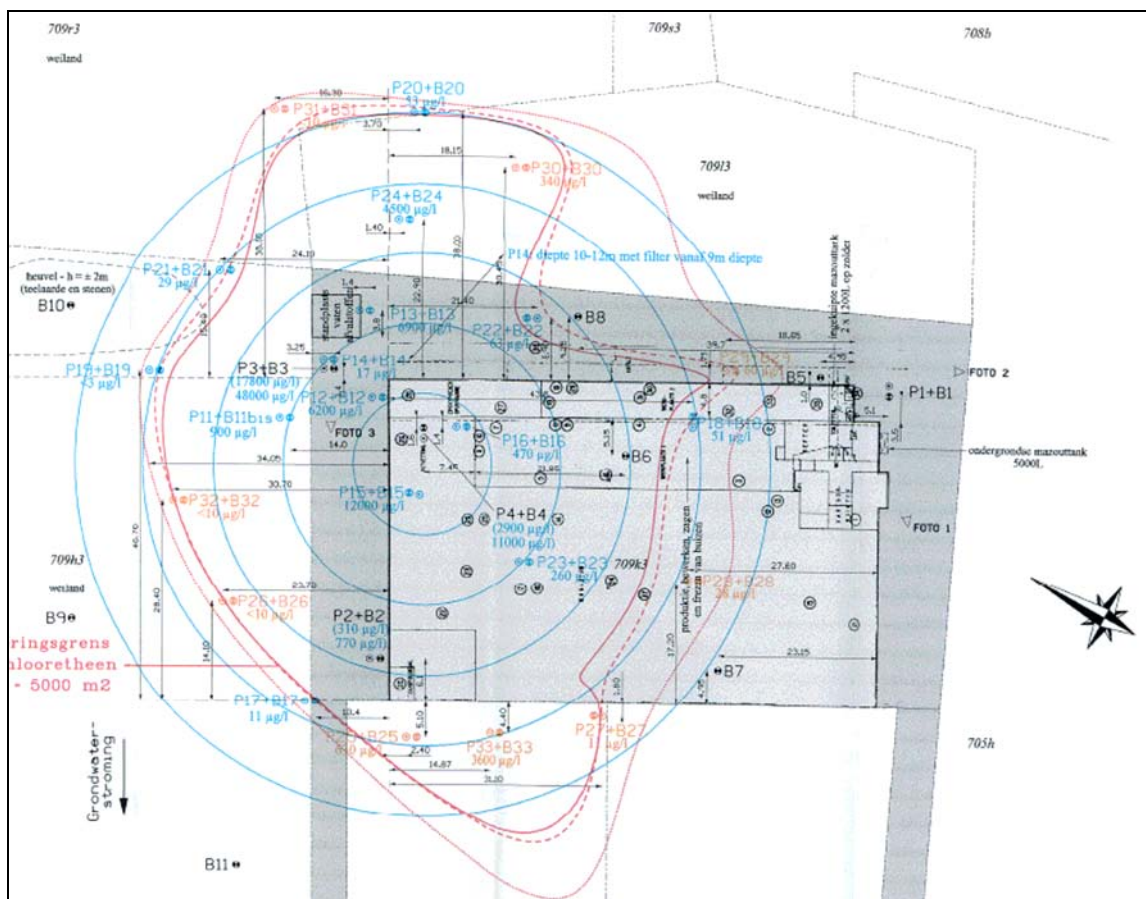


Figure 14. Plan of the site with indicated groundwater pollution contours and concentrations (plan copied from descriptive site investigation available).

²³ "Bodemsaneringsproject in het kader van overdracht van het perceel te Kortrijk met kadasternummer 8^{ste} afdeling (Heule) Sectie B nr. 709h3 en 709k3" (29739_BS01_mdc.doc), 30 July 1999

The “source area” was believed to be located at the Northern side of the building (light grey in Fig. 14), where groundwater concentrations of up to 44000 µg/L TCE were reported. The groundwater flow direction, according to these reports, was Southerly or Easterly.

Site investigation reports mention the existence of a groundwater pumping well for local use, supposedly present in the northern part of the building. This pumping well was used occasionally, according to the reports, and was reported to have had an influence on local groundwater flow direction. It is also mentioned that, upon analysis, high CAH levels had been detected after which the pumping well was shut down.

During the last phase of the site investigation, elevated TCE levels were measured at a neighbouring site (monitoring wells PP33 and PP25; parcel 709a3; containing TCE concentration levels of 3600 and 630 µg/L, respectively).

Conductivity tests were performed in two monitoring wells and the reported average conductivity established was 0.038 m/d. The estimated horizontal groundwater velocity was estimated to be 1.27 m/y.

The soil remediation plan listed the following technical possibilities to remove the pollution:

1. Dual phase extraction combined with air sparging (52 extraction wells screened at 1 to 6 m bgl. Well diameters were 75 mm for dual phase wells and 125 mm diameter for deep wells. In total 9 of the planned 52 wells were designed as deep wells). The calculated groundwater extraction rate in the remediation plan was 3 to 5 m³/h. Pumped water would be purified using a stripping unit and activated carbon. The design mentions a planned soil vapour extraction rate of 300 m³/h. Additionally, air sparging would be executed in 17 injection wells of 10 m depth and 25mm diameter, screened “between 5 and 10 m bgl” according to the remediation plan. Air would be injected at a rate of max. 50 m³/h at max. 8 bar. Estimated total remediation duration was 20 months. Remediation target levels were set to 80% of groundwater concentration limit values (e.g. 56 µg/L TCE).
2. The same as alternative “1.”, however without the use of air sparging. This remediation alternative included instalment of 45 groundwater extraction Wells screened between 2 and 8 m bgl. Remediation duration was supposed to be 24 months in this case, with the same target levels;
3. Air sparging combined with soil vapour extraction. This option involved 27 sparging wells screened at 4-5 m bgl and 36 soil vapour extraction wells screened at 0.5-1.5 m bgl. Three individual pumping units (“INSAAN 100/9p”) of 180 Nm³/h at 180 mbar were part of this design. Estimated remediation time needed with this design was 3 years according to the plan. Remediation targets were identical as alternatives 1 and 2.

The soil remediation plan concluded that alternative 1 was the best choice. The remediation plan did not evaluate other potential technologies such as in-situ chemical oxidation (ISCO) or bioremediation. At that time these technologies were however not yet commonly accepted as relevant remediation alternatives for CAH pollutions.

The remediation plan did not include a detailed monitoring plan to evaluate remediation performance and groundwater quality. It merely mentions that “after execution of the remediation, an annual groundwater sampling and analysis of the source-zone monitoring well will be executed to establish that no groundwater pollution remains”.

Evaluation of the soil remediation plan:

The remediation plan is incomplete. It contains insufficient information about the pollution, more specifically the estimated pollution mass present and contours of the source zones (containing DNAPL). It also lacks a monitoring plan to evaluate remediation efficiency. The remediation technique opted for, however, is suitable in general to remediate CAH pollution source zones.

3.2 Start of remediation

Two interim reports were produced²⁴ about remediation activities executed between May 2000 and December 2001. The remediation was reported to be installed according to the proposed plan, and started in December 2000. Until 28 November 2001 in total 4050 m³ groundwater had been pumped, with an average rate of 11 m³/d. No rates nor cumulative mass removal realized by soil vapour phase extraction were reported. It is not clear if vapour phase extraction was performed nor is it clear if air sparging (as proposed in the soil remediation plan) was executed. What is clear from the interim reports is that the TCE-concentration in the extracted groundwater (overall influent) initially was 1270 µg/L after start-up, increasing to 3920 µg/L in April 2001 and then decreasing to 300 µg/L after 1 year of pumping. Some sets of pumping wells however produced higher CAH concentrations (up to 26,2 mg/L).

The second interim report states that about 10.5 kg CAHs were removed from the subsoil by the remediation system, and that another 4.4 kg of CAHs remained to be removed at that moment. Another 1.2 to 1.5 years were claimed to be needed to remove this remaining CAH mass. These calculations obviously were incorrect (CAH mass adsorbed to the solid soil phase were not taken into account, nor CAHs potentially present as a DNAPL phase).

A groundwater monitoring campaign was executed and reported in the second interim report. The results were (mistakenly) interpreted as that the pollution had decreased in intensity and size (calculated plume area prior to remediation: 4875 m² with max. 50 mg/L TCE in the source zone; after one year of remediation claimed to have been reduced to 4507 m² with a maximum of 10 mg/L TCE).

At the end of 2001 the remediation activities were suspended because of bankruptcy of the firm financing the remediation (Afriglass).

3.3 Continuation of remedial activities (under the auspices of OVAM)

Preparations to restart the remediation were reported in 2004²⁵.

The existing network of extraction wells was checked by the contractor. Forty-nine **extraction wells** were still operational. **Eleven air sparging wells** were still present, of which 2 were damaged. These were replaced. One **deep well** that had been used during the previous remediation phase (presumed depth: 10 m bgl) turned out to be still intact. This deep well was also taken back into operation.

Air sparging wells present were screened from 9 to 10 m bgl. The 49 extraction wells were subdivided into 9 clusters. Air sparging wells and the single deep well had separate control (steering per individual well).

Additional new monitoring wells, screened at 3-5 m bgl were also installed (see Fig. 15). On 12 November and 3 December 2003 a monitoring campaign was completed (establishing groundwater concentrations before remediation restart: "T0"). The groundwater table then was at about 3 m bgl. Relatively low CAH levels were measured, as compared to previous measurements. MW105 contained the highest TCE-level (4400 µg/L). Other monitoring wells showed lower concentrations (below soil remediation standards for wells 101, 102 and 103 and slightly exceeding those limits in wells 100, 104 and 106).

On **3 December 2003** the remediation was restarted. From 3 December 2003 to 9 January 2004 groundwater was extracted using the deep well (average rate 2.07 m³/d) and the dual phase system (average rate 10.6 m³/d). On 10 December 2003 the groundwater extracted by the dual phase influent contained 780 µg/L TCE and the influent of the deep well 1710 µg/L TCE.

²⁴ "Tussentijds verslag I" and "Tussentijds verslag II", refs: BS_29739_BS02_nvt.doc (27 June 2001) and BS_29739_BS03_nvt.doc (5 April 2002).

²⁵ "Milieukundige begeleiding installatie sanering Afriglass Kortrijk te Heule", R001-9512471PMA-C01, 16 februari 2004.

The dual phase system was operated at underpressures of 0.3 to 0.5 bar. Reported extracted vapour rates were 0.3 to 15.5 m³/u.

In the period 2004-2006 several interim reports of the remediation activities were submitted to OVAM²⁶. On 23 August 2006 also another site investigation was reported.

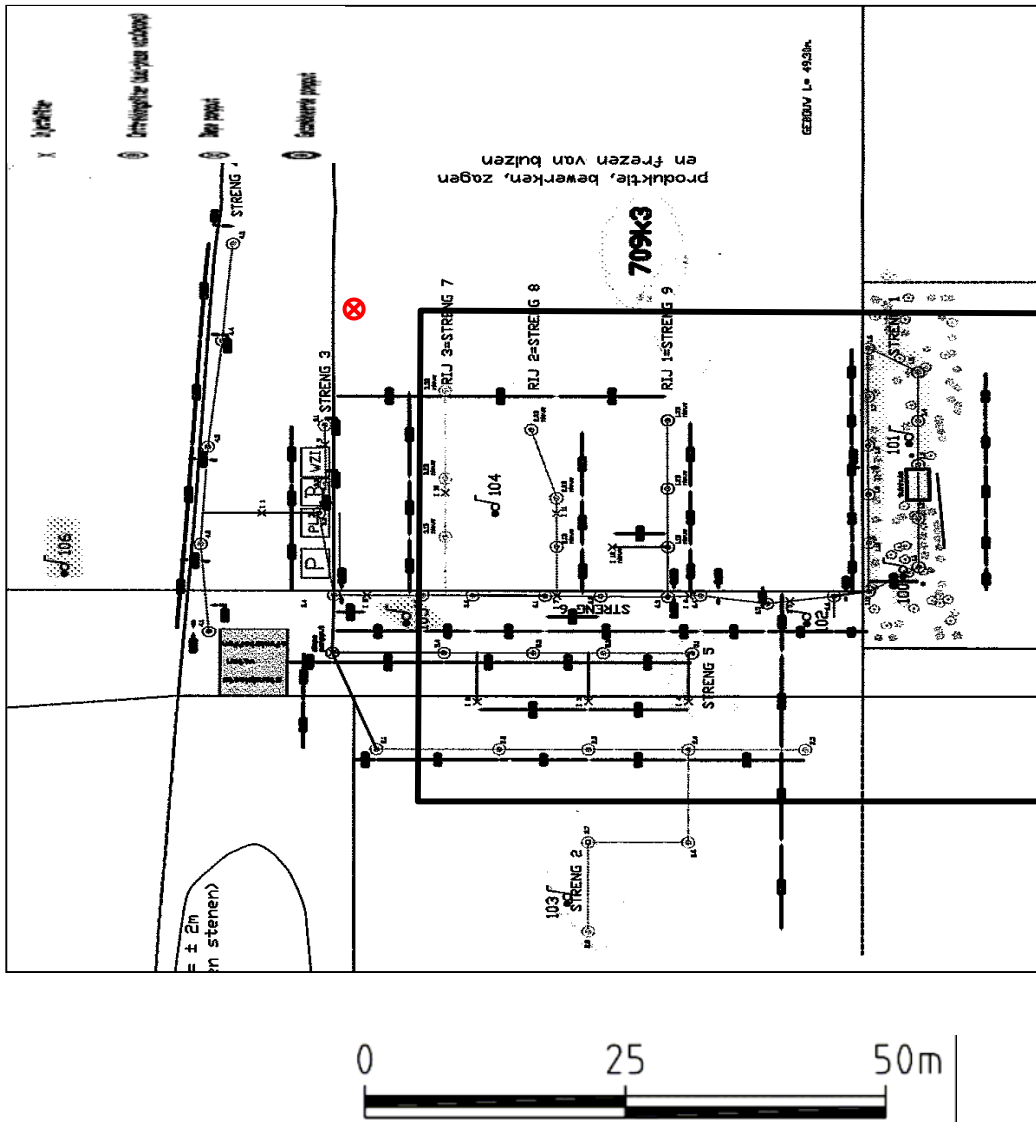


Figure 15. Schematic plan of the site (as copied from interim reports available) indicating monitoring and remediation wells. The deep well is indicated as red circle.

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- "Milieukundige begeleiding Afriglass Kortrijk te Heule – tussentijds rapport", 16 August 2004
- "Milieukundige begeleiding Afriglass Kortrijk te Heule – tussentijds rapport", 28 February 2005
- "Milieukundige begeleiding Afriglass Kortrijk te Heule – tussentijds rapport", 26 August 2005
- "Tussentijds verslag sanering Afriglass Kortrijk te Heule", 21 March 2006

3.3.1 Interim report August 2004

According to the interim report, a total of 2764 m³ of groundwater was extracted between remediation restart and 16 June 2004, of which 621 m³ from the deep well. The average groundwater extraction rate via the deep well was 3.18 m³/d; the average groundwater extraction rate realized by the dual phase was 10.94 m³/d. The reported average extracted vapour phase rate was 2 m³/h between 6 January 2004 and 25 March 2004. After then (owing to a drop of the average groundwater level) vapour phase extraction rates increased drastically to averagely 37 m³/h (25 March – 24 June 2004). The cumulative extracted vapour volume was 106320 m³ on 24 June 2004. Pollutant concentrations in the extracted vapour phase were monitored using PID. The PID readings were transformed to TCE concentrations (taking the response factor of the PID into account). From 3 December 2003 to 16 June 2004, eleven such PID measurements were conducted. Results varied from 0 to 305 ppm, with an average of 94 ppm. The corresponding pollutant mass removal via the vapour phase extraction realized from restart to 24 June 2004 was thus estimated to be about 70 kg. In the vapour phase effluent (activated carbon filter) PID recordings were close to 0 ppm.

On 9 March 2004 and 25 June 2004, additional chemical analyses of the extracted vapour phase were done using activated coal adsorption tubes. Observed concentrations were 0.036 and 0.009 g/Nm³ in the influent (and 0.0003 and 0.0004 g/Nm³ in the effluent).

Using PID, calculated TCE-concentrations were 2.2 g/m³ (13 February); 0.11 g/m³ (25 March) and 0.71 g/m³ (16 June). *These values are much larger than the concentrations obtained using the adsorption tube procedure.* The interim report concludes that the chemical analysis results were incorrect due to condensation water in the influent phase. No further efforts were done to investigate the exact reasons for this difference.

Via the extracted groundwater (dual phase + deep well) a CAH recovery was calculated of about 3.45 kg over the same period of time.

Groundwater samples were taken from the 5 monitoring wells every three months (see further).

3.3.2 Interim report February 2005

Between March 2004 and January 2005 the average vapour phase extraction rate was 42 m³/h. The total (cumulative) volume extracted was 419086 m³ according to this report. At 5 occasions PID measurements were done in the influent vapour phase. An average read-out of 49 ppm was recorded (minimum: 33 ppm, maximum: 86 ppm). Based on those results, calculated removed pollutant mass until then, by the vapour phase extraction, equalled 145.11 kg CAHs. Effluent vapour phase PID-readings were 2 to 2.5 ppm (4 measurements between August – October 2004) and 0 ppm in December 2004. On 11 January 2005, another chemical analysis (one within that period) was collected on the vapour phase influent. The result was a CAH-concentration of 0.54 mg/Nm³ which again was much lower than expected based on the PID measurements. Again, the result of the chemical analysis was rejected (on the same arguments: interference when using the adsorption tubes, due to water condensation).

Since remediation restarted, until 17 January 2005, 5454 m³ of groundwater was pumped up, of which 1026 m³ from the deep well. The average water extraction rate from the deep well was 2.46 m³/d. The average water extraction rate from the dual phase system was 10.74 m³/d. Based on influent CAH-concentration measurements, a calculated mass removal of 6.23 kg CAHs was realized via the water phase.

3.3.3 Interim report August 2005

Between 11 January and 14 June 2005 an average vapour phase extraction rate of 27 m³/h was recorded. In total (start to July 2005) an extracted vapour phase volume of 520396 m³ was reported.

In March, May and June 2005, another set of influent vapour phase measurements with PID were executed. Results were 33, 17 and 14 ppm, respectively. Based on PID measurements it was calculated that, over the total remediation period, **176.45 kg CAHs should have been removed by via the vapour phase.**

From December 2003 to July 2005 a total volume of 7115 m³ of groundwater was extracted, of which 1635 m³ using the deep well. The average extraction rate was 2.75 m³/d. The average water extraction rate pumped by the dual phase system was 9.24 m³/d. The cumulative amount of CAHs extracted via the water phase over that period was **11.25 kg.**

3.3.4 Interim report March 2006

Until 27 January 2006 the total volume of groundwater extracted equalled 8967 m³, of which 2429 m³ by the deep well. The average extraction rate using the deep well was increased to 5.1 m³/d between June 2005 and January 2006. The average water rate pumped via the dual phase, on the other hand, was lowered to an average 3.7 m³/d. Based on groundwater influent concentrations (see further for an overview), a calculated mass removal (via the water phase extraction) of 22.5 kg CAHs had been realized.

From 14 June to 27 January 2006 an average vapour phase extraction rate of 15 m³/h was realized. A total of 605301 m³, extracted vapour phase volume via the dual phase system, was reported.

Concentration levels observed in the influent vapour phase (detection tubes) were 4 mg/Nm³ (17 August 2005) and 24 mg/Nm³ (13 December 2005). A PID-measurement yielded a level of 27 ppm (195 mg/m³) on 22 August 2005. The total CAH mass removal realized via the vapour phase (until 27 January 2006) was reported to be 195 kg.

In this interim report it is proposed to halt the dual-phase extraction but to continue the groundwater extraction from the deep well, and to also continue air sparging. It was furthermore recommended to perform additional site investigations to study soil and groundwater quality in the direct vicinity of the deep well. A further sampling of existing monitoring wells was also recommended to evaluate a potential rebound of CAH groundwater concentrations. If rebound would be observed, it was suggested to consider additional remedial actions, such as a stimulation of natural attenuation.

Evaluation:

- The extraction of groundwater using the deep well has obviously resulted in an accelerated migration of dissolved TCE from a source zone (containing DNAPL) present at unknown exact location at the site. Additional site investigation will be necessary to try to locate it.
- Increasing the groundwater extraction rate from the deep well during the last months of the remediation seems to have further increased attracting groundwater containing large dissolved TCE concentrations. Pumping groundwater from deep wells to remove CAHs from soil systems impacted by DNAPL is not efficient, as discussed before. It may be an effective containment strategy, but that was not intended here. The recommendation to continue the deep well extraction therefore seems inappropriate.
- The recommendation to continue air sparging without simultaneous soil vapour extraction neither is advisable: injected air may migrate in an uncontrolled manner, eventually discharging, loaded with CAHs, into outdoor or indoor air.
- Regarding the air sparging conducted as part of the remediation: no details are reported in the interim reports (injection volumes, pressures per sparging well, frequency,...).
- Induced groundwater migration during remediation (piezometric mapping, radius of influence) was never reported, although this is recommended by the CGP for P&T.
- Observed groundwater concentration trends (as observed by regular sampling of the monitoring wells screened at 3-5 m bgl) are presented in Figures 16 and 17. In monitoring well 105, TCE concentrations have decreased by a factor of 5. However, in well 100 the TCE level remained more or less constant. TCE levels measured in groundwater extracted from the deep well (representing groundwater from the deeper subsoil) contains much higher TCE levels than those from the 3-5 m bgl monitoring wells.

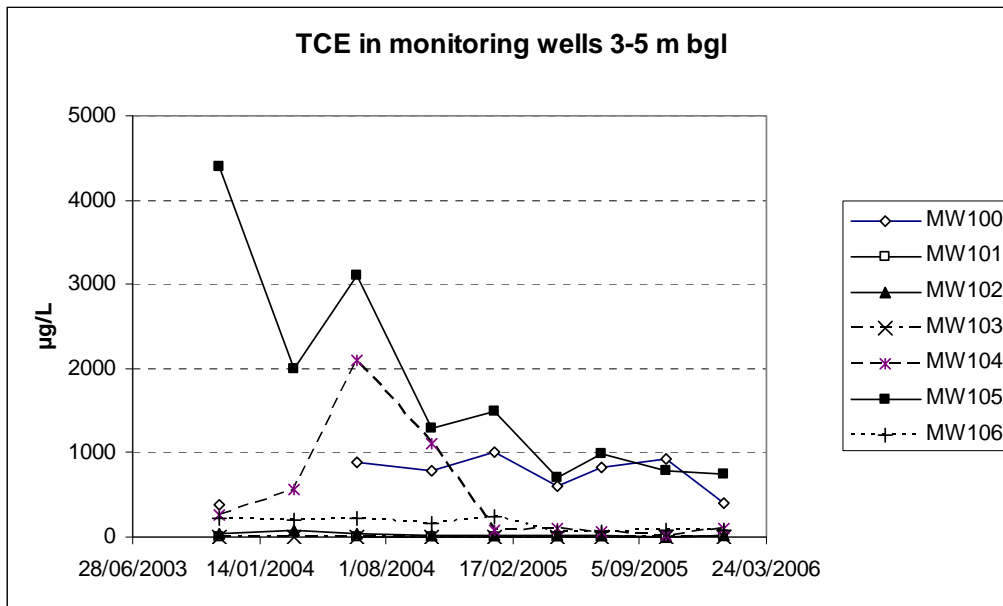


Figure 16. Observed groundwater concentrations of TCE in monitoring wells during remediation (source: interim reports).

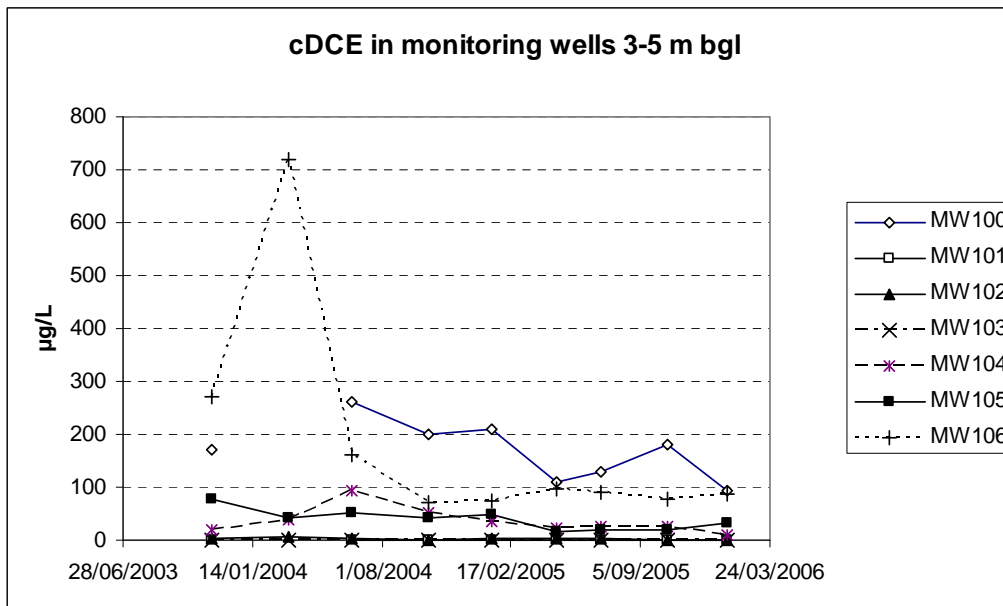


Figure 17. Observed groundwater concentrations of DCE in monitoring wells during remediation (source: interim reports).

3.3.5 Final monitoring report (2007)²⁷

On 3 May 2006 the dual-phase extraction was shut down. By then, estimated total pumped volumes by the dual-phase system were 7031 m³ groundwater and 686943 m³ vapour phase. Estimated CAH recovery via the vapour phase then was 200 kg.

As proposed in the previous report, the deep well groundwater extraction was continued, at an increased pumping rate of about 11 m³/d. By 13 April 2007 in total 4812 m³ of groundwater had been extracted from the deep well. Accordingly, an estimated total mass of 46.3 kg of CAHs were removed since pumping from the deep well was commenced.

The air sparging was also continued during the first three months 2007, without soil vapour extraction.

The groundwater quality in the monitoring wells was not further studied in the period February 2006 – April 2007.

The interim report concludes with the following recommendations:

- Shut-down of the deep well groundwater extraction;
- Start monitored natural attenuation, additionally considering ISCO in case DNAPL-source areas are still found to be present.

Evaluation:

- CAH concentrations in groundwater pumped up by the dual phase system varied considerably (Figure 18) during remediation, ranging between about 100 µg/L and 1300 µg/L. At later stage of the dual-phase, average concentrations in the influent decreased.
- Short-term CAH concentration variations in groundwater pumped up from the deep well varied much less than observed in the dual phase (Fig. 19). At remediation start-up, the TCE-concentration was about 2000 µg/L. Later on, concentrations steadily increased, accelerating in the course of 2005. The average concentration then levelled off to about 10 mg/L.
- Figure 20 shows the TCE-to-DCE ratio as a function of time. This ratio equalled about 10 in 2004 and in the beginning of 2005, to increase afterwards. This increase can be explained by increased attraction of TCE from a TCE-DNAPL zone.
- In the dual phase influent no trend is visible in the TCE:DCE-ratio. An average ratio-value of about 10 was observed (Fig. 21).
- As mentioned in the previous paragraph, it was not a good idea to shut down soil vapour extraction while continuing air sparging. To which extent this has led to uncontrolled migration of volatilized CAHs towards the atmosphere is not known.
- The recommendation to consider ISCO is reasonable. This however requires additional feasibility testing (see study case 2) *in the CAH source area(s)*. The pollution source probably is NOT located at close proximity of the deep well, for it took some time before increased TCE levels effectively reached the deep well. An additional site investigation is needed to try to locate DNAPL-source zone(s) and to delineate it three-dimensionally.

²⁷ Milieukundige begeleiding van de sanering op het terrein van Afriglass te Kortrijk, concept report, 30 May 2007.

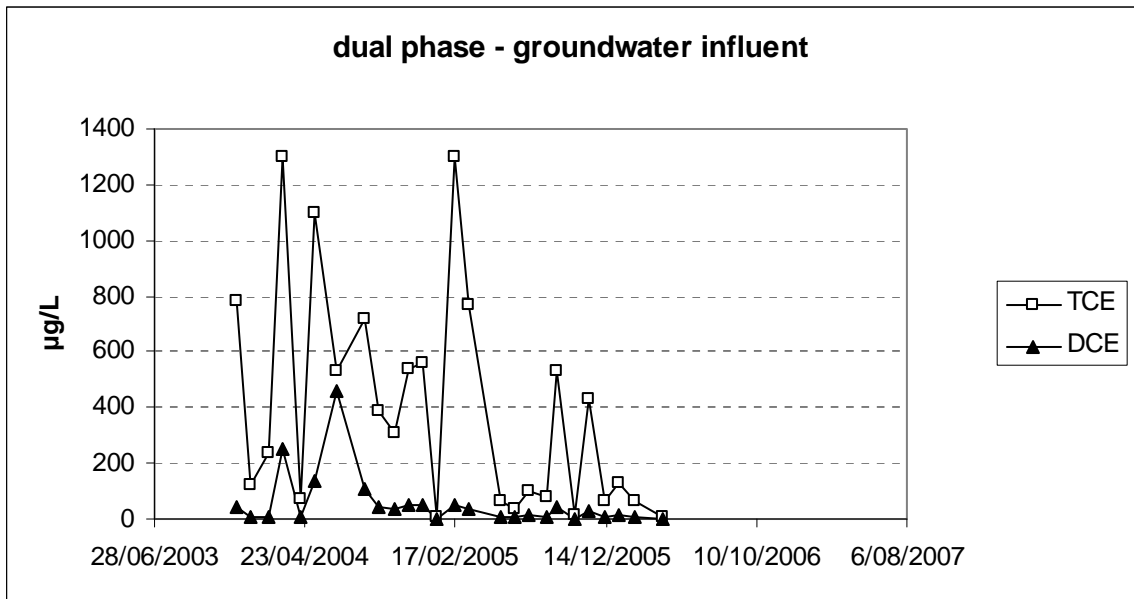


Figure 18. Observed groundwater concentrations of TCE and DCE in the extracted groundwater from the dual phase system (source: interim reports).

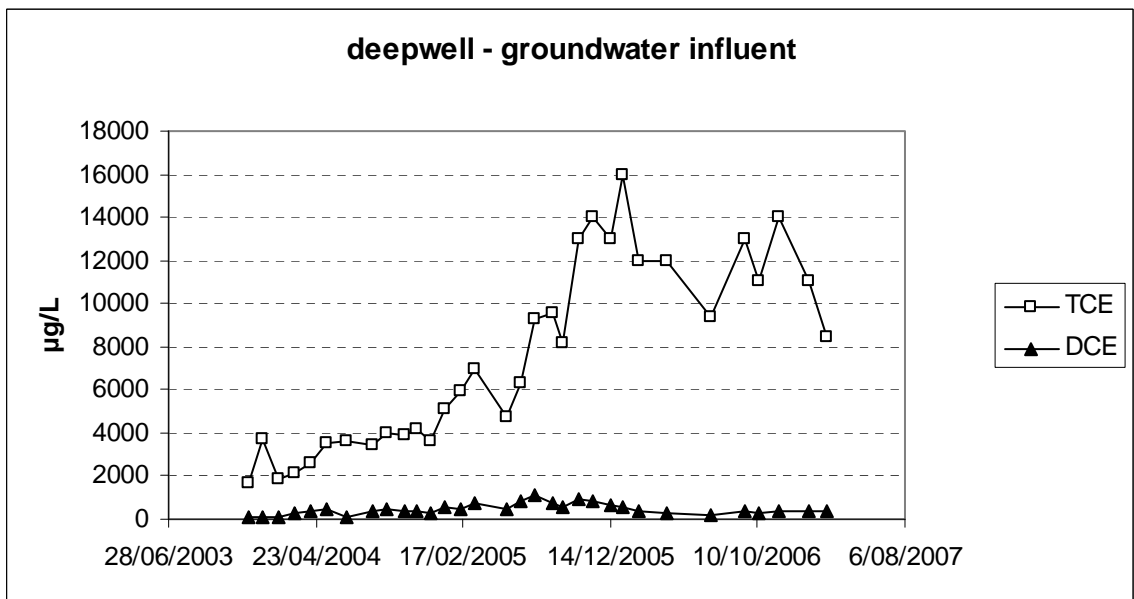


Figure 19. Observed groundwater concentrations of TCE and DCE in the extracted groundwater from the deep well (source: interim reports).

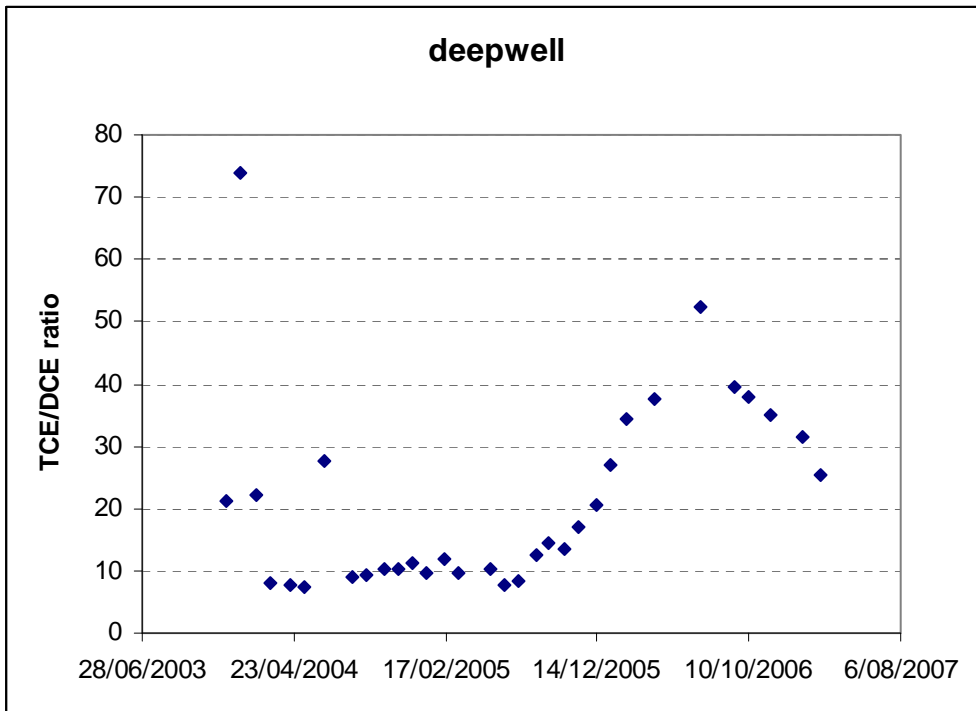


Figure 20. Calculated TCE-to-DCE ratio in the extracted groundwater from the deep well (source: calculated from TCE and DCE analysis data available in interim reports).

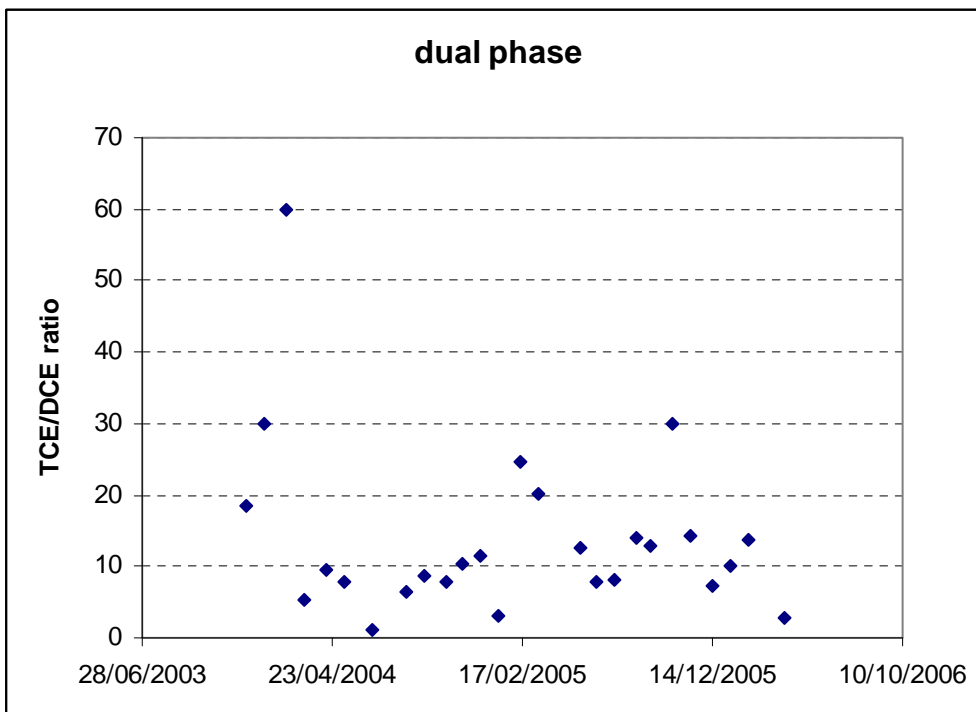


Figure 21. Calculated TCE-to-DCE ratio in the extracted groundwater from the dual-phase extraction (source: calculated from TCE and DCE analysis data available in interim reports).

3.4 Actualized soil and groundwater investigation and suggested further research (April 2006 and May 2007).

On 22 June 2006 a set of monitoring wells were resampled as part of an additional site investigation (report of 23 August 2006). Sampled monitoring wells are indicated in Figure 22.

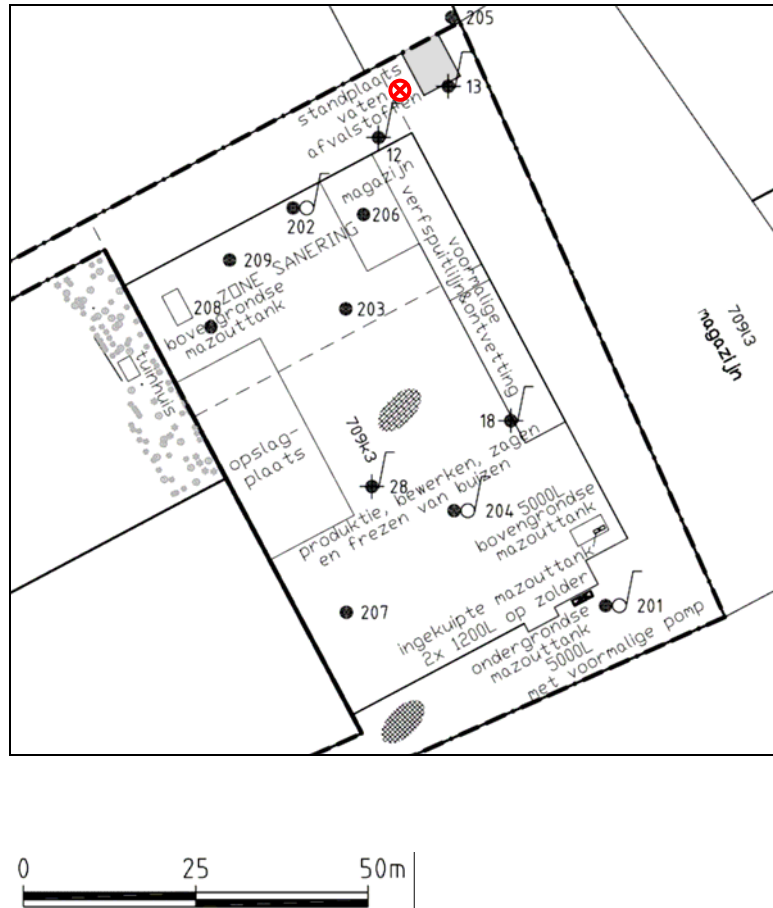


Figure 22. Site map indicating resampled monitoring wells in June 2006. The deep well location is also indicated (red circle).

Table 3. Results of resampled monitoring wells in June 2006

Monitoring well number and screen depth in m bgl	TCE ($\mu\text{g/L}$)	DCE ($\mu\text{g/L}$)
201 (1-3)	0.2	<0.1
202 (1,5-3,5)	21	0.6
204 (1,5-3,5)	33	0.5
12 (1-3)	200	6.1
13 (1-3)	5000	3200
18 (1-3)	5.5	<0.1
28 (1-3)	29	0.7

Monitoring well 13 had the highest TCE and DCE concentrations. This well is located near the deep well.

Considering these results, as well as the large influent concentrations that were observed in the deep well, the consultant proposed to conduct a further study to investigate soil and groundwater quality in the deeper soil layers in the vicinity of the deep well. One deep boring on the neighbouring parcel had suggested the presence of confining clay at about 20 m bgl. At depths of 9 to 15 m bgl another more clayey layer was claimed to be present.

More specifically, it was proposed to install:

- One boring to 10 m bgl, next to the deep well, to obtain a detailed soil profile and to take soil samples for CAH-analysis from directly above the clay layer at 9 -15 m bgl, if present.
- One deep monitoring well, screened at 14-15 and 17-18 m bgl, and take soil samples at approximately 10, 15 and 18 m bgl.
- Three monitoring wells around the deep well (screening depths depending on observations).

3.5 General conclusions

- CAH concentrations in the more shallow groundwater seem to have decreased, generally spoken, as a result of the executed remediation. However, the concentration limit values, as preset in the remediation plan, have by far not been reached;
- Groundwater pumping from the deep well was not useful and instead, has probably caused further migration of the TCE-plume containing high concentrations;
- CAH groundwater concentrations measured at larger depths are considerably larger than concentrations at lower depths. The remediation efforts have not been very effective in that respect.
- Additional investigations are needed to try to locate DNAPL-source zone(s) and to delineate it three-dimensionally.
- This case study once again shows, as for the other two sites studied, that it is not a good idea to start remedial actions prematurely, at a moment when there are still significant uncertainties, e.g. three-dimensional distribution of the pollution mass in the subsoil. In cases that it is technically not feasible to find DNAPL source areas, it is more advisable NOT to opt for a mass removal strategy but to choose a long-term containment strategy. The latter is only necessary in cases where the CAH pollution plume is expanding and threatening potential receptors.

The following general conclusions can be formulated regarding the soil and groundwater remediation executed at the three sites studied:

1. all remediations were started prematurely: at a moment that the pollution had not yet been sufficiently mapped (and no sufficient distinction had been made between source zones (containing residual DNAPL) and plume zones. In general, when using an in-situ remediation technology and evaluating its efficiency, it is essential to compare removed pollutant mass with total pollutant mass initially present. It is therefore essential to spend enough (investigation) efforts prior to starting remedial actions, in order to obtain a realistic estimate of pollutant mass present.
2. Pump & treat is not an efficient remediation technology for CAH-mass removal (if, as in most cases, DNAPL source zones are present). Groundwater extraction from deep wells screened deeper than the actual CAH pollution leads to downward migration of dissolved CAHs and should be avoided. Likewise, groundwater extraction from wells located at some distance from actual DNAPL source zones, leads to increased horizontal migration of dissolved CAHs and must be avoided, unless the pumping is a chosen strategy to provide hydrological containment of CAH plumes (but not as an attempt to remove CAH mass from the subsurface!);
3. Dual phase (“multi-phase”) extraction - either combined with air injection (“sparging”) or not – is an efficient mass removal strategy for CAH source zones present in soil compartments not too deep below groundwater levels. Most of the pollutant recovery occurs via the gas phase. In the cases studied however, the mass removal realized by the soil vapour extraction was inadequately assessed. A better (on-line) monitoring of in- and effluent extracted gas phases (active carbon filters) is recommended. Sampling of the spent activated carbon is useful to measure recovered CAH masses.
4. It is essential to focus dual phase extraction to the source zones only (and not to the plume areas). When installing extraction wells, it is recommended to use that opportunity to also additionally evaluate soil quality (PID-screening, soil and groundwater analyses) and get extra information about the pollution intensity present. The number of extraction wells and their surface density (number of wells per unit of surface area) may be changed (with respect to the original plan) based on such additional results. It is therefore recommended that the remediation consultant is present during installation of the wells
5. CAH pollutions are in general difficult to remediate. A combination of techniques will be necessary. E.g., after dual-phase extraction source zone treatment, it is possible to use the same wells for secondary plume treatment (e.g. by injecting an organic substrate into them to induce further biological reductive dechlorination).
6. In situations where deeper DNAPL-zones are present, dual phase recovery may not be feasible. Other source zone treatment technologies should be evaluated in such cases, such as ISCO or detergent/co-solvent flushing. In cases where DNAPL-source zone removal is technically not feasible, it is recommended to choose a containment strategy.
7. In cases 2 and 3, total subsoil CAH mass present was underestimated; (2) in all cases remediation time scales needed were underestimated and (3) all remediation plans had unrealistic target concentrations set. It is recommended NOT to focus on reaching certain target concentration levels, but to focus on risk-removal and obtaining a “stable” situation in which concentrations are declining and/or the contaminated soil volume is no longer expanding. Such a risk-based approach was recently adopted by “Vlabotex” (Fund for the remediation of drycleaning sites in Flanders), is to focus on source-zone removal and subsequent more passive plume remediation (MNA, bioremediation,...). A manual (Code of Good Practice) is available (in Dutch) at <http://www.ovam.be/jahia/Jahia/pid/1785>.