SN-004

In-situ bioremediation of contaminated groundwater by Funnel & Gate

Evaluation test phase, Lijnbaan/Westeinde at The Hague

dr. G. Lethbridge B.Sc. Ph.D.(Shell, Global Solutions)
prof. J.F. Barker (University of Waterloo)
ir. B. Satijn (SKB)
ing M.P.M. Koenraadt (Ingenieursbureau 'Oranjewoud' B.V.)
ir. D. Tijdeman (Ingenieursbureau 'Oranjewoud' B.V.)
ir. A.D. Rooden (Ingenieursbureau 'Oranjewoud' B.V.)

October 2003

Gouda, SKB

Stichting Kennisontwikkeling Kennisoverdracht Bodem

Report title
In-situ bioremediation of contaminated groundwater
by Funnel & Gate
Evaluation test phase
Lijnbaan/Westeinde at The Hague

SKB report number
SN-004

Project report number
SN-004

Author(s)
dr. G. Lethbridge
prof. J.F. Barker
ir. H.M.C. Satijn
ing. M.P.M. Koenraadt
ir. D. Tijdeman
ir. A.D. Rooden
ing. J. Hullegie

Number of pages
Report: 90
Number of Appendices: 9
Maps: 10

Executive organisation(s) (Consortium)
Shell, Global Solutions (dr. G. Lethbridge B.Sc. Ph.D.)
University of Waterloo (prof. J.F. Barker)
SKB (ir. H.M.C. Satijn)
Ingenieursbureau 'Oranjewoud' B.V (ing. M.P.M. Koenraadt, ir. D. Tijdeman, ir. A.D. Rooden)
Municipality of The Hague, Department of urban management
Technical University of Delft

Publisher
SKB, Gouda

Abstract
Due to spillages and leakages on a petrol station, in operation from 1948 up to 1984 on the site Lijnbaan/Westeinde in the Hague, mineral oil and hydrocarbons have caused a soil contamination. In 1984 part of the contamination was excavated, but residual contamination was still implicating risks for environment. Therefore a funnel and gate system was installed to control and remediate the emissions from the residual contaminants. The report presents the set up, results and conclusions and recommendations of the test phase, one year after installing and getting into operation of the system.
The funnel consists of a sheet piling up to a depth of 6 mtr –gl. with a length of totally 21,5 mtr. The gate consists of a subsurface biological treatment unit with inlet and outlet construction.
Due to natural groundwater flow and supported by extraction of groundwater in the treatment unit followed by infiltration of the effluent upstream, groundwater is forced to pass the “hot spots” with residual pure contaminants. The contaminated water flows guided by the funnel into the treatment unit. In the treatment unit a combination of sand filter, biotreatment and settling tank is taking care for treating the water.
Leaching out the contaminants seem to be a slow process. The performance of the bioreactor is good; the capacity is more than enough. Optimization of groundwater flow and operation of the treatment unit are very well possible.

Keywords

Controlled terms
bioreactor, leaching, mineral oil,
volatile aromatic hydrocarbons

Uncontrolled terms
biotreatment, extraction,
Funnel and gate system, infiltration

Project title
In-situ bioremediation of contaminated groundwater
by Funnel & Gate

Projectmanagement
Oranjewoud, ir. D. Tijdeman

This report can be obtained by: SKB, PO Box 420, 2800 AK Gouda, The Netherlands
Netherlands Centre for Soil Quality Management and Knowledge Transfer (SKB)

Titel rapport	SKB rapportnummer
Biologische sanering van verontreinigd grondwater op locatie door middel van “Funnel & Gate” Evaluatie testfase Lijnbaan/Westeinde te Den Haag	SN-004 **Project rapportnummer** SN-004

Autheur(s)
dr. G. Lethbridge
prof. J.F. Barker
ir. H.M.C. Satijn
ing. M.P.M. Koenraadt
ir. D. Tijdeman
ir. A.D. Rooden
ing. J. Hullegie

Aantal blzadzijden
Rapport: 90
Aantal bijlagen: 9

Kaarten: 10

Uitvoerende organisatie(s) (Consortium)
Shell, Global Solutions (dr. G. Lethbridge B.Sc. Ph.D.)
Universiteit van Waterloo (prof. J.F. Barker)
SKB (ir. H.M.C. Satijn)
Ingenieursbureau 'Oranjewoud' B.V (ing. M.P.M. Koenraadt, ir. D. Tijdeman, ir. A.D. Rooden)
Gemeente Den Haag, Afdeling Stedelijk beheer
Technische Universiteit Delft

Uitgever
SKB, Gouda

Samenvatting
Als gevolg van gemorste en gelekte stoffen bij een tankstation dat in gebruik was van 1948 tot 1984 op de locatie Lijnbaan/Westeinde in Den Haag is er ter plaatse bodemverontreiniging ontstaan met minerale olie en koolwaterstofproducten. In 1984 is een deel van de verontreinigde grond afgegraven, maar een restverontreiniging leverde nog steeds milieurisico’s op. Daarom is er een “funnel and gate”-systeem geplaatst om de uitstroom van de restverontreiniging te controleren en saneren. In het rapport wordt verslag gedaan van de voorbereiding, resultaten en conclusies en aanbevelingen van de testfase, een jaar na plaatsing en ingebruikname van het systeem.
De doorstroomopening (funnel) bevindt zich in een plaat tot een diepte van 6 meter onder het maaiveld met een totale lengte van 21,5 meter. De ondoorlatende schermwand (gate) wordt gevormd door een ondergrondse biologische behandelingsinstallatie met een inlaat- en uitlaatconstructie.
Als gevolg van de natuurlijke grondwaterstroom in combinatie met de onttrekking van grondwater in de behandelingsinstallatie, gevolgd door infiltratie van de bovenstroomse afvalwaterstroom, wordt het grondwater langs de plaatsen geleid waar zich nog hoge concentraties verontreinigende reststoffen bevinden. Het verontreinigde water stroomt via de doorstroomopening de behandelingsinstallatie binnen. In de behandelingsinstallatie zorgt een combinatie van zandfiltering, biobehandeling en een bezinktank voor zuivering van het water. Het uitfilteren van de verontreinigende stoffen lijkt een traag proces. De werking van de bioreactor is goed; de capaciteit is meer dan voldoende. Optimalisering van de grondwaterstroom en gebruik van de behandelingsinstallatie zijn zeer goed mogelijk.

Trefwoorden

Gecontroleerde termen:	Vrije trefwoorden:
bioreactor, uitfilteren, minerale olie, vluchtige aromatische koolwaterstoffen	biobehandeling, onttrekking, “Funnel and gate”-systeem, infiltratie

Projecttitel	Projectleiding
Biologische sanering van verontreinigd grondwater op locatie door middel van “Funnel & Gate”	Oranjewoud, ir. D. Tijdeman

Dit rapport is te verkrijgen bij: SKB, Postbus 420, 2800 AK Gouda, Nederland

Nederlandse Stichting Kennisontwikkeling en Kennisoverdracht Bodem (SKB)

CONTENTS

SUMMARY

In-situ bioremediation of cantaminated groundwater by Funnel & Gate

1. Background information

Introduction

In the Western part of the Netherlands in the Hague a petrol station caused soil contamination due to leakage of petrol products. A consortium with Shell International, the Municipality of the Hague, Technical University of Delft, SKB and Oranjewoud investigated the case and proposed to install a F&G system to remediate the site. After implementation a test phase of one year (the year 2000) has been introduced to test the performance of the system and to prepare recommendations for the exploitation of the system.
In this report the approach, results and recommendations of the test phase are presented.

Description area of investigation

The area of investigation is situated at the corner of the Lijnbaan and Westeinde in The Hague (picture S1). A petrol station was situated at this location in the period 1948-1984. During this period petrol products have been leaking into the subsoil, causing soil contamination with BTEX and mineral oil as principal contaminants. Presently the area serves as a public garden and is bordered by roads. The garden has a surface area of 1,200 m^2.

Picture S1. Site Lijnbaan/Westeinde.

Up to a depth of about 16.5 m –gl. the soil profile consists of moderately fine to moderately coarse sand with thin clay layers at a depth of about 8 m –gl. The permeability of the sand package varies between 5 and 20 metres/day. Below this sand package the “Basis Veen” (Peat) is situated with a considerable resistance, separating the Holocene upper layers with the Pleistocene aquifer underneath.
The average water table is approx. 1,5 m –gl. The shallow groundwater flows in south-eastern direction at a rate of 10 to 20 metres per year. The vertical flow rate is about 1 metre per year.

Description of the soil contamination

Initially three spots with contaminated soil were discovered and investigated. In 1984 part of the contaminated soil was excavated within a sheet piling construction, followed by a pump and treat system during a short period of time.

Investigations showed that at several locations pure product is left behind in the soil (see figure 0.1). Horizontally, the solved product in the groundwater plume was found downstream up to 10 metres of the retention zone. In vertical direction the plume has migrated up to a depth of about 9 m –gl.

During the test phase the most important retention zone has been delineated more accurately, by making use of two specialised methods, the differentiated extraction method and the dynamic monitoring method. The product occurs in an area of 125 m^2 at a depth between 2 and 4 m –gl. The highest concentrations of mineral oil and BTEX measured in the retention zone are respectively 1.000 - 5.000 and 100 – 1.000 mg/kg.dm. Peak loads in the groundwater are respectively 10 and 100 mg/l.

Remediation of the residual contamination was considered urgent in view of the actual spreading risks. On 16 December 1998 the Municipality of The Hague ordered to implement the remediation phase 2, starting with the first step by applying a modified F&G system. Objective of remediation is to attain the Dutch intermediate values for volatile aromatics and mineral oil in the groundwater entering the gate. As soon as this objective has been achieved active remediation can be stopped and a passive remediation based on natural attenuation combined with monitoring of the plume will be sufficient.

2. F&G principle and description of the system

The intention of F&G is to increase the groundwater flow through a hot spot and to canalise the contaminated groundwater in between funnels (isolating walls) to a gate (figure S1). The gate is a reactive zone or treatment facility, in which contamination is being degraded and/or immobilised. The original F&G principle is based on a ***passive*** extensive approach, making use of the natural groundwater flow and the attenuation capacity of the soil as much as possible. The energy to pass the F&G is provided by the natural groundwater flow.

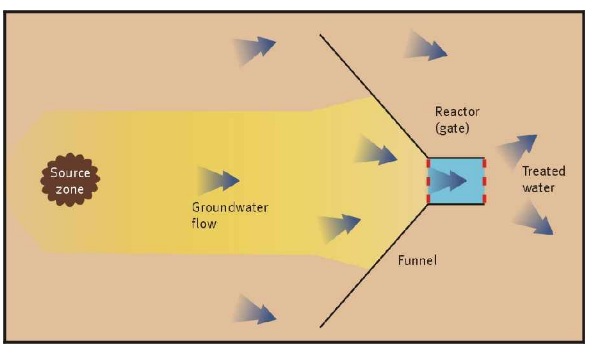


Fig. S1 Original Funnel and Gate principle

In The Hague an alternative ***active*** system had to be applied (figure S2). The retention zone is being flushed in a forced way in order to achieve the remediation objective within a period of 30 years. This is achieved by infiltration of water in the retention zone and by extraction of water in the gate. Infiltration and extraction was necessary due to the gentle natural slope of the phreatic groundwater. Together with the impossibility to lower the water table too much at the site (due to the sensitivity to land subsidence), it means that it is necessary to pump the water around in such a way that the groundwater drawdowns are limited.

Secondly, contaminated groundwater is treated in a bioreactor, constructed in the gate instead of being treated in bioscreen filled with soil or sand. In this way there is more control on the resistance and the processes in the gate.

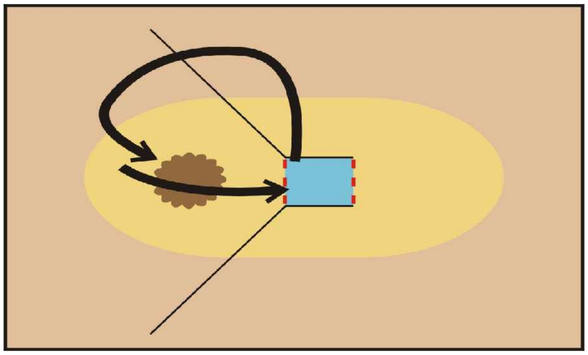


Fig. S2. The active F&G principle.

The system has been installed at the transition from the source zone and the plume. In this way no additional contaminants will reach the plume, which was formed before remediation. The residual contaminants in the plume will thus being degraded by natural attenuation processes.
The position of the funnel and the gate, as well as the location of the most important retention zone is shown in figure S3 and on drawing 17856-I-4.

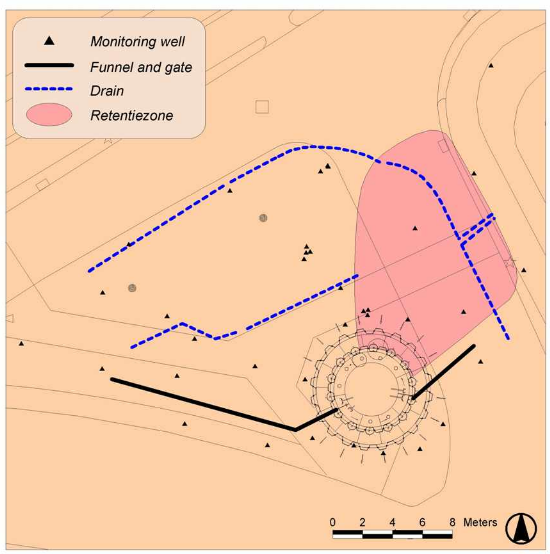


Fig. S.3. Position of the F&G system and the source zone.

The position of the system has furthermore been determined by the presence of above ground and underground infrastructure, the location of the retention zones and the groundwater flow. In view of the underground infrastructure at Westeinde, it was not possible to enclose the most important retention zone totally.
The funnel has been installed on a thin resisting layer at a depth of about 8 m –gl. This layer has a moderate resistance, so the funnel is not closing off the plume completely. It is a so-called hanging funnel.

The treatment system in the gate consists of pre-treatment (de-ironing, sand filtration), a bioreactor (with and without carrier material) and a polishing filter (sand filtration). Infiltration of the effluent in the plume is possible in order to stimulate biological degradation in the plume.

Main objectives of the testing phase

The system has been installed mid 1999. In the year 2000 the system has been tested and investigations have been conducted. The main objectives of the test phase were to get insight into functioning and optimisation of the following elements:

- the groundwater pattern initiated by the system;
- the interaction between groundwater, the retention zone and the plume, especially the leaching behaviour from source to plume;
- the water treatment in the gate.

3. Interaction between retention zone and plume

The interaction between the retention zone and the plume is rather complex. The oil products in the retention zone forms a source, emitting BTEX and mineral oil into the unsaturated soil by evaporation and into the saturated zone by dissolving, forming the contamination plume. The emission process towards the groundwater is determined by the diffusion processes in the pure product and by the transfer processes at the interface between pure product and groundwater. In the source the contaminants are distributed over several zones, determining by the diffusion, dissolving and emission processes:

- The residual zone with small blobs distributed well over the soil particles and thus forming a big interface between product and ground water. This residual zone can be situated in the unsaturated or saturated zone, depending on the site specific circumstances and the history of the leakage;
- The floating layer, floating on the water table and going up and down with the season. It is a continuous pure product zone (big blob) with less interface and thus a limited emission towards the plume;

The distribution of the pure product over the distinguished zones in relation with the groundwater flow and groundwater table determines the interaction between source and plume. This has also its influence on the permeability of the retention zone.

Permeability

It is known that due to the presence of pure product less soil pores are available for flowing of the groundwater. Measurements have shown that at this site permeability in the retention zone is reduced with more than 50%. As a result increase of the groundwater flow is less effective as theoretically expected due to the decreased permeability. Water has the tendency to pass around the source.

Water table

The water table determines also the contact area between pure product and groundwater. The supply of contamination to the plume is increasing as the water table is higher and as a result the interface is bigger.
Consequently, the emission to the plume is partly determined by the water table and fluctuating in time. At low water table the supply to the plume may even be negligible.

4. Estimated remediation period

An important design criterion is that the active remediation has to be completed within a period of 30 years.

The remediation period is defined as the period with active mitigative measures to achieve a groundwater quality in the plume at the gate equal to about 50% of the intervention value (for xylenes35 μgr/ltr). At present the concentration is 1.000 – 10.000μgr/ltr).
Understanding of the leaching behaviour of product has further developed in the meantime (NOBIS 95-2-11, Restrisk, SKB SV-415, Model Code), showing that the flow rate is not the only determining factor for the remediation period. The leaching of a source is complex with a mix of diffusion, dispersion, dissolution, adsorption and dissorption and geo- and biochemical reactions.
In phase 1 of the flushing process contaminants are dissolved at the interface pure product-groundwater. This emission is high in the mobile zones of the source, especially where pure product is finely distributed over the soil, so in the residual contaminant zone. Increasing of the groundwater velocity will increase the mass of contaminants removed.
Gradually in phase 2 the more mobile components are removed, the mobility of the components gets less and mobile zones are flushed. For mineral oil first the short chain aliphates (C8-C12) will get dissolved and gradually the longer chains (>C12) turn up slowly. The emissions towards the groundwater will get diffusion limitated; components will have to migrate through diffusion towards the interface and via stagnant zone towards the mobile zone of the saturated zone. The characteristics of the source is changing; "weathering" is taking place. Increasing the groundwater flow doesn't increase the mass removal. The emissions will decrease to such a degree that active pumping is no longer effective and needed. Hopefully the load in the plume is small enough to meet the remediation target and natural attenuation processes will eliminate the residual components downstream. Further migration of contaminants will no longer occur. This means that a stable final situation has been achieved, which is an important criterion in the new Dutch soil policy.

An important question is how much time is needed and whether this is achievable within a time period of 30 years.

During the test phase the retention zone was renewed only twice. The load in the gate can be called high and is fluctuating as a result of changes in the flow rate in the retention zone. Besides, no shift in the concentrations in the retention zone and the influent of the gate was observed. Consequently, the flushing process is still in an initial phase and an estimate of the contamination period is hard to provide.

To be able to provide an estimate, it is recommended to gather additional information from the source and the plume:

- An additional characterization of the source, determining the residual zones, floating layers if present, smear zones and the compact pure product zones; very interesting are the changes during the last years if determinable;
- The characterization of the oil components in the source zones and again especially the changes in time; how much of the mobile fractions have been leached out during last years and how much is still there;
- The characterization of the natural attenuation capacity of the plume zone.

In other NOBIS/SKB projects new concepts and models are developed and under development to predict the remediation period. Especially a Model Code of SKB-project SV-415 for modelling the behaviour of source and plume of mineral oil could be of help.

Another important question if measures can be taken to optimise the remediation process. This information refers to the infiltration of the treated water.
As a result of infiltration of water in the retention zone the concentrations and loads in the gate are high using drains 3 and 6. It should be noticed that infiltration has to take place <u>in</u> the reten-

tion zone. If not, the water has a preferred flow around or underneath the retention zone to the gate. Figure S.4 shows the difference in groundwater flow.
The recommended investigations in the exploitation phase will provide information on potential measures to optimise the source removal. One could think of extra dosage of surfactants, and warming up the drainage water for drains 3 and 6. At present the possibilities are limited due to the boundary conditions of the site. During the exploitation phase the optimum exploitation of the system will be investigated.

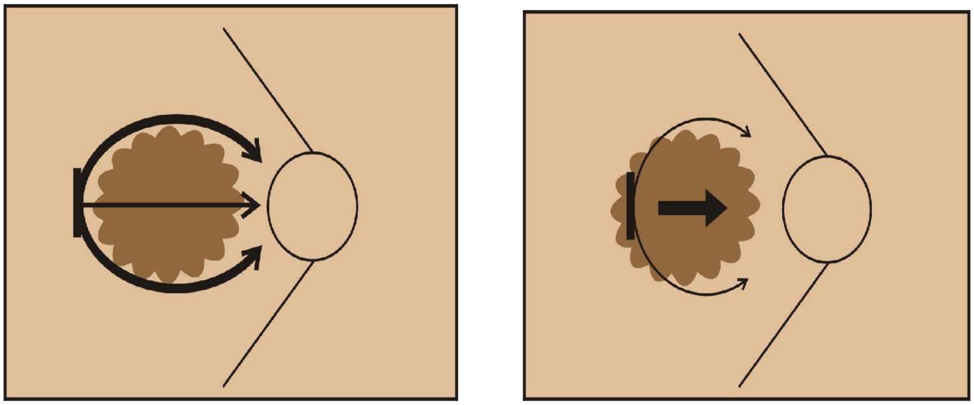


Fig. S4. Groundwater flow in and nearby a source zone.

By infiltrating effluent of the treatment system in the plume the oxygen content of the groundwater in the plume will increase and consequently the conditions for biological degradation will improve. Also residual nutrients and micro-organisms in the effluent assist in the biodegradation process in the plume.
The results of the test phase show that infiltration in the plume downstream of the gate has to take place intermittent. In case of continuous infiltration in the plume the velocity and direction of the groundwater flow behind the gate will change substantially thus endangering undesired spreading of contamination. Natural attenuation processes may be insufficient to prevent this spreading.

5. Groundwater flow

The sphere of influence of the F&G system is about 4 times the width of the system. This area of influence corresponds with the results of studies carried out in the past by the University of Waterloo.

The site specific conditions with a high water table and limited possibilities to allow a large draw down (risk for land subsidence), require an accurate management of the water table around the system with as most important criteria that:

- Maximum quantity passes the source;
- All flow lines passing the source do pass also the gate and no flow lines are passing around or underneath the funnel.

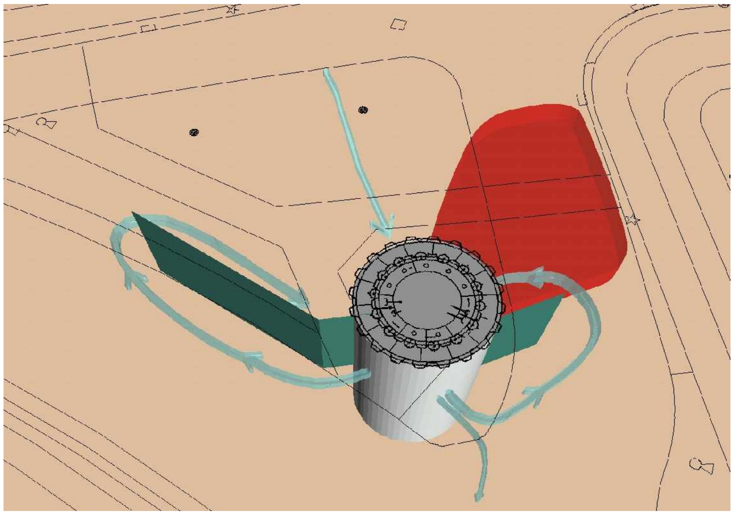


Fig. S5. Groundwater flow in case of infiltration in the plume.

For the time being infiltration is being limited by the shallow water table; at the location of the infiltration facilities; the water table can be raised with one metre only. As a result the infiltration drains can be infiltrated at a rate of 2 m^3/m^1 according to model calculations.

Figure S6 shows the groundwater flow as initiated by extraction and infiltration in the retention zone.

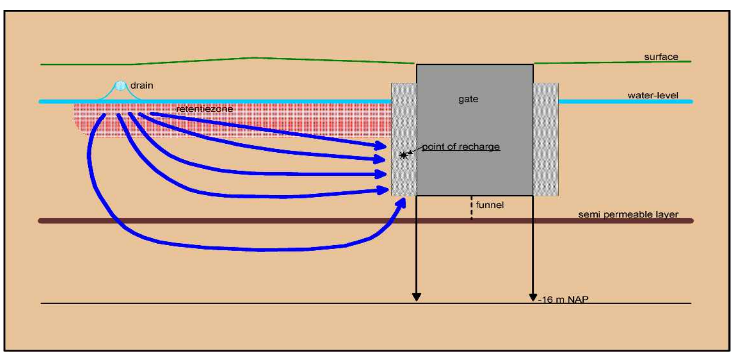


Fig. S6. groundwater flow in a cross section.

Concentration measurements actually show that in case of infiltration near the short wing of the funnel, flow around the funnel has taken place. Therefore, the length of the short wing, which is determined by the presence of cables and pipelines, limits the use of drain 6.

In the design it has been recognised that infiltration of water is a critical activity. For that reason the extraction and infiltration systems have been dimensioned largely. In the gate sand filtration has been applied to stop unsolved substances. After more than a year no indications of clogging of whatever nature have been observed.

The groundwater model applied during the design phase has been detailed and calibrated during the test phase. By geohydrological standards the differences in calculated and measured water tables can be considered as limited (< 0.25 metre). However, at detail level differences may be considerable. This is not surprising, considering the fact that in a limited area at different levels groundwater is being extracted and infiltrated and sharp contrasts in the permeability do occur (soil-funnel, inside and outside retention zone).

The lesson learned is that for other sites preference shall be given to a solid system in which the retention zone is being enclosed totally and the funnel is being installed on a separating layer.

6. Water treatment in the gate

The treatment system in the gate as applied in the test phase consists of pre-treatment (de-ironing, sand filtration), a bioreactor (with and without carrier material) and after-treatment (sand filtration). The results of the test phase show that the extracted groundwater has been purified totally. Very low concentrations of BTEX and mineral oil were measured in the effluent. Furthermore, nitrification has taken place in the installation, being a process which only occurs when easily oxidable organic compounds like oil components have been decomposed.

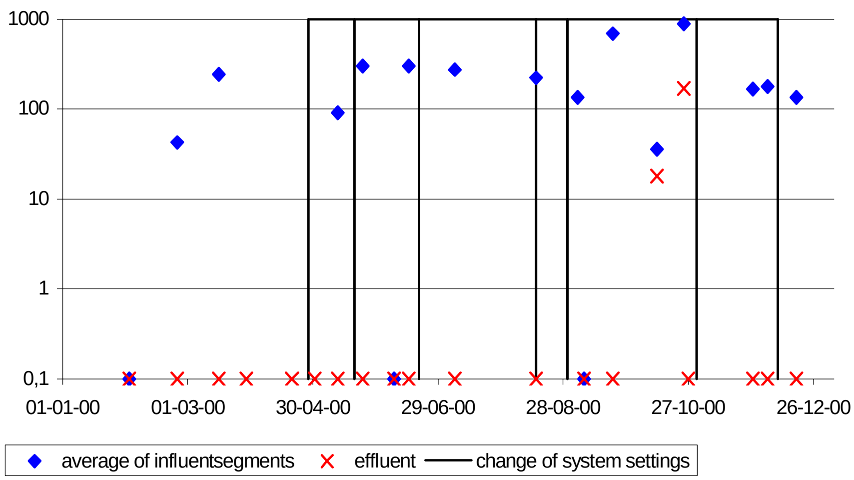


Fig. S7 Concentrations of benzene in influent and effluent.

Removal of substances mainly takes place during pre-treatment (de-ironing, sand filtration). The limited last step of the decomposition takes place in the bioreactor with carrier material. No degradation takes place in the open reactor, which can be explained by the low organic load and insufficient silt mass. Therefore, the silt-on-carrier bioreactor and sand filters, if necessary, need to be applied.

It can be concluded that the treatment system has been over dimensioned considerably. For an experimental set up, it provides a flexibility to optimise the design for future applications. In future F&G systems it can be much more simplified.

7. Feasibility of Funnel and Gate systems in the future

Remediation is a process of applying energy to extract and remove contaminants from soil and groundwater to reduce the risks involved.
Intensive remediation technologies, like excavation or steam injection, a lot of energy per m^3 contaminated soil in a short time is applied. Especially with hot spots at moderate depths with high concentrations these technologies are feasible. Lower concentrations and/or greater depths do match with more extensive technologies like enhanced biorestauration, pump and treat and F&G. These technologies require more time. If time is not a constraint and concentrations are low, than natural attenuation processes are feasible.

In general the best remediation strategy is built up upon a combination of the three groups of technologies, starting with the most intensive one to remove the hot spot as much as possible, to follow with an extensive technology to deal with residual contaminations in the source and the plume with as last step a monitored natural attenuation to polish the situation.
Remediation is a question of applying the appropriate energy in the right form on the right place and time, which determines the cost efficiency.

Selection of the remediation technology depends on a lot of site specific conditions. Among others soil and geohydrological conditions, type and distribution of contaminants (sources and plumes) over unsaturated and saturated zone, in LNAPL's or DNAPL's, present and future function of the site and surrounding, risk profile and desired risk reduction, time and space available.
F&G is a treatment technology in which the natural groundwater flow near a contamination source is canalised between two funnel walls and passes a treatment gate. Concentration of flow will increase the leaching effect on the source and desorbtion of contaminants will increase.

Conditions for application of F&G are:

- The groundwater flow is manageable; without too much detrimental effects and costs it is possible to canalise the flow through the source and between the funnel walls into the gate. Canalisation always requires energy; water table is rising before the gate and is dropping behind the gate to provide the energy to cope with the resistance in the system. In case of a passive system the natural groundwater system should allow this rising (see figure 0.8). Because of the resistance of the F&G system, the width of the funnel has to be larger than the width of the source to avoid short-circuiting of contaminated groundwater along the funnel.
  In case the unsaturated zone is limited or the width of the funnel is restricted, than a passive system is no longer feasible and pumping is required (see figure 0.9). By applying pumps in combination with infiltration drains and the valves in the gate it is possible to manage the flow and enhancing the remediation processes in the source;
- The source is leachable; mobilisation of (the mobile fractions of) the contaminants is possible. This means that the permeability of the soil is reasonable, also in the source, and adsorbtion forces are not too high;
- The contaminants in the plume are treatable in the gate. For aliphatic and aromatic compounds this is no problem by applying bioreactors. For chlorinated compounds like TCE and PCE iron walls are feasible solutions;
- Infrastructure on the site allows the construction and exploitation for a longer period of the F&G system.

Compared to Pump and Treat (P&T) the initial costs of F&G are higher and the exploitation costs may be lower. This will be the case if optimum us can be made from the natural groundwater flow and natural attenuation capacity. Extensive experience has been gained with P&T, while in America and Canada only recently insight is being obtained in the long-term exploitation costs of F&G systems. Various alternatives are being carried out presently showing increasingly positive results both from a technical and a financial point of view. More knowledge of and experience with long-term exploitation are being gained, since this technology will be applied more and more in full-scale projects.

Application of F&G systems in the future depends largely on site-specific conditions. The system built in the Hague was an experimental set up, with quite a lot of extra facilities to do experiments and to gain experience Compared to the system in the Hague in future F&G systems will be built much more simple, especially the gate. There it was necessary to construct an underground treatment facility. But an above ground bioreactor with standard facilities will be much cheaper in general.

8. Conclusions

The conclusions of the test phase can be summarised as follows.

Groundwater flow

- The differences between modelled and measured water tables can be considered as limited (< 0.25 metre). Although limited compared to geohydrological standards, it is still difficult to get a detailed picture of the streamlines around the funnels, due to the anomalies of these structures. Models are not fit to deal with these situations;

- In case infiltration in drain 6 is too high, migration of dissolved contaminants around the funnel might occur. By means of the groundwater model the infiltration capacity of the drains has been fixed maximally at 2 m^3/dag.m^1. The flow rate through the most important retention zone has been calculated at about 1m^3/day. There are no indications yet of clogging of the drains;

- The permeability of the retention zone has decreased by at least 50% as a result of the presence of oil. The natural groundwater flow through the retention zone rate is low (3 – 5 m/year). Leaching of contaminants is less than theoretically to be expected.

Remediation

- Three retention zones were distinguished in the soil investigation. The first zone was excavated during the installation of the gate. The results of the test phase show that the emission of contaminants from the retention zone at the location of drain 1 is limited compared to the supply from the retention zone near drain 3 and 6, which was by far the highest. Based on this information the extraction strategy was adjusted. The four segments receiving water from this retention zone, were kept open, while the other four segments were closed off.

- The highest load is being removed when infiltration in the retention zone is applied, due to increasing the groundwater flow and the interface between contaminants and groundwater flow. Infiltration outside the retention zone is less effective, because the retention zone forms a barrier for the groundwater flow.

- Infiltration of treated water in the plume has caused spreading of the contamination. The flow rate and duration of infiltration have to be attuned to the purifying capacity of the soil.

- In 2001 en 2002 the concentrations in the gate have been decreased furthermore. The concentrations of benzene and mineral oil are now lower than the intervention values. Based on the concentrations in the gate in 2001 en 2002, the expectation is that the remediation is finished within 30 years.

Water treatment

- Total treatment of extracted groundwater is taking place in the gate. Removal of contamination mainly takes place during the pre-treatment phase. In the reactor with carrier material biological decomposition takes place as well on a limited scale. Probably, the supply of nutrients is the limiting factor for biological decomposition. Biological decomposition does not take place in the ‘open’ bioreactor. This can be explained by the fact that the organic load of the contaminated groundwater is low and therefore insufficient sludge mass is being developed (‘thin water’).

- Targeted research of the ideal options for biological treatment was found to be impossible. Contamination was removed in the pre-treating step already. The treatment facilities were over dimensioned.

9. Recommendations

F&G in The Hague

The test phase has made clear the preconditions for an optimum operation of the F&G system. The optimum extraction and infiltration strategy has been determined and are operationalised:

- Drain 3 is used for an effective flushing of the most important retention zone. The infiltration capacity of drain 3 is not higher 15 m^3/day.

- The segments receiving water from the most important retention zone, are still operational, the others are closed.

- Infiltration in the plume for the purpose of stimulating biological degradation downstream of the gate has to be of short duration. The flow rate and duration have to be determined in more detail and are related to the natural attenuation processes in the plume.

- It is recommended to optimise the water treatment by leaving out the pre-treatment and the 'open' reactor.

- At a later stage the effluent of the bioreactor can be aerated as well in order to infiltrate water rich in oxygen and thus increasing the biological activity in the retention zone and in the plume, if necessary.

- It is recommended to introduce a calibration moment of the remediation after two to three years. After this period the retention zone will have been flushed approximately 10 times at a flow rate of 15 m^3/day and the concentration changes at that time will provide insight into future concentration changes and the possible end concentration. Then a mathematical model that describes the most important remediation processes can be used for the purposes of these predictions. It is also recommended that the oil characterisation method will be applied to detect changes in the source.

General

The most important guidelines for the design and operation of an active F&G system are:

- A solid F&G system has to be installed. Preferably, the funnel should be installed on a layer with a low permeability and the retention zone(s) should be enclosed as much as possible with sufficient space in between to capture as much as possible the natural groundwater flow to pass the retention zone.

- The reactor in the gate has to be simple and cheap in order to be competitive with other techniques. In case a bioreactor will be applied, than preferably a standard one above ground or if necessary an underground one. If feasible, preference is given to an active soil zone.

- The infiltration facilities have to be installed in the retention zone in order to achieve an effective leaching of the source.

As far as known, in general no models are available in which the source function is made dependent of the hydrology of the retention zone. It is recommended to integrate the hydrology of the retention zone in the project in which a model code is being developed for the source function of oily contaminants to the surroundings (SKB-project SV-415). The concentration measurements in the gate will be used for the validation of this model code.

CHAPTER 1

INTRODUCTION

1.1 Background information

In the early 1990s the University of Waterloo in collaboration with Shell Research and Technology Centre Thornton developed a new concept for the remediation of contaminated groundwater: 'Funnel and Gate'. In this technique contaminated groundwater is directed to a controlled reactive zone in the soil (the gate), using the natural groundwater flow and installed isolation walls (the funnel). In this reactive zone groundwater contaminants are removed. This concept is mainly appealing owing to its simplicity; once installed, the system uses little more than the natural groundwater flow.

In 1997 the project entitled 'In-situ bioremediation of contaminated groundwater by funnel and gate' was started in the Netherlands, the aim of which was to further optimise the 'Funnel and Gate' concept and make it suitable for the Dutch market. A consortium made up of Shell Global Solutions, University of Waterloo, Technical University of Delft, Ingenieursbureau 'Oranjewoud' B.V. and the Municipality of The Hague have been conducted the project. The project is being paid for out of the research and remediation budgets of the consortium members and a subsidy from the Dutch Research Programme for Biotechnological In-situ Remediation (Nederlands Onder-zoeksprogramma Biotechnologische In-situ Sanering = NOBIS). The consortium's 'pen holder' is Ingenieursbureau 'Oranjewoud' B.V.

In order to meet this objective, a number of selected locations has been examined on the basis of a number of criteria designed to determine the appropriateness of locations for 'Funnel and gate' systems. Eventually, the location 'Lijnbaan/Westeinde' in The Hague was selected as test site.

An active version of the 'Funnel and Gate' concept has been developed as part of the above-mentioned project in order to achieve the remediation goals within 30 years. A system has been devised that not only provides sufficient information to optimise the concept but is also suitable for remediate the soil contamination present on the site.

The system is installed in 1999. The consortium pondered over the set-up an extensive test phase. The test phase aimed at:

- evaluating system design;
- gathering general data suitable for the design of other 'Funnel and Gate' systems;
- optimising operating the system.

Formally the test phase was commenced on 1 January 2000 and was terminated on 31 December 2000. In order to collect the right kind of data, a testing and monitoring program was developed by the consortium which is used as a guide during the test phase [1]. The current report aims at providing a full overview of all results collected during the test phase.

1.2 Reading guide

The history of the project is described in chapter 2.
The design and installation of the system, as well as control of the direction of the groundwater flow and water treatment are described in chapter 3.
The objective and the program of the test-phase are the subject of chapter 4. Chapter 5 primarily discusses the groundwater flow during the test phase.
How the groundwater abstraction and re-infiltration was optimised is described in chapter 6.
Experience acquired with water treatment and clogging during the test phase can be found in chapter 7 and 8.
Legislation aspects are discussed in chapter 9.
The state of the art of 'Funnel and Gate' is described in chapter 10.
Guidelines for application and design of active ‘Funnel and Gate’ systems are given in chapter 11.
The report is finalised with a chapter containing conclusions and recommendations (chapter 12).

CHAPTER 2

DESIGN AND REALISATION

2.1 **Lijnbaan/Westeinde test site**

Location

The site is located at the corner of 'Lijnbaan' and 'Westeinde' streets, The Hague. The location consists of a public park (figure 1). Public streets border the site in all directions. The total area of the site is approximately 1,200 m^2.

Historical information

From 1948 until 1984, a petrol station was located at the site. The tank installation included several subsurface fuel tanks (gasoline, diesel, used oil and lubricant oils). In July 1984, a groundwater abstraction was carried out as part of a soil remediation, during which the contaminated superficial soil layers were removed. To improve the efficiency of the remediation, an impermeable screen was installed into the soil to a depth of 10 m below the surface. In November 1984, the screen and the groundwater abstraction installation were removed. In the period 1989-1998 the Municipality of The Hague commissioned (soil) surveys, which confirmed that residual contamination was still present.

Fig. 1. Test site (public park).

Soil profile
The soil profile, on a regional scale, is summarised in table 1.

Table 1. Soil structure and geohydrology of remediation location.

Formation	Sedimentary deposit	Position (m -gl)	Type
-	Medium fine sand	0-2	Fill material, phreatic water-bearing stratum
Westland (Hollandveen)	Medium fine sand	2.0-3.5	Covering layer
Westland (Calais)	Medium fine sand	3.5-4.5	Covering layer
Westland	Sand and clay	4.5-15	Shallow aquifer
Westland base peat	Peat and clay	15-17.5	Separating layer
Twente, Kreftenheye	Fine to coarse sand	17.5-70	1st aquifer
Kedichem	Clay	70-80	Separating layer

Using the profile descriptions and the results of the soil samples, the local soil structure has been deduced:

- 0-9 m below surface : sand
- 9-9.2 m : clay with sandy layers
- 9.2-16.5 m : medium fine sand
- 16.5-17.8 m : clay with sandy layers
- 17.8-19 m : sand

The results of soil samples demonstrate that the retention zone of the contamination, over the depth interval 8.0 to 10.0 m, does not contain any soil layers of poor permeability. In the case of the other soil samples such layers do exist.

Geohydrology
The site is located in a zone where water infiltration occurs; water is flowing from the shallow water-bearing layer towards the first water-bearing layer. On the actual date of execution of the field activities, the average depth of the groundwater level was approximately 2.0 m below soil surface (circa 0.5 m below normal Amsterdam level).
In the past, several pumping experiments have been performed in the immediate vicinity of the site. Measurements indicate a permeability (of the shallow water-bearing soil layer) of about 5 to 10 m per day. The horizontal phreatic groundwater velocity is estimated to be 10 to 20 m per year.

Contamination situation
Using soil and groundwater analysis, a three-dimensional picture of retention and retardation zones was established (figure 2).

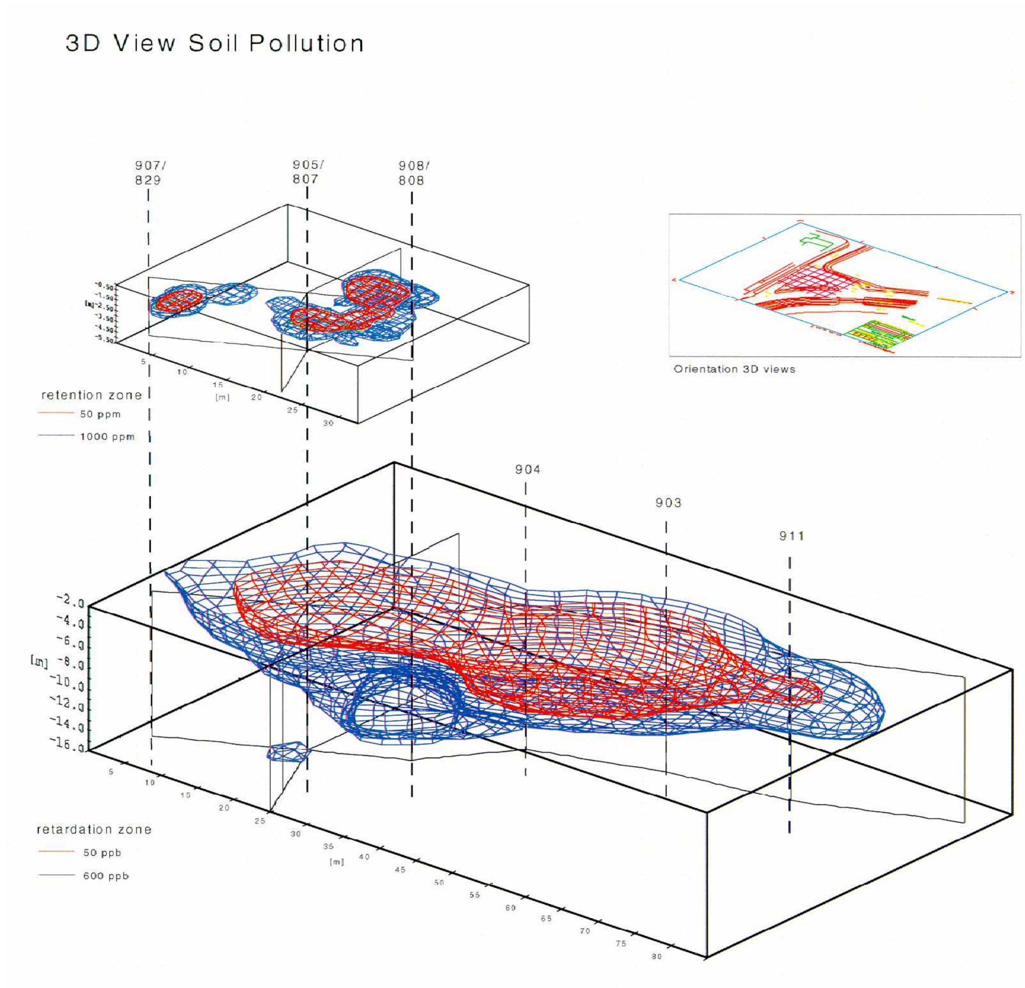


Fig. 2. 3D view soil pollution.

The retention zone is defined as the contaminated zone in which free-phase (liquid) oil is present in the pores of the soil system. In the (water saturated) retardation zone, oil components are present in dissolved form, emanating from the retention zone.

The results are evaluated using the 'Reference Framework for Concentrations of Several Contaminants in Soil and Groundwater' (part of the Dutch legislation, the so-called 'Wet bodembescherming').

In the soil at the location of the public garden, light to strong oil and/or aromatic odours have been perceived at depths of 1.3 to 5.0 m below the soil surface. Within this depth interval, positive oil-on-water tests were observed. The sensorial
observations are affirmed by the results of chemical analyses: slightly to strongly elevated contents of mineral oil and BTEX were measured.

The contamination extends itself to practically the complete area of the public garden and the neighbouring bicycle path. In eastern direction the soil contamination is stretched away up to and under the road joining the 'Lijnbaan' and 'Westeinde'. In northern direction the contamination is extended partly up to and below the street 'Westeinde'.

The size of the retardation zone was measured using a probe for groundwater sampling, the so-called 'cone-sipper', in combination with on-site gas chromatography analysis and sampling of monitoring wells, using laboratory analysis (figure 3).

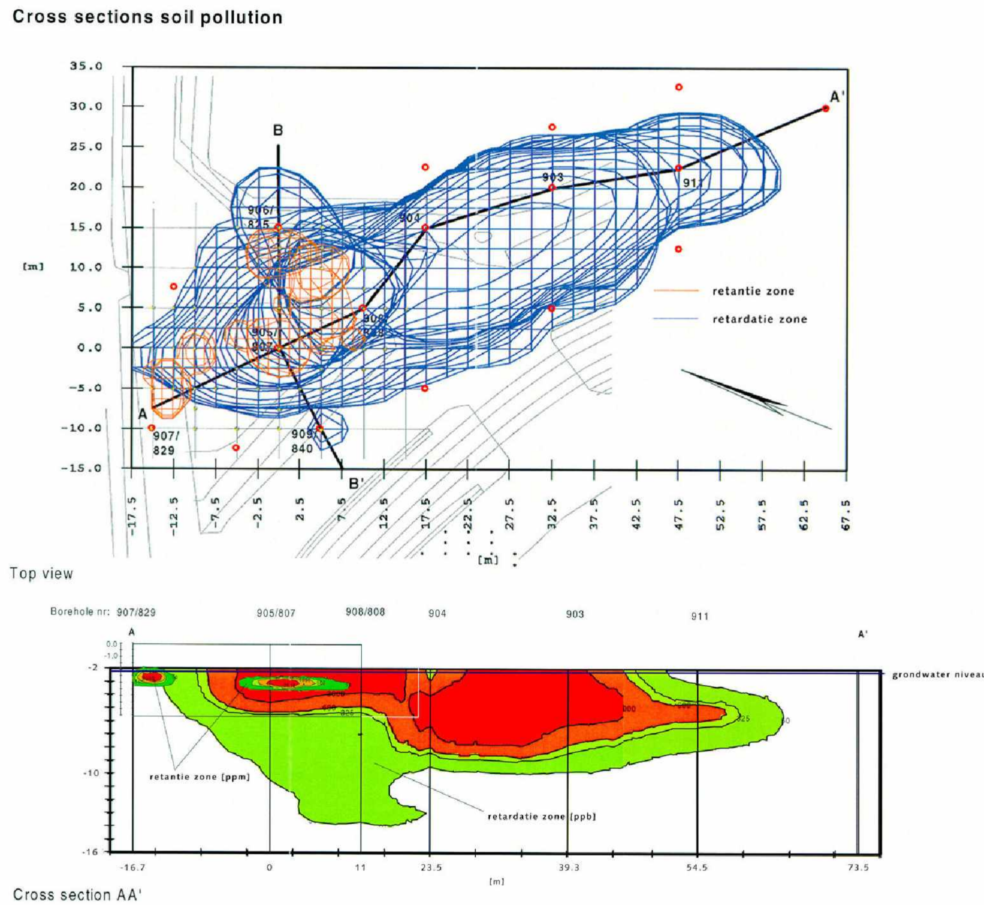


Fig. 3. Cross sections soil pollution and top view.

Most elevated oil and BTEX concentrations in the groundwater were measured in the retention zone at depths of 5.0 m below the soil surface. In the retention zone the contamination has moved downwards to the depth of the separating soil layer at approximately 17 m below the soil surface. The groundwater contamination in the plume has not descended as deeply as the contamination in the retention zone has. This observation can be explained by the presence or absence of silt and/or clay layers at a depth of about 7 to 10 m below the surface. The observed dispersion of the contamination in the soil and the groundwater can be related to specific (local) soil structural details.

In horizontal direction, the contamination is equally far directed upstream as the soil contamination itself. Downstream the contamination is extended in the direction of the rail track (south-Southwest).

2.2 **Soil remediation with 'Funnel and Gate'**

Multifunctional remediation is not necessary for the present use of the site (public park). Because the contaminated topsoil on the site was remediated in 1984, there are currently no human and ecological risks. Eventually migration of the contaminants via the groundwater, however, have to be eliminated.

In a remediation survey source clean up (by excavation) and source control were investigated and compared. The costs for source clean up and for source control were calculated respectively on NLG 3,700,000 and NLG 2,600,000.

The Municipality of The Hague was interested in using alternative remediation systems. 'Funnel and Gate' fits in well with the concept of functional remediation. A financial assessment was made to determine whether 'Funnel and Gate' was also cost-effective for the Lijnbaan/Westeinde location. The basic project plan includes an estimate of the cost of a functional remediation variant using a passive 'Funnel and Gate' system. The costs for a passive system amounted to NLG 2,900,000. Later on, an active the system has been designed to achieve the remediation goals within 30 years. The costs for an active 'Funnel and Gate' system were calculated on NLG 3,200,000.

'Funnel and Gate' offer a number of major advantages over the conventional clean-up option by excavation:
- the overall remediation costs are lower
- the number of pipe and cable crossovers is much smaller, which means less complex (temporary) measures are required
- the groundwater levels at the location and in the surrounding area are lowered to a lesser extent, if at all
- sheet piles do not have to be driven right alongside the buildings at Westeinde

On the 'Lijnbaan/Westeinde' site 'Funnel and Gate' cuts off the retention zone from the retardation zone. The objective of the remediation is to remove (mobile) contaminants that end up in the groundwater due to subsequent discharge from pure product (source clean up). The contaminants delivered subsequently are channelled through the reactive zone of the 'Funnel and Gate' system by means of (natural or artificial) groundwater flow. In this zone the collected groundwater contaminants are biologically degraded.

2.3 'Funnel and Gate' construction used

2.3.1 *Principle*

An active system has been developed for the Lijnbaan/Westeinde site, in which the inflow opening of the gate is provided with abstraction wells directed upstream. The abstraction is installed to flush the retention zone more thoroughly, thereby causing mobile components to leach away more quickly and reducing the duration of the remediation. Just like the passive variant of 'Funnel and Gate' (i.e. without abstraction), the active variant is constructed entirely underground. Only the groundwater flows are controlled; treated groundwater is not discharged into the sewage system but is infiltrated back into the soil. The system has three infiltration options:
- infiltration via six gravel drains (1 meter below ground level) in the unsaturated zone (upstream of the gate)
- three vertical infiltration wells (diameter 125 mm and filters from 2 to 5 m below soil surface) (upstream of the gate)
- infiltration via five vertical segments in the saturated zone (downstream of the gate)

The gravel drains and vertical infiltration wells are located so that the infiltration of treated groundwater also results in a more thorough flushing of the retention zone (and, inherently, a shorter remediation time). In geohydrological terms the impact is only detectable at local level.

The position of the funnel, the gate and the infiltration drains and pits (see map 17856-S-1) are chosen according to the boundary conditions, imposed by the nature and dimensions of the contamination, geohydrology and available space on the site of relatively small size. The presence of a high-pressure sewage canal, cables and conduits, as well as streets with busy traffic at all sides of the site, have had a major impact on the possibilities for installing the system.

2.3.2 *Funnel construction*

The funnel is constructed of two vertical walls to a depth of 7 m below normal Amsterdam level. The funnel walls consist of sheet piles, welded together in pairs and vibrated into the soil. The walls are circa 16 and 5.5 meters long and finish below ground level.

2.3.3 *Gate construction*

The gate consists of two circular walls, forming double rings (figure 4). The inner ring presents the part performing the remediation. The outer ring is the abstraction and infiltration unit; its wall was removed after installation.

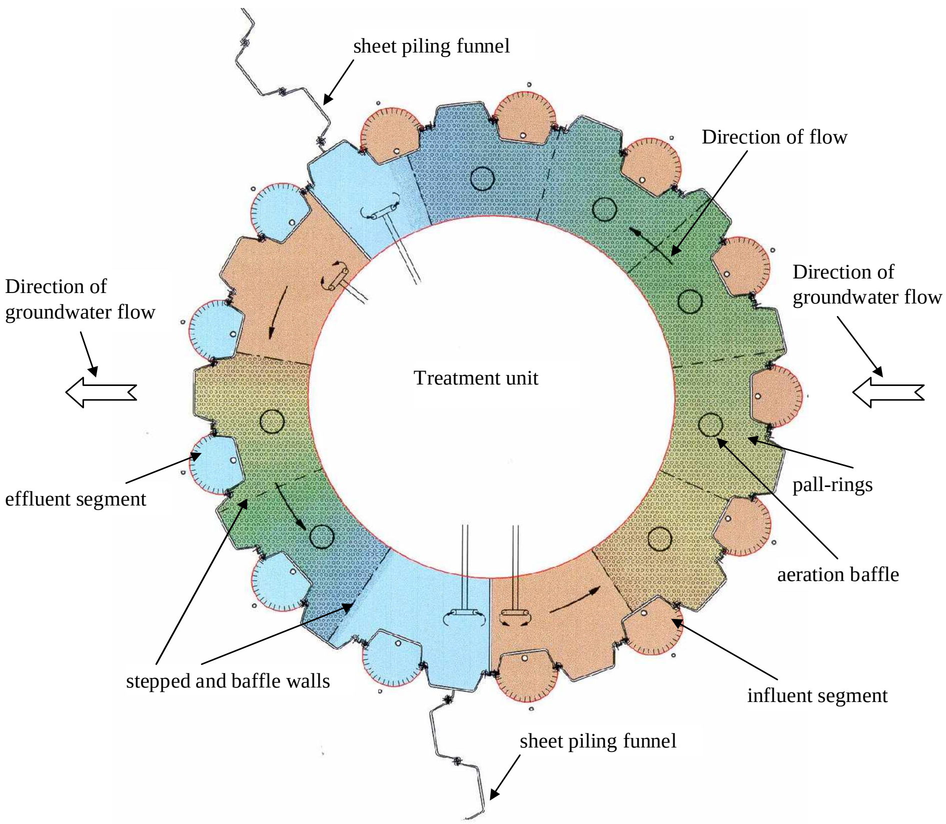


Fig. 4. Gate construction.

The walls consist of a sheet-pile screen to a depth of 16 m below normal Amsterdam level. To prevent leakage from the screen, these sheet piles have been welded together in pairs to 7 m below normal Amsterdam level and vibrated into the soil. The remaining seams are lock-sealed to a depth of 7 m below normal Amsterdam level.
The circular installation of vertical screens is innovating; its feasibility was not evident. Firstly, the screen sheets were welded together per two under the desired angle. In this way, it turned out to

be relatively easy to obtain a well-fitting circle of vertical screens. The only real difficulty pertained to soil compaction resulting from the installation procedure by vibration. During the installation of the second, outer wall, the vibration power had to be increased to a high level. Some sheets could not be driven into the enclosing soil layer.

The gate was finished entirely underground and is provided with abstraction segments, a treatment unit and infiltration segments (figure 4).

Abstraction segments

On the upstream side of the gate there is a gravel bed with eight vertical abstraction segments separated from each other by vertical steel partitions. The gravel bed is filled with stone chips (diameter 2 to 6 mm) to a depth of 4.9 m below normal Amsterdam level. The walls of the abstraction segments consist of vertical moon-shaped plastic filters with a diameter of 630 mm. The filter segment is located at a depth of circa 0.4 to 4.9 m below normal Amsterdam level.

Treatment unit

The treatment unit is circular (figure 5) with a diameter of almost 5.5 m.

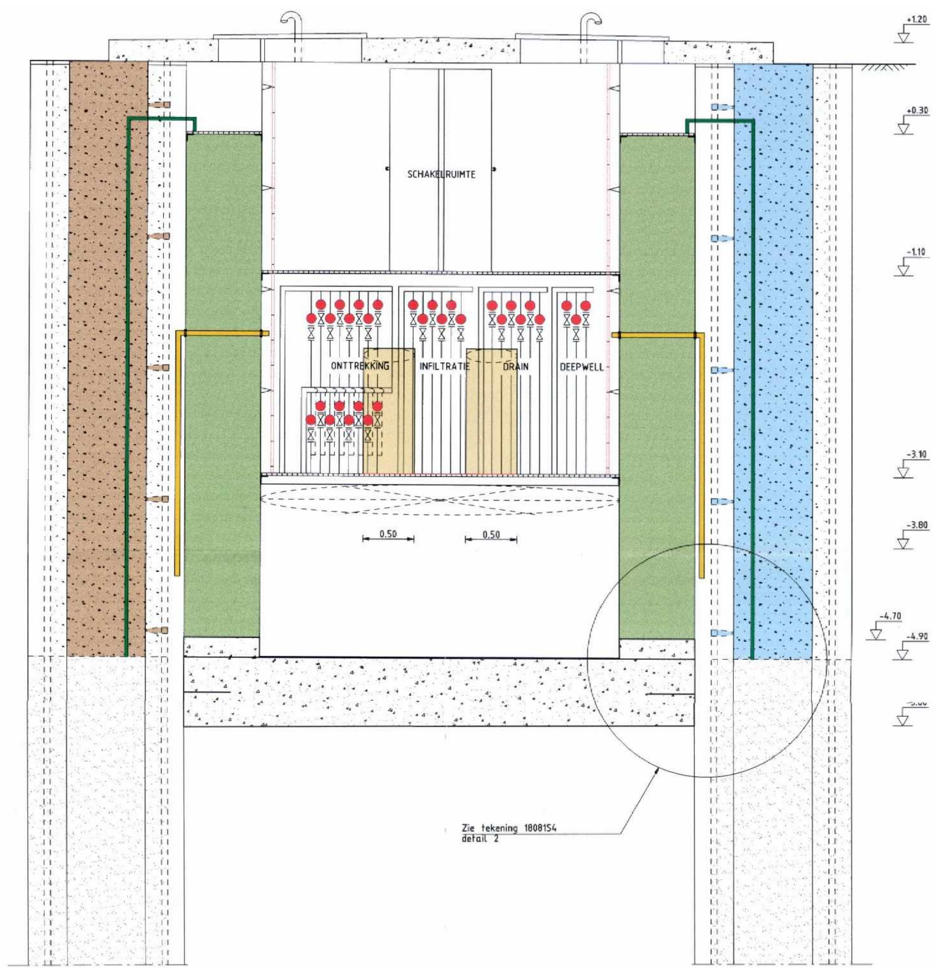


Fig. 5. Treatment unit.

The treatment unit is provided with a reinforced concrete floor, the top of which is situated 4.9 m below normal Amsterdam level. A prefabricated steel internal plant (diameter 3.5 m) is installed in the treatment unit. This internal plant consists of a cylindrical tank with two grid floors, creating three levels:

- the first level contains a switchbox with a PLC control unit and a Central Alarm and Recording System (CARS)
- the second level contains manually and electrically operated valves and four sand filters
- the third level contains eight water buffers (T01 – T08)

The space between the cylindrical tank and the sheet-pile screen is divided by means of two vertical partitions into a long and a short biological treatment zone. The two zones are fitted with stepped and baffle walls, creating seven and four compartments respectively. In the first compartment the groundwater to be remediated is admitted and in the last compartment the remediated groundwater is pumped out. The other compartments are fitted with aeration baffles and, where appropriate, pall-rings (as carrier material for bacteria). The direction of flow of the groundwater to be treated in both zones is therefore anti-clockwise.

Susceptible components, such as the walls of the treatment unit, the prefabricated internal plant and all vertical steel partition plates have been coated to prevent corrosion. Air is continuously abstracted from the treatment unit. The abstraction system consists of a fan and an active carbon filter. In the interest of safety the unit is equipped with an emergency system so that in the event of calamities remediated water can be discharged into the sewage system.

Vertical infiltration segments

There is also a gravel bed on the downstream side of the gate. This bed has five vertical infiltration segments. The gravel bed is filled with stone chips (diameter 2 to 6 mm) to a depth of 4.9 m below normal Amsterdam level. The walls of the infiltration segments consist of vertical moon-shaped plastic filters with a diameter of 630 mm. The filter segment is located at a depth of circa 0.4 to 4.9 m below normal Amsterdam level.

2.4 Installation of the system

Installation of vertical wall rings

The gate construction consists of a permanent vertical wall ring with a diameter of 5.3 metres, installed within a temporary vertical wall ring with a diameter of 7.5 metres (map 17856-S-1). Both rings were built from steel vertical wall sheets, welded two-by-two before installation into the soil (using a vibrating block; figure 6). Total vertical wall length was circa 16 meter. All wall locks are supplied with prefab lock closings.

As a result of the presence of debris in the soil and an increasing compaction of the sand layer, the outer ring could not be lowered to a depth of NAP -16 meter. However, this did not cause any problems since the outer ring merely was temporary and only used for the installation of the 'Funnel and Gate' system. After installation of both rings deepwells were placed and both the inner and the outer ring were excavated to depth (Picture 2.3). To enhance stability beams were installed between both vertical wall rings.

Placement of concrete floor

The bottom of the excavation, located at NAP -4.9 m, was provided with a layer of concrete of 70 cm thickness. After cleaning and coating of the vertical walls against corrosion, the abstraction and infiltration segments were installed between both vertical wall rings.

Fig. 6. Installation of temporary outer ring and permanent inner ring.

Fig. 7. Excavation inner and outer ring.

Installation of abstraction and infiltration segments

Six metre long moonshaped PVC filter-tubings were placed against the outer side of the inner ring (figure 8). These filters have a diameter of 0.63 metres and a slit-size of 1 mm. The filters are perforated over a length of 4.5 metres (filter NAP -0.4 to -4.9 m). In order to be able to separate the inflowing groundwater per influent segment, partition walls were installed into the gravel layer at the upstream side of the system. The spacing between the moon-shaped filters and the outer ring was then filled with gravel. Into the gravel layer air injection filters were installed that can be used for the high-pressure regeneration of the gravel. These air injection filters have a diameter of 32 mm. The lower meter of the filters is perforated.

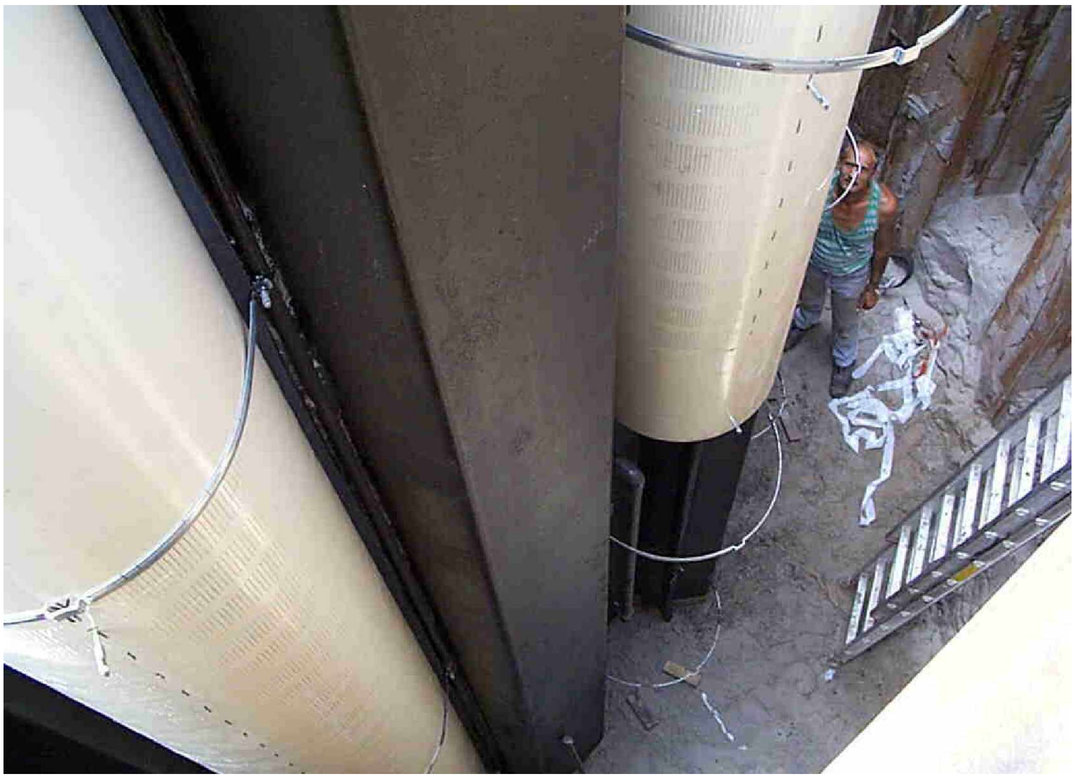


Fig. 8. Installation of moon-shaped abstraction and infiltration segments.

After placement of the gravel layer the vertical wall sheets of the temporary outer ring were pulled out. The sheets of the inner ring were cut at a height of NAP +1 m. Onto the ring a steel rim was constructed; onto the rim the concrete lid of the gate was placed. The gravel layer was solidified and covered with foil with a layer of sand on top of it.

Installation of funnel walls

The vertical wall sheets of the funnel were also installed with the use of a vibrating block. These wing walls are depicted on map 17856-S-1. The length of the walls equals approx. 15.5 metres for the western wing and approx. 5 metres for the eastern wing. The walls were, close to the gate, installed through the gravel layer and water-tightly connected to the inner ring. The funnel wall reaches approx. NAP -7 m; the upper part is located at circa 1 m below the soil surface.

Installation of prefab water treatment unit

After levelling of the 'Funnel and Gate' systems contours (the vertical wall rings and the wing walls) a prefab water treatment unit was installed. This unit consists of a cylindrical steel tank (diameter 3.5 metres) of three levels:

- a first level containing the switch box with control unit (PLC) as well as the central alarm and registration system (CARS)
- the second level contains manifolds, flowmeters and four sand filters
- the third level contains buffer tanks

The spacing between the cylindrical tank and the inner vertical wall ring (see figure 4) is divided into a long and short biological treatment zone. Both treatment zones possess stepped and baffle walls (figure 9), by which respectively 7 and 4 treatment compartments are formed. Contaminated water flows into the first compartment; in the last compartment the treated water is pumped out of the zone into the effluent side. The other compartments possess air injection saucers (figure 9), for the aeration of the contaminated water. A compartment in the short treatment zone also possesses bacteria-supporting material (so-called pall rings). A ventilator continuously refreshes the air in the treatment unit.

Finally, the complete gate is covered with a concrete lid.

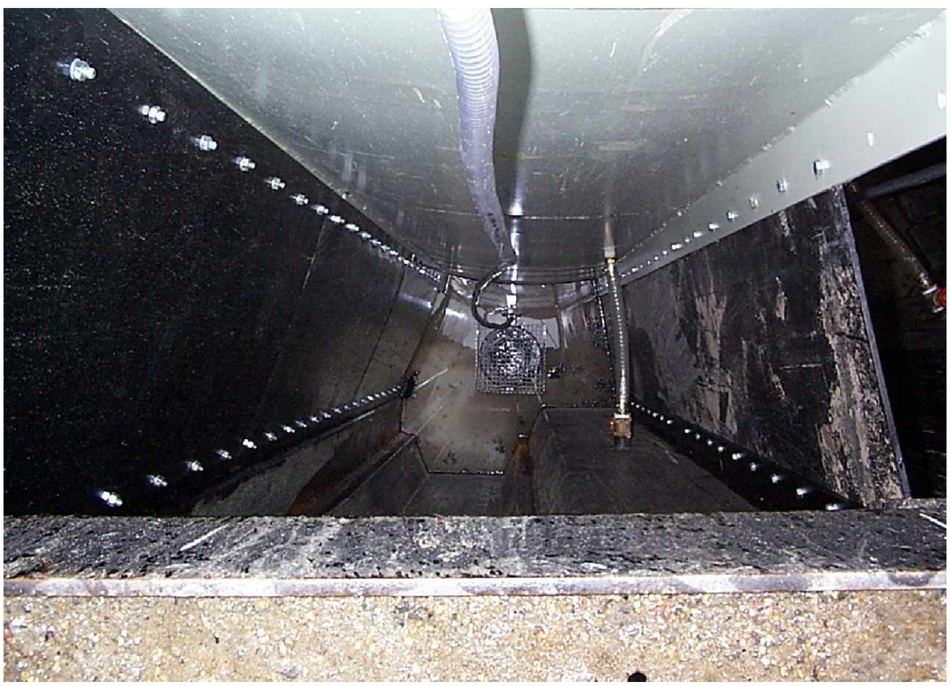


Fig. 9. Water treatment compartment: view of the spacing between the vertical wall (lower side) and the treatment tank (upper side); left: baffle wall; right: stepped wall; below an aeration saucer is visible.

To the upstream side of the system six infiltration drains were installed, which can be used for intensive flushing of the retention zone (see map 17856-S-1). The depth of the drains is 1 m below soil surface. Also three vertical infiltration wells were installed. These wells have diameters of 125 mm; the length of each well is 5 metres. For the permeable soil layer in which the drains are present, use was made of coarse sand.

The installation was performed from July until November 1999.

CHAPTER 3

OPERATION AND CONTROL

3.1.1 *Introduction*

In order to optimise the 'Funnel and Gate' concept a high degree of flexibility was incorporated into the detailed design. The water treatment is fully underground and tailor-made. Optimal biological treatment conditions are set by on-line measurement of oxygen levels in the influent. The system was furthermore designed to permit water treatment in variable ways. This implies that residence times, treatment techniques as well as aeration regimes can be varied as chosen. The treated water can be reinfiltrated at six locations upstream and five locations downstream. This allows the system to meet the predefined requirements (boundary conditions at the location).

As the number of system variables increases, the need rises for sophisticated control of the groundwater abstraction, treatment and reinfiltration. Manual measurements and control can only partly fulfil these needs. The consortium therefore decided to install an additional telemetrical measurement and control system. This system allows operation and control at distance (from the office). The current chapter provides information on this system. Before turning to the description of the manual monitoring (section 3.3), the on-line measurements (section 3.4) and the telemetrical operation (section 3.5), the treatment system is described.

3.2 **Operation of the system**

The abstraction segments are used to abstract contaminated groundwater from the upstream side of the gate. This water is stored temporarily in an influent buffer (1,3 m^3) on the third level of the cylindrical tank in the treatment unit, where the abstracted water is thoroughly aerated. The water is then pumped through the first sand filter (to trap any iron flocks) to the long or short biological treatment zone. The short and long treatment zone have contents of respectively 24 and 36 m^3. The water in these zones is aerated to stimulate the biological degradation of the groundwater contaminants. Wherever possible, the residence time in the zones is attuned to the influent quality and the abstraction rate. In the first and last compartment of each zone oxygen sensors are installed for the management of the aeration baffles.

After a sufficiently long residence time the treated water is pumped to an intermediate buffer, following which it is again channelled through a sand trap (to remove any sludge) and stored in an effluent buffer. The intermediate and effluent buffers are also located on the third level of the cylindrical tank in the treatment unit. From the effluent buffer the water is finally infiltrated through six gravel drains and the three vertical infiltration wells (upstream of the system) and/or the five vertical infiltration segments (downstream).

3.3 **Manual monitoring**

3.3.1 *Monitoring wells*

Monitoring wells were installed for measurement of groundwater levels and groundwater quality. To monitor groundwater levels in the surroundings, 30 monitoring wells up to a distance of 150 m were placed (tp01 to tp28, tp47 and tp48). Monitoring wells numbered 204, 702, 705 and 706 still existed from previous soil investigations. Monitoring well co-ordinates are indicated on map 17856-O-1.

In and below the retention zone and downstream the system (retardation zone), monitoring wells were installed as well (tp45, tp46, tp51 to tp54, pbA01 to pbA21, pbB01, pbB02 and pbC01 to pbC03). Filter lengths of these wells are 1.0 m.
The filter depths of the monitoring wells are mentioned in appendix 9. Also is mentioned the depth of the filter in relation to the position of the retention zone.
Monitoring wells with codes pbB and pbC are placed deeper into the soil. Filter depths of these wells equal, respectively, NAP -6 to -7 m and NAP -9 to -10 m.
The required cables and pipes are placed below ground level in pipe sleeves.

Water pilots were installed into a large number of monitoring wells close to the location. Some wells at larger distances possess divers (see section 3.4). For delineation purposes as well as for control of the groundwater quality downstream, monitoring wells tp29 to tp44 were installed.

3.3.2 *Sampling points*

The flow scheme and sampling points are indicated on map 17856-F-1. For monitoring of the water treatment process, the following sampling points are used:

- MN01: influent buffer (8 compartments a to h);
- MN02: collector pipe (for aeration buffer);
- MN03: between aeration buffer and sand filter;
- MN04: between sand filter and biological treatment zone;
- KS01 en KS04: first and fourth compartment short treatment zone;
- LS01 and LS07: first and seventh compartment long treatment zone;
- MN11: in front of sand filter;
- MN12: after sand filter;
- MN07: effluent after buffer container.

The groundwater enters the treatment unit via eight influent pipes. Each influent influx (MN01A to MN01H) can be sampled. The collector pipe also contains a sampling point (MN02). The collected influent then reaches the aeration buffer tank (T-01). Next the water passes the sand filter (F-01) to reach the short treatment zone. Both the effluent stream of the aeration tank (MN03) and the effluent from the sand filter (MN04) can be sampled.

The water passes all compartments of the short street, then is lead through all compartments of the long treatment zone. Each compartment can be sampled if necessary. After the treatment zone the water flows through buffer tank T-05, then to the sand filter F-04. After the buffer tank MN11 and the sand filter (MN12) sampling points are present.

The effluent of the last sand filter again is led through a buffer tank and then reinfiltrated into the soil. The final effluent can be sampled via point MN07.

3.4 **On-line measurements**

A Central Alarm and Recording System (CARS) monitors the abstraction and treatment process. CARS on-line measures and records the following parameters:

- oxygen level;
- working hours of pumps and ventilators;
- water levels;
- flow;
- backflow frequency of sand filters;
- pressure difference over sand filters;
- interruptions/disorder in pumps and ventilators.

Oxygen concentration

On-line oxygen measurements are carried out at four places in the gate; in the first and last compartment of the short and long zone. The on-line measurements are performed using oxygen sensors (membrane-covered, amperometric 2-electrode measuring cell). The results of the oxygen measurements are used for purposes such as adjusting the aeration baffles.

Regulating the ventilation

The gas phase of the treatment unit contains LEL (Lower Exposure Limit) detectors. These detectors regulate the ventilation in the space. Abstracted air is discharged through an active carbon filter. Measures are taken to measure the air quality before the active carbon filter.

Water levels

Water pilots are used to control the abstraction and infiltration part of the system on the basis of water levels measured (see section 3.5). This may be useful for the infiltration of treated water through infiltration drains for instance (mpD01 u/i mpD06). Float switches are used to record (ground)water levels continuously in:

- the treatment compartments
- filters in the retention zone
- filters immediately downstream of the gate
- infiltration segments
- infiltration drains

Divers record groundwater levels in the vicinity of the system.

Flow measurement

The influent flow rate and the effluent flow rate are measured on-line, so that the load and efficiency of the treatment can be calculated. These flow rates establish the residence time. It is also important to measure the flow rate of the gas leaving the treatment compartments.

3.5 **Telemetrical control**

Water can be selectively abstracted and reinfiltrated (by time and/or flow rate). For this purpose setpoints are manually selected. Examples of setpoints are:

- highest and lowest water levels, at which the abstraction segment is switched on or off, respectively;
- segments from which water is abstracted for the long and short treatment zone, respectively;
- the resistance level at which sand filters should regenerate;
- the highest and lowest oxygen concentration in the influent, at which occasion the aeration is switched on or off, respectively;
- boundary water levels at which occasion the infiltration per infiltration segment is switched on or off, respectively.

The computer continuously compares the on-line measurements with the selected set points and decides which measures should be taken in order to maintain proper system functioning (e.g. opening/closing valves, switching on/off pumps or aeration installation).

CHAPTER 4

RESEARCH PROGRAM TEST PHASE

4.1 Objective of the testphase

Consideration has been given to the way the test phase is to be carried out as far as the consortium and a number of research questions have been used as the basis for a joint testing and monitoring programme.

The following parts of research were chosen by mutual agreement:

A. research into the effect of biological treatment at different influent concentrations and variable abstraction rates;
B. research into the impact of a 'Funnel and Gate' system on the geohydrological situation and natural attenuation;
C. research into the occurrence of precipitation in the abstraction and infiltration segments and in the treatment process and the risk of clogging;
D. inventory of policy-related and legal boundary conditions that could constitute an obstacle to the application of the 'Funnel and Gate' concept;
E. development of guidelines for designing 'Funnel and Gate' systems.

In order to arrive at a suitable testing and monitoring program, the consortium has selected the research questions to be answer for each part of research (see tables 2 to 5).
The duration of the test phase has been set at 1 year. The research into ‘Biological treatment (A)’ and ‘Geohydrological situation/natural attenuation (B)’ is to be conducted within this time. The results will be evaluated at the end of the test phase.
The research into ‘Clogging the system’ and ‘Policy-related and legal boundary conditions’ is long-term. For these parts of research the interim results and (cautious) conclusions will be presented at the end of the test phase. These parts of research will only be completed after a considerable time, during the remediation phase.

The research into 'Guidelines for application' has a co-ordinating role. This research draws on the results of the design and installation phase. In May 2000 the report ‘In situ Bioremediation of contaminated groundwater by application of ‘Funnel and Gate’ (NOBIS 97-1-13) was published [3]. In this report guidelines for the use of passive and active ‘Funnel and Gate’ systems are presented, based upon the acquired experience at that moment.

The current report adds additional aspects to these guidelines (based upon the test results) as well as some additional conclusions and recommendations, which can be used for the design of comparable (active) systems at other locations in The Netherlands.

The results and the findings of the test phase will be used, eventually, to optimise the enhanced bioremediation of the retention zone, the plume control and the biological treatment.

Table 2. Questions for research into 'Biological treatment'.

	Primary research questions	Answering in Paragraph
A1	Is aeration and/or compressed air injection a suitable method for adding oxygen in the gate?	7.5
A2	Are influent contents demonstrably affected by the infiltration and abstraction rates?	6.3
A3	Is the removal rate achieved by biological treatment in the gate demonstrably affected by the flows to be abstracted and infiltrated?	7.5
A4	What residence time is required to remediate extracted groundwater to a satisfactory level (in relation to the flow rate and the influent concentrations)?	7.5
A5	Does the actual biodegradation in the gate meet the expectations based on the laboratory tests?	7.5
A6	What is the capacity of the biological treatment unit?	7.5
A7	What is the removal rate of remediation (influent/effluent quality)?	7.5
A8	Is it sensible to have differentiated remediation (in two treatment zones)?	7.5
A9	When does aeration become stripping (what is the optimum method for adding oxygen)?	7.5
A10	Can a mass balance be created for the treatment?	7.5
A11	Is a PLC/CARS system suitable for controlling biological water treatment processes?	7.5
Secondary research questions		
A12	Can the system operate passively (with no pumps, only aeration)?	5.6

Table 3. Questions for research into 'Geohydrological situation'.

	Primary research questions	Answering in Paragraph
B1	At what flow rates does leakage from behind and underneath the 'Funnel & Gate' system occur?	6.4/6.5/6.7
B2	Is the risk of leakage from underneath and behind the system increased unacceptably by the use of deep wells in the retardation zone?	6.7
B3	Is it possible to show a relationship between the flow rate through the retention zone, the infiltration rate and the abstraction rate?	6.7
B4	What is the relative (im)permeability (in terms of quality) of the sheet-pile wall?	5.6
B5	What is the infiltration capacity of the gravel drains and the vertical infiltration segments?	5.5
B6	How big is the impact of the active 'Funnel and Gate' system on the original geohydrological situation?	5.3/6.6
B7	Does the retardation zone grow in size under the influence of the infiltration of remediated groundwater at the rear of the gate?	6.6
B8	Is natural degradation in de retardation zone detectable?	6.6
B9	Can the soil be shown to become clogged in the immediate vicinity of the system?	5.5
B10	How does the Central Alarm and Recording System (CARS) work?	7.5
Secondary research questions		
B11	Can the system operate passively (with no pumps, hanging funnel) and how big is the impact on the original geohydrological situation?	5.6

Table 4. Questions for research into 'Clogging of the system'.

	Primary research questions	Answering in Paragraph
C1	Does the infiltration capacity of the gravel drains and infiltration segments decrease over time?	5.5/8.3
C2	Is biological activity detectable in the second sand filter?	7.3
C3	Can the system and/or soil be shown become clogged in the immediate vicinity of the system?	5.5/8.3

Table 5. Questions for research into 'Policy related and legal boundary conditions'.

	Primary environmental research questions	Answering in Paragraph
D1	Do the contaminants leach away in the retention zone as expected?	9.4
D2	What happens to the size of the retardation zone?	6.6
D3	Does leakage from underneath or behind the system occur?	6.4/6.5/6.7
D4	Does the effluent quality of the gate conform to the requirements of the various permits?	6.3

4.2 **System settings**

Abstraction and infiltration

The current evaluation comprises the period 1 January to 31 December 2000. Early January 2000 the system was set to an abstraction flow of 15 m^3/day and a full reinfiltration of purified groundwater downstream the system (in the effluent segments directly behind the gate). Other variables were kept constant.

In January it followed that the vacuum pump, with which contaminated groundwater from the abstraction segments was pumped up, could hardly be kept at a constant flow rate; the capacity of the segments seems to be lower than the minimum capacity of the vacuum pump. It was therefore decided to remove this pump and to allow the groundwater to passively enter the system. Since then automatic switching of valves regulates the influx.

In the time interval end of April to mid August 2000, the flow rate doubled to 30 m^3/day. Then the system was switched off for two weeks to allow maintenance. From the beginning of September to the end of October, groundwater abstraction occurred at a flow rate of 15 m^3/day, which was completely reinfiltrated upstream via drains 3 and 6.

The settings are summarised in table 6.

Table 6. Settings of the system.

Period	Abstraction (m3/day)	Segments	Infiltration (m3/day)	
			Downstream	Upstream
1/1 - 28/4	15	8 (all)	15	0
29/4 - 20/5	30	8 (all)	30	0
21/5 – 15/8	30	4 (b,c,d,e)	30	0
16/8 - 30/8	-	-	-	-
31/8 - 13/11	15	4 (b,c,d,e)	0	15 (drains 3 and 6)
14/11 - 7/12	15	4 (b,c,d,e)	15	0
8/12 - 31/12	5	4 (b,c,d,e)	5	0

Settings water treatment

During the complete test period the short and long treatment zones were connected serially and was the 2nd sand filter in use. Neither the 1st sand filter nor the aeration in the buffer tank has been continuously in operation. The relevant settings are summarised in table 7.

Table 7. Settings water treatment.

Period	Component				
	Aeration buffer tank	1nd sand filter	Aeration short zone	Aeration long zone	2nd sand filter
1/1 - 22/3	+	+	-	-	+
23/3 - 15/08	-	+	-	-	+
15/08 - 30/08	-	-	-	-	-
31/08 – 26/10	-	-	-	-	+
27/10 – 27/11	-	-	+	+	+
28/11 – 7/12	+	+	+	+	+
8/12 – 31/12	+	+	-	-	+

4.3 **Measuring program**

4.3.1 *Geohydrology*

Water levels

The water levels were measured in three different ways:

- daily measurements with water pilots in the retention zone
- daily measurements with divers in the retardation zone
- periodically with manual measurements

A water pilot is installed in the observation well and automatically measures the water level. The results of the measurements are directly sent to the CARS-system. The water level can be automatically measured by means of a diver as well. However, these divers are not connected to a central system; the data are read periodically by means of a computer. At three locations several filters have been installed to get insight into the vertical groundwater flow. By recording the groundwater levels it is possible to deduce whether the abstraction is yielding the desired geohydrological result.

The water level in the effluent segments was monitored by means of water pilots. The water level in the observation wells downstream was measured by way of water pilots as well.

Permeability

The permeability was measured in the field by means of Fall-Head experiments. Distinction was made between the retention zone and the soil layer beneath. A description of the method as well as the results is given in appendix H. The results are also mentioned in section 5.2. Furthermore samples from both soil layers were analysed for particle size distribution.

4.3.2 *Optimisation of abstraction and infiltration*

Concentration measurements

Concentrations of total petroleum hydrocarbons (mineral oil) and volatile aromatics (BTEX) in the groundwater from the segments were periodically determined. The evolution of these concentrations in time is, per segment, depicted in appendix C. In the period from 1 January to 28 April, abstraction was performed using 8 segments. Starting from 28 April, abstraction occurred selectively with 4 segments (B, C, D and E).

Monitoring wells pbA1 to pbA8, pbA14, pbA19 and pbA20 in the retention zone were sampled periodically and analysed for mineral oil and BTEX. Results are presented in appendix D.

Monitoring wells pbA9 to pbA13 as well as monitoring wells tp33 to tp36 in the plume zone were also periodically sampled and analysed (same parameters). Results of these measurements are also presented in appendix D.

Oil characterisation

Initially, the intention had been for the consortium also to calibrate the oil model developed previously (at NOBIS). A range of oil characterisations and model computations would be used to investigate whether the behaviour of oil can be predicted in practice. Although the conditions are completely controllable, the consortium is currently convinced that this type of calibration is best carried out in a stable geohydrological environment. As infiltration and abstraction rates can fluctuate considerably during the test phase, there is no question of a stable geohydrological environment in the first year. For this reason it was decided not to include this research in the test and monitoring program. Calibration of the oil model will still be considered during the remediation phase, but not as part of this project.

4.3.3 *Treatment*

Concentration variation in the treatment process

Periodically measurements were carried out at various locations in the treatment unit to determine the following parameters:

- mineral oil and volatile aromatics
- oxygen, acidity, electric conductivity and temperature
- nitrogen-Kjeldahl, chemical and biological oxygen demand
- ammonium, sulphate, nitrate and phosphate
- iron, manganese, calcium and carbonate

Air-phase measurements

The concentration of BTEX in the exhausted air was measured to allow control if legislation demands are met. The air exhaust therefore was sampled at several instances and analysed for BTEX.

CHAPTER 5

GEOHYDROLOGICAL ASPECTS

5.1 Geohydrological situation

The local soil structure is deduced from profile descriptions (in the field) and soil samples. The soil structure can be summarised as follows (m -gl: metres below ground level):

- 0-9.0 m-gl medium silty, medium fine to medium coarse sand
- 9.0-9.5 m –gl clay with sandy layers
- 9.5-16.5 m –gl medium silty medium fine to medium coarse sand
- 16.5-17.8 m –gl clay with sandy layers
- 17.8-19.0 m –gl medium coarse sand

The groundwater level at the location averages NAP -0.7 m (approx. 2 m -gl). The location is situated in an area where infiltration occurs of phreatic groundwater towards the first water-bearing soil layer. The direction of groundwater flow in the first water-bearing layer is Southeast (Groundwater map 30D, 30 East, ‘s-Gravenhage). For further details about the hydrological situation reference is made to appendix a.

5.2 Permeability

Regional

In the past several pumping experiments have been performed in the immediate vicinity of the site. Measurements close to the location Tripstraat/Loosduinseweg indicate a permeability of approx. 5 to 10 m/day in the shallow water-bearing soil layer.

Locally (field measurements, soil particle fractions)

The permeability of the soil was measured in the field by means of Fall Head tests. Monitoring wells tp51 to tp54 were used for this purpose. Monitoring wells tp51 and tp53 have filters located inside the retention zone. Results of these tests are summarised in Table 8 and appendix H.

Table 8. Permeability measured by Fall Head tests.

Well No.	Filter depth (m –gl)	Permeability (m/day)
tp51	2.0-3.0	approx. 2
tp52	5.0-5.5	approx. 7 (corrected)
tp53	2.0-3.0	approx. 2
tp54	4.5-5.0	approx. 7

Based on the particle size distributions of three soil samples from boring tp53, the permeability was calculated using the empirical formula of Hooghoudt. These results are summarised in table 9.

Table 9. Permeability calculated from particle size distribution.

Soil layer	Description	Permeability (m/day)
2.1 – 2.5 m –gl	Medium coarse sand	13
3.4 – 3.8 m –gl	Medium coarse sand	17
4.2 – 4.5 m –gl	Medium fine sand	6

Measured and empirically determined permeabilities of the subsoil (> 4 m -gl.) agree well with each other. The conductivity of the shallow soil layer is, according to particle size distributions, clearly higher, which is in accordance with field observations (appendix G). Measured permeabilities in the field and calculated permeabilities (empirical formula) of the same soil layer differ substantially.

The effective porosity of the sand (dune sand) is assumed to be 0.4. Using the empirical formula earlier mentioned, the effective porosity of the retention zone is estimated to be 0.25.

Local (deduced from groundwater level differences)
An indication of the average permeability of the shallow aquifer was obtained by an analytical calculation (Darcy formula).

$Q = A * k * i$

with:
- Q abstraction rate (m^3/day)
- A flow-through surface area (m^2)
- k average permeability (m/day)
- i groundwater gradient (-)

The calculation was performed for the upstream flow-through surface area (directly in front of the gate). The surface area equals 52 m^2. Using the former formula, a permeability of 6 m/day is calculated, for both the abstraction rate 15 m^3/day as well as the rate of 30 m^3/day. This result agrees well with the field measurements (2 m/day in the soil layer of 1.5 m thickness and 7 m/day for the soil layer with 5 m thickness).

The permeability of the retention zone is lower than the permeability of the same layer outside the retention zone. The difference is attributed to the presence of oil components. The groundwater model is adjusted at this point.
The average permeability of the shallow aquifer is derived from Darcy calculations and the result fits with early measurements.

5.3 Description of the groundwater flow

At and in the vicinity of the site groundwater level data were periodically collected. These data were then transformed into maps of iso-lines (equal water levels). In the following section these maps are described and interpreted. The different settings of the system and sampling moments were taken into account when choosing water-level measurement moments.

Comparing flow-data to concentration measurements especially enhanced the insight into the vertical groundwater flow. The interpretation of concentration measurements is related to groundwater movement, which enhances the scale of support of concentration measurements. This way of interpretation of data is called dynamic monitoring. Its principles are further described in appendix B.

The groundwater flow is discussed for the following periods:

- June 1999 (system not present);
- November 1999 (system present, not in operation);
- March 2000: abstraction at 15 m3/day (8 segments); downstream infiltration;
- mid June 2000: abstraction 30 m3/day (4 segments); downstream infiltration;
- mid October 2000: abstraction 15 m3/day (4 segments); upstream infiltration.

June 1999

The recordings of June 1999 were transformed to an iso-groundwater line map (map 17856-I-1). At that moment the 'Funnel and Gate' construction was not yet installed. The groundwater level at the location was NAP -0.7 m, the groundwater level gradient is approximately 0.0007 m/m and the velocity of the groundwater flow approx. 5 m/year. Groundwater flows in south east direction.

November 1999

The flow situation of November 1999 is depicted in map 17856-I-2. The system has been installed but is not yet in operation. The average groundwater level is NAP -0.65 m, the level gradient is approx. 0,001 m/m and the flow velocity 7 m/year (section 5.4). Map 17856-I-2 clearly shows that the influence of the system on the surroundings is limited to several tens of metres.

March 2000

The iso-line map of water levels is depicted on map 17856-I-3. The groundwater flow patterns starting from the effluent segments, alongside both funnel segments towards the front side of the gate are clearly visible. Looking at the level difference at both sides of the wing, it is clear that part of the infiltrated water passes beneath the wings towards the gate. As a result of the back flow of a large fraction of the effluent towards the water inlet, a locally 'closed' system is established.

From the groundwater levels in monitoring wells pbA01, pbA02 and mpD02 it follows that the water coming from the surroundings collects at Westeinde. Groundwater flows in second instance to the gate following a path below the above mentioned locally 'closed' system. The groundwater coming from Northwest directions is directed towards deeper layers in this way. The deeper groundwater at the front of the gate moves upward at the water inlet construction as well as the part of the infiltrated water that flowed underneath the wings. The vertical groundwater movement is illustrated in map 17856-DP-1.
This interpretation of the groundwater flow is partly a result of the measured concentration evolution in the filters with code pbB and pbC.

The influence of the system on its surroundings is very low because a locally 'closed' system is established.

June 2000

At this date groundwater is abstracted in a differentiated manner at a rate of 30 m^3/day. The same flow patterns as in March are visible. The strength of the streams however, is different (map 17856-I-4). The incoming groundwater seems to be transported more quickly than in March.

October 2000

From the beginning of September water is infiltrated at a rate of 15 m^3/day, upstream with drains 3 and 6 in the street. The abstraction rate also equals 15 m^3/day. The groundwater level in the street is approx. 0.10 m higher than was the case in June.

The groundwater velocity in the street is also higher compared to June. Run-off of infiltrated water towards the public garden occurs. Back flow at the short wing does not seem to occur. In this situation too, little water flows from the surroundings towards the water inlet.

Extraction and infiltration provide a clear picture of the groundwater flows around the F&G system. In case of infiltration in the plume groundwater flows are being formed along the funnel to the front of the gate. The groundwater flowing in from the surroundings is being pushed up against these main flows and flows underneath these flows to the gate. At a flow rate of 15 m^3/day the approaching flow lines cross the retention zone and contamination is being pressed to the depth. At a flow rate 30 m^3/day the approaching flow lines turn away upstream of the retention zone.
Also in case of infiltration in the retention zone a ‘closed’ water system is being created.

The retention zone has an intrinsically isolating capacity. The natural groundwater flow rate is low (3 – 5 m/year) and the permeability of the retention zone has decreased by at least 50% as a result of the presence of oil. Therefore, the retention zone offers resistance to groundwater flow.

5.4 **Groundwater modelling**

Introduction
During the design stage of the 'Funnel and Gate' system in 1998, use was made of a groundwater flow model. For several reasons the same model was also used during the test phase:
- for the prediction of the results of alterations (of the settings of the system)
- to answer several research questions

The model had been calibrated with a limited amount of data. Later on, more data have become available about the subregional groundwater flow and the soil layering. As such some of the insights have changed, especially concerning the influence of the near-by sewage system. This has resulted in an adjustment of the existing model, which has been again calibrated and validated. The calibration period is summer 1999, validation was performed for the situation in November 1999.

The modelling (adjustment, calibration and validation) is described in Appendix 1. Simulated flow patterns of mid March, June and October 2000 were compared to the actual measurements. Flow-line calculations were also conducted and scenarios for future phases in the project were established. These calculations are described in section 6.7.

Range of influence of the system in the groundwater model
The boundaries of the model area in 1998 were determined through existing experience at the University of Waterloo in Canada. At the occasion of earlier model studies by this institute it was clear that the hydrological influence of a funnel and gate at a distance of 2 to 3 times the width of the system was no longer detectable.

For the location at the Lijnbaan this meant, starting from the length (at that time) of the system of approx. 30 m, that the range of influence maximally equals approx. 70 m. The size of the model area therefore was set to 250 x 250 m at that time.

Using the revised model, for the design situation of 15 m^3/day with downstream infiltration, a range of influence of approx. 100 m was established. This equals approx. four times the width of the system.

March 2000
The measured and calculated flow patterns of March 2000 are depicted in map 17856-I-3. Both patterns agree reasonably well with each other. An important difference is the origin of the water: in the model a large part of the abstracted water consists of the infiltrated water (behind the gate), in reality only a small 'short circuiting' occurs. In the calculated pattern also no water collection at Westeinde is predicted.

The stagnant zone at the southern side of the western vertical wall, identified by the measurements, also does not exactly match with the calculations. The stagnant zone at the east side, deduced by the measurements, did match - on the contrary – with the model calculations.

The groundwater level gradient in the soil layer beneath the retention zone (NAP -2.2 to -4.0 m) equals in both cases approx. 0.02 m/m.

June 2000
In map 17856-I-4 measured and calculated groundwater levels are put together. The calculated and measured upstream level gradient respectively equal 0.03 m/m and 0.02 m/m. The calculated groundwater levels are globally 0.25 m lower than the measured groundwater levels.

The measured situation downstream agrees well with the calculations; levels, level differences as well as directions are comparable.

October 2000
The measured and calculated flow pattern for October 2000 is depicted in map 17856-I-5. The calculated pattern again agrees well with the measured pattern. The gradient equals to 0.04 m/m for both cases.
The vertical flow pattern behind the gate is not well predicted by the calculations.

Additional model calculations (flow line calculations) show that the water at the eastern side from the drains infiltrates via deeper layers (between NAP -2.2 m and NAP -7.0 m) and finally reaches the gate.

By geohydrological standards the differences in calculated and measured water tables can be considered as limited (< 0.25 metre). These differences are too high to be able to give a clear picture of the groundwater flow at the location of an active F&G system.

5.5 **Aspects of infiltration**

Downstream
The differences between the level inside the effluent buffers and the monitoring wells at the downstream side of the system are quite constant in time. An increase of these differences would suggest clogging of the soil at the location of the segments; this would indeed give rise to an extra water level difference in order to maintain flow.

The infiltration velocity is low compared to the value on which the design of the infiltration systems is based in [11]. The mean velocity of infiltration at the surface area of infiltration (gravel pack – soil, approx. 100 m^2) equals to 0.15 m/day (at 15 m^3/day) up to 0.30 m/day (at 30 m^3/day). This is a figure that is still much lower than the common design infiltration velocity of 0.5 to 1.0 m/hour.

The groundwater level has risen as a result of the infiltration, but did not end up higher than the signal value of the infiltration (0.5 m –gl). By means of the groundwater model the quantity of water has been calculated that can be infiltrated at a groundwater level of 0.5 m –gl. (NAP +0.5 m) in the effluent segments.

The model predicts a maximal infiltration rate of 60 m^3/day. This corresponds to an infiltration velocity of 2 m/day, a figure which still is much lower than the common design infiltration velocity of 0.5 to 1.0 m/hour at the level of the boring hole wall [11].

Upstream

The maximal infiltration rates are determined by the dimensions of the slit, the geohydrological conditions (groundwater level, acceptable rise of groundwater level, soil permeability) and the entrance resistance at the surface area related to the quality of the infiltration water (possible clogging). The maximal infiltration rate in the drains 3 and 6 (length 15 m, width 1.0 m) is calculated with the groundwater model.

For the model calculations the following boundary conditions were used:

- the groundwater level is NAP -0.5 m;
- the level of the bottom of infiltration slit is NAP +0.1 m;
- the acceptable groundwater level is NAP +0.6 m;
- no entrance resistance.

A maximal infiltration rate of approx. 30 m^3/day is calculated. The infiltration rate is lower if the groundwater level is higher and the entrance resistance increases.
In the aforementioned situation the drain slit is completely saturated till 0.5 m –gl. Because the horizontal permeability is much higher than the vertical permeability, the water is mostly infiltrated through the walls of the slit. If the slits of drain 3 and 6 are saturated till 0.5 m –gl water can be infiltrated through approx. 16 m^2 wall surface. The mean infiltration velocity is therefore approx. 2 m/day, a figure that is still much lower than the common design infiltration velocity of 0.5 to 1.0 m/hour [11].

5.6 Other aspects

Vertical walls (B4)

Substantial differences in water levels alongside the vertical walls were already detected during the test phase of the system. We conclude that these walls are sufficiently water-tight. It should be stressed however that small leakages couldn't be detected with the current density of the measurement grid. The probability of the occurrence of such leakages however is estimated to be low: at the time of the installation the seams that are used were lock-sealed. The locks of the double vertical walls were also filled with a swelling product.

Passive system (B11)

To answer this research question, the groundwater model was used. To do so, a gravel bed replaced the gate. The model calculation reveals that the gate does not capture the groundwater originating from the most contaminated zone in the street. This water flows along the gate in southeastern direction.

In principle, the water can flow into the gate without abstraction and be aerated subsequently. The flow rate is related to the resistance that the water meets when flowing through the gate system.

5.7 **Conclusions**

The permeability of the retention zone is lower than the permeability of the same layer outside the retention zone. The difference is attributed to the presence of oil components. The groundwater model is adjusted at this point.
The average permeability of the shallow aquifer is derived from Darcy calculations and the result fits with early measurements.

Groundwater flow
At an abstraction rate of 15 to 30 m^3/day and downstream infiltration, a large part of the effluent is directed towards the inlet construction. A locally ‘closed’ system arose and a part of the incoming water (from northwest directions) sunk away.
At an abstraction rate of 15 m^3/day and upstream infiltration the groundwater level rose and the velocity of the groundwater increased in comparing with the early periods. Run-off of infiltrated water towards the public garden occurs. Back flow at the short wing does not seem to occur. In this situation too, little water flows from the surroundings towards the water inlet.

The groundwater flow within the retention area is reasonably well predicted by the groundwater model used. The origin of the water in the model however shows differences with real behaviour: in reality less water originates from the system itself (downstream infiltration). This can be attributed to local variability in permeability and drainage by sewer systems, which characterise urban areas. This leads to the conclusion that, despite the large quantity of measuring data, groundwater modelling at such local scales in urban areas, remains difficult.
Using the upstream infiltration can partly solve these problems; the water then indeed flows directly towards the gate. For design purposes, the model therefore is a useful tool.

By geohydrological standards the differences in calculated and measured water tables can be considered as limited (< 0.25 metre). These differences are too high to be able to give a clear picture of the groundwater flow at the location of an active F&G system.

With the adjusted model, in the case of the design situation (15 m^3/day; downstream infiltration), an area of influence was deduced equalling approx. 100 m. This is, more or less, four times the width of the system.

Downstream infiltration
Within a time period of approx. 8 months water has been infiltrated at the downstream side of the gate at rates of 15 to 30 m^3/day. The corresponding infiltration velocity (0.15 to 0.3 m/day) can be called relatively slow. Above that suspended material, iron and biological compounds were removed from the water. This clarifies why no infiltration problems occur.

The rate of infiltration is in this situation governed by geo-hydrological conditions. The maximal infiltration rate is approx. 60 m^3/day and is fixed by calculation with the groundwater model. The rate is lower to the extent that the entrance resistance increases in time.

Upstream infiltration
The upstream infiltration using the drain at the location of the street does not cause any difficulties during the test phase. According model calculations is the capacity of infiltration approx. 2 m/day and is therefore lower than the design value.

CHAPTER 6

OPTIMISING ABSTRACTION AND INFILTRATION

6.1 Introduction

The contaminants in the retention zone will be removed through the water phase. The groundwater in the retention zone will be replaced by groundwater from the surroundings or by treated groundwater from the gate. One of the test phase priority objectives is to determine the system settings that will capture as much load of oil components as possible in the gate (research question A2). At this system setting that part within the retention zone will be caught where the most load of dissolved oil components is and from which as much of the mobile oil components as possible will be mobilised.

In the test phase the test settings have been changed once more (see table 6). The optimum system setting for the short term has been derived from the data collected and calculations with the groundwater model.

6.2 Localising the retention zone

Method

The most heavily contaminated parts of the retention zone have been derived from the soil survey [8,9] and the location of these areas has had further verification and plotting by dynamic monitoring. Interpretation of the concentration measurements in the gate was carried out in conjunction with the changes in groundwater movement. By ascertaining the origin of the groundwater sampled in the gate an insight will be gained into the concentration distribution upstream of the gate.

The interpretation of the concentration measurements is dependent upon benzene. Benzene is used as a tracer substance because the retardation of this substance is relatively low (between 1 and 2). Consequently, changes in benzene concentration can be better related to changes in the groundwater flow. The retardation of the other oil components examined is significantly higher. This means the relationship between the concentrations of these substances and changes in the groundwater flow, brought about during the test phase, can because of this be difficult or impossible to recognise.

It should be noted that, for optimising the load, the measurements made on 2 February, 8 June, 4 and 7 September and 12 October have not been used. The concentrations measured on those days were very low since the system was shut down and because of the construction of the groundwater inlet. This aspect will be examined further in section 6.5

Localising

The soil survey [8] showed there are three areas in the retention zone where the concentrations are higher than the intervention values. One of these coincided largely with the gate and was thus excavated during the construction of the gate. In addition there are considerably increased concentrations of BTEX and oil in the soil under the street between the Westeinde and the Lijnbaan (further referred to as street). Finally a ‘spot’ was shown below the Westeinde (at drilled point 844).

The concentrations in the gate are by far the highest in the period that the water was infiltrated upstream (in the drains). The highest concentrations are measured in the segments B, C and D.
In conjunction with the flow pattern of mid October the contours of the retention zone in the street were derived. Where the boundary of the retention zone on the opposite side of the street lies can not be determined by this method. However, this boundary has been determined [8, 9]. The most heavily contaminated part of the retention zone has been determined in this way. The area is shown in map 17856-I-3 et seq. The western boundary agrees closely with the border of the excavation in early stage i.c. the line of the sheet piled pit as shown in [9].

The foregoing was checked once more by dynamic monitoring of concentration measurements in the first two periods (till mid May). This showed that the concentrations in segments A to E during these periods could be connected with the presence of contaminants in the street. So in the first period high concentrations were measured in segment E, because in this period flow lines through the area described above came out in segment E (see map 17856-I-3).

Contamination is also present above the groundwater level. So, during the installation of the infiltration drains in the street about 10 m^3 of heavily contaminated soil came out of the drain trench. Because of infiltration in these drains the groundwater level has also risen and as a consequence more contaminated soil has water flowing through it. A consequence of this is the marked increase during the third period in concentrations in the gate.

It may be put forward, on the basis of concentration measurements in the gate that the extent of leaching out of the ‘spot’ at drilled point 844 is markedly lower than the leaching out of the contaminants in the street. The raised concentrations in segment F measured in the first period can possibly be connected with this spot. The concentration level in segment F is markedly lower than in the other segments. In the periods that followed, if the flow lines come out through this spot in segment E, the concentrations in segment E are still lower.

Three retention zones were distinguished in the soil investigation. The first zone was excavated during the installation of the gate. The results of the test phase show that the supply of contaminants from the retention zone at the location of drain 1 to the groundwater is limited compared to the supply from the retention zone at the location of Westeinde, which was beyond expectations. By far the highest concentrations were measured in the last-mentioned retention zone.

6.3 **Optimum groundwater exchange in the retention zone**

The next question is, at what setting of abstraction and infiltration the most contaminants are mobilised in the retention zone in the street. To answer this question it has first been ascertained in which period the highest load per day has been mobilised from the retention zone in the street and captured in the gate. For this, the load in the segments B, C and D on the days they were sampled were calculated. The greatest part of the load from the retention zone in the street is captured in these segments. Figure 10 shows the calculated loads graphically.

The BTEX load has increased in each period till November. The increase in period 2 is attributed to increasing concentrations and the increase in the mean groundwater velocity in the retention zone (from about 0.05 to 0.15 m/day).
The increase in period 3 is caused by the increase of the concentrations; the mean groundwater velocity in the retention zone is in period 3 hardly increased. The increase in concentrations in period 3 is attributed to the higher groundwater level by which more contaminant came in contact with groundwater and so mobilised.

As a result the BTEX load is related to the flow rate and the location of infiltration. This relationship is being confirmed once again during the last period (as of mid November). During this period the water is infiltrated downstream again at a daily rate of 15 m^3/day, like during period 1. The groundwater level lowers and the groundwater velocity decreases compared to the preceding period. A lower BTEX load is the consequence.
The load of mineral oil is represented in figure 10 as well. The increase in load is clear during the period the water is being infiltrated in the retention zone. The increase of the load is attributed to the raise of the groundwater level and, with that, the mobilisation of oil components in the unsaturated zone. During the final period the load of mineral oil stabilised more or less.

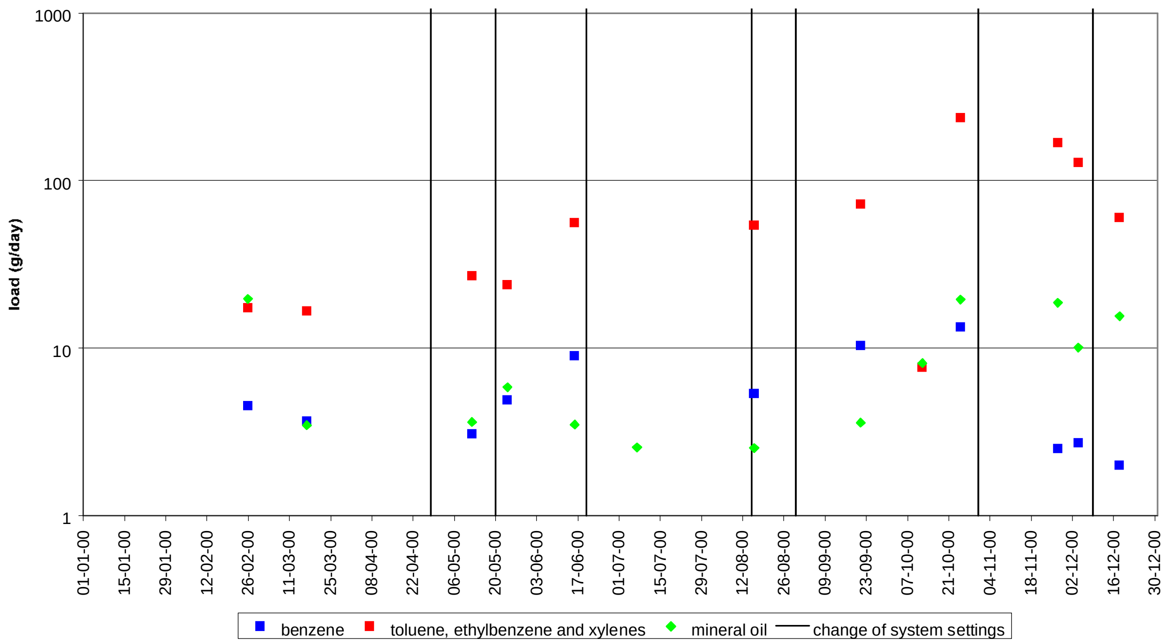


Fig. 10. Load removed from segments B, C and D.

Until the end of October the retention zone has had about 2 water exchanges using groundwater from the surroundings. The remediation is now still in the phase where the groundwater that has been in contact with the oil for many years and is very heavily contaminated is being flushed out of the retention zone. The mass in permeable zones is removed by advective transport. Slow transport processes like desorption and diffusion do not play a part during this phase and will only determine the load in the gate at a later stage. Since the load is removed by advective transport during this phase, it may be assumed that the load removed is greater to the extent that the groundwater velocity is higher.

After the phase mentioned above groundwater will be abstracted that shall be a much shorter contact with the oil. The concentrations in the gate will then also fall during this phase. The concentrations will then be determined by such slow processes as diffusion and desorption of the contaminants in the retention zone. The optimum groundwater velocity during the second phase can only be determined during that phase. Also, during this phase the optimum groundwater velocity will change with time.

The thickness of the saturated retention zone will thus increase by infiltration. It is just that oil which otherwise would be above the groundwater level and only precipitation water flows along that enters the saturated zone. It is evident that this oil leaches out more than the oil that has been in contact with the groundwater for many years.

The highest load is being removed when infiltration in the retention zone is applied. The drains 3 and 6 have to be used for an effective flushing of the retention zone. The four segments receiving water from the retention zone, has to be keep open.

6.4 **Pass-flow**

From the flow patterns from periods 1 and 2 it appears that there has been no pass-flow. The groundwater flow in the retention zone was directed towards the gate.

In period 3 a flow of 15 m^3/day of groundwater was infiltrated via two drains (drain 3 and 6) into the retention zone. From the marked increase in the concentrations in tube A21, which is outside the 'Funnel and Gate' system, it appears that some flow lines through the retention zone do not end in the gate. So the condition there may be no spreading to the plume zone, has not been complied with. Furthermore, a part of the infiltrated water streamed through the retention zone to the public gardens (see map 17856-I-5). The concentrations in mpD03 and mpD06 have, as a result increased. These contaminants will, however, according to a flow lines calculation return to the gate. It has been investigated in which way the water can be infiltrated upstream. A description of this investigation is given in section 6.7.

As a result of remediation in the retention zone (drain 6) pass flow along the funnel will occur.

6.5 **Under flow**

The appearance of under flow has been examined by dynamic monitoring. The concentration measurements in the series from the monitoring wells pbA, pbB and pbC have been used as well as the concentration measurements in the gate.

Concentration measurements in the series ABC
The contour of the contamination has been established, based on the first concentration measurements, when the system was still not in operation. The contour of the contamination is shown in map 17856-DP-1.

Period 1 and 2
The groundwater flows from the infiltration wells, along the two wings to the front of the gate are clearly recognisable in the maps 17856-I-3 and 17856-I-4. Considering the raised height difference on both sides of the wing, a part of the infiltrated water has flowed next to it under the wings and has returned to the gate. From the groundwater levels in the filters pbA01, mpD02 and pbA02 it has been found that the groundwater flowing in from the surroundings is dammed up near the Westeinde.

This groundwater then has sunk away and has flowed under the groundwater stream described above through to the gate. The groundwater flowing in from the surroundings sank deeper in period 2, because the stream along the wings is bigger in period 2.The vertical groundwater movement in this series is illustrated in maps 17856-DP-1 and 17856-DP-2.

This interpretation of the groundwater movement came about partly from the following interpretation of the measured change in concentrations in the filters pbB and pbC during the periods 1 and 2. The benzene concentration (the guide parameter) in filter pbC03 was first high and then very low because the middle-depth groundwater (at level pbB) was arriving. The benzene concentration was again high from mid April. Contamination out of the uppermost part of the aquifer had then reached filter pbC03. In the same period peak concentrations were measured in filter pbC02.

The low concentrations seen in mid August indicate that in period 2 the flow lines through pbC02 and pbC03 have not come from the contaminated soil section. The groundwater flowing in from the surroundings sank deeper than in period 1. This flow has gone through the filters pbC02 and pbC03.

Period 3
Mid August the groundwater was investigated again. At that moment the abstraction had been inactive for about two weeks. The concentrations in filters C turn out to be higher again than the last time. Apparently, the groundwater flow has changed in the meantime as a result of the interrupted abstraction and the deeper groundwater below the less permeable layer is still contaminated.

In period 3 only one concentration measurement was carried out (mid October). The next measurement was carried out when the abstraction had been stopped and during the last measurement the extracted groundwater was infiltrated downstream again. Mid October the concentrations were much higher than in August. The development of the concentrations afterwards would have provided more information on the origin of the groundwater sampled at this depth. A non-decreasing trend would have indicated that the groundwater sampled has previously flowed through the retention zone. So, in that situation a part of the infiltrated water comes below the less permeable layer at NAP -7 m. Decreasing concentrations indicate that leakage to the deeper groundwater below the less permeable layer at NAP -7 m is not taking place anymore and that furthermore that in the course of time under flow of contaminated groundwater will not occur.

Based on the collected information it cannot be excluded for the time being that contamination below the less permeable layer at NAP –7 m is being extracted as a result of the strategy following during period 3. Furthermore, it is not clear whether contaminated groundwater is seeping up again to the inlet or flows below the wings (under flow).

There is no doubt that under flow of contaminated groundwater occurs if the groundwater abstraction should be stopped now (temporarily). In this situation deeper groundwater will move itself in a horizontal direction below the wings. That contaminants will be drawn down into the deeper groundwater seems to be possible, considering the design of the inlet. The inlet opening of the abstraction tubes is at NAP -4 m. The groundwater is withdrawn from this level, which is about 2 metres below the retention zone. Besides, the gravel package is present up to about NAP -5.5 m, about 1.5 m above the lower side of the wings. Since the resistance of the gravel package against the groundwater flow is very low, the groundwater level is the same in the entire package. As a result the extraction will reach a greater depth compared to a construction with a gravel package less deep.

Concentration measurements in the gate
Very low BTEX concentrations have been measured at a number of times in the gate. This low concentration level has been connected with the operation of the system and the design of the water inlet.

The concentrations in the segments were in the initial period very low. This low concentration level was connected to the changes in the groundwater flow as a result of the well point drainage in the gate. The groundwater in the retention zone flowed first in a southerly direction and from early February has bent around to the gate. Moreover, groundwater from the retention zone has been drawn downwards. The flow routes have thus changed; the contaminated groundwater flows by other routes than it did formerly. Other areas for adsorption are therefore available to the contaminants. Breakthrough of the contaminants was shown in most of the segments at the end of February.
The groundwater sampled on 8 June, 4 and 7 September, as well as on 12 October contained no demonstrable concentrations of BTEX and mineral oil or at concentrations markedly lower than at the previous concentration measurement. It is noticeable that each time the system is out of operation for several days or weeks and several days before sampling it is put back into operation. That this method of operation of the system has influenced the concentration in the gate appears from the following. The groundwater in each segment is abstracted through an abstraction tube in the gravel pack. The inlet entry of the abstraction tubes is at NAP -4 m, about 2 metres below the retention zone. When abstraction is started, first the groundwater at the level of the inlet opening is drawn in. Because the flow is relatively low, it takes a number of days before the heavily contaminated water from the retention zone breaks through significantly into the groundwater abstracted.

Based on the interpretation of the coherence between the concentrations and the initiated groundwater flow data in the contaminated area (dynamic monitoring), it is tentatively concluded that contaminants migrate to below the resisting layer in case of extraction and infiltration in the retention zone. By extending the measuring grid to behind the system it will be investigated whether contamination is spreading to below the ‘hanging’ funnel as well.

Strongly contaminated groundwater is being pressed down as a result of the deep extraction point and the inlet made of gravel. A higher inlet point would not only limit the chance of under flow but would lead to a better flushing of the retention zone as well.

6.6 Natural attenuation in the plume zone

Zero situation

A supplementary groundwater examination has been conducted in mid-1999 to verify the presence of contamination on the downstream side of the system. It appeared from this examination that the plume zone was not as long as had been assumed in 1998 and that the contamination had spread in Southeast direction. Following this a check was made of how this deviation was caused at the position of a filter where samples were taken normally and with the cone sipper and were analysed. The analysis results were in good agreement with each other. It was concluded that the deviation was not caused by sampling but by the analysis technique.

The plume is not longer than 10 meter. Because monitoring wells are not present in the plume information which could be a relation to biodegradation can not be obtained.

Partly because of the isolating capacity of the retention zone the plume is limited in size.

Changes in the groundwater flow

From measurements and calculations it appears that a groundwater flow on all sides in the plume zone has been initiated by infiltration behind the gate (see map 17856-I-3 and -I-4). This

groundwater flow has changed the concentration distribution in the plume zone. Thus, the concentration level in filter tp35 has increased markedly. It appears moreover, from concentration measurements in the water behind the gate that spreading outside the original plume zone has not taken place. When the infiltration behind the gate is continued the plume zone will certainly become wider.
The groundwater flow in the plume zone changed again in the third period. The flow lines along the two wings of the funnel converge behind the gate (see map 17856-I-5). With the condition that no contaminated water flows into the plume zone, the plume zone will be made narrower by this groundwater flow.

Infiltration of treated water in the plume has caused spreading of the contamination. The flow rate and duration of infiltration have to be attuned to the purifying capacity of the soil.

6.7 **Synthesis**

Based on the findings above the following approach to the contamination is proposed:
- abstraction and infiltration under the street for the flushing of the retention zone in the street;
- monitoring of the plume zone.

Abstraction and infiltration in the street
The setting in period 3 has lead to a pass-flow (see section 6.4). The system will be reset in 2001. The treated water will be infiltrated in drain 3. The effect of this setting on the groundwater movement and the concentration in filter A21 will be examined. For an even flow through the retention zone in the street segments B to E of the gate remain open, while segments A, F, G and H remain closed.

Some other settings have been examined to maximise the load in the gate. The following limitations apply:
- The abstraction flow will not, for the present, be increased as long as it has not been demonstrated that the residence time in the treatment system can be less than 4 days;
- The infiltration capacity of each drain is 15 m3/day (see section 5.5);
- The flow lines through the retention zone must end in the gate, thus without pass-flow;
- The flow lines through the ‘spot’ near drilled point 844 must also end in the gate.

The load in the gate is higher when the groundwater level and the groundwater velocity in the street are higher. The groundwater levels and the groundwater flows resulting from the settings below have been calculated using the groundwater model:
1. Abstraction of 15 m^3/day and infiltration of 15 m^3/day in drain 3 (the present setting)
2. Abstraction of 15 m^3/day and infiltration of 10 m^3/day in drain 3
3. Abstraction of 15 m^3/day and infiltration of 15 m^3/day in drains 2 and 3
4. Abstraction of 15 m^3/day and infiltration of 10 m^3/day in drains 2 and 3
5. Abstraction of 30 m^3/day and infiltration of 15 m^3/day in drain 3

Only for settings 4 and 5 will, according to the calculations, there be no flow lines from the retention zone ending in the plume zone. The highest groundwater level will be reached with setting 1. The flow through the retention zone with these settings will be about 1 m^3/day.

The pass-flow along the short wing of the funnel is a critical factor. This determines the maximum permissible infiltration flow, in particular. The short wing has not been made longer because of the presence of the sewer in the street.

The following is proposed as the continuation. The effect of the present setting on the groundwater movement and the concentration in filter pbA21 will be determined first. If the desired situation (no pass-flow, falling concentration in pbA21) is established, then the infiltration and abstraction will be continued on the same lines. When the desired effect does not appear setting 4 will be applied.

Monitoring of the plume zone

Monitoring of the plume zone will continue. There is, at present, no indication that an active approach is required. Spreading of the contamination outside the contour of the value aimed for has not been shown.

The monitoring must be directed at, in particular, the pass-flow (filter pbA21), under flow and possible flow of contaminants towards the public gardens. To detect any under flow two deep filters will be placed at the positions of filters pbA09 and pbA21 and at approximately 8 metres below NAP and 11 metres below NAP. A number of shallow and deeper filter filters will also be placed at the edge of the public gardens.

Fall back measures

The following measures are possible when there is a spread of contamination:

1. Laying an infiltration drain along the edge of the gardens (outside the retention zone);
2. Abstraction of groundwater in the gate without infiltration (discharge into the sewer);
3. Abstraction of groundwater nearby filter pbA21 and in the gate and infiltration in the street;
4. Abstraction of groundwater behind the gate to act against spreading through the deeper groundwater, with abstraction in the gate and infiltration in the street;
5. Abstraction of groundwater to control the plume zone.

When there is abstraction of groundwater near the ‘Funnel and Gate’ structure no spreading will occur as long as the groundwater withdrawn, after treatment, is again infiltrated. When controlling the plume zone the pit will be placed at some distance from the ‘Funnel and Gate’ structure and, moreover, the flow is so low that spreading from the retention zone is not considered to be probable.

Finally, it is noted that for a passive variant possibly not all the contamination will pass through the gate. A part will flow along the short wing.

6.8 Conclusions and recommendations

Conclusions

Three retention zones were distinguished in the soil investigation. The first zone was excavated during the installation of the gate. The results of the test phase show that the supply of contaminants from the retention zone at the location of drain 1 to the groundwater is limited compared to the supply from the retention zone at the location of Westeinde, which was beyond expectations. By far the highest concentrations were measured in the last-mentioned retention zone. Based on this information the extraction strategy was adjusted. The four segments receiving water from this retention zone, were kept open, while the other four segments were closed off.

The highest load is being removed when infiltration in the retention zone is applied. This can be explained by the fact that by way of infiltration in the retention zone firstly the hydraulic gradient is getting higher and consequently the groundwater flow rate and secondly the water table is increasing and as a result the contact area between the oil and the groundwater is getting larger as well. Infiltration outside the retention zone is less effective, because the retention zone forms a barrier for the groundwater flow.

The drains 3 and 6 have to be used for an effective flushing of the retention zone. In view of pass flow it is recommended not to use drain 6. Taking into consideration the aforementioned infiltration capacity, the flow rate for the remediation if using drain 3 cannot be much higher than 15 m^3/day. The flow rate through the most important retention zone has been calculated at about $1 m^3$/day.

An indication of the remediation duration can be obtained at the moment that the ‘old’ contaminations have been removed from the retention zone and insight is obtained in the supply behaviours of the solving oil. That moment has not arrived yet in the test phase. Therefore the duration of the remediation cannot be predicted yet.

Infiltration of treated water in the plume has caused spreading of the contamination. The flow rate and duration of infiltration have to be attuned to the purifying capacity of the soil.

Recommendations
The test phase has made clear the preconditions for an optimum operation of the F&G system. The optimum extraction and infiltration strategy has been determined and are made still in practise:
- Drain 3 is used for an effective flushing of the most important retention zone;
- The segments which receiving water from the most important retention zone, are still operational, the others are not;
- The flow rate is limited by the infiltration capacity of drain 3 and is not higher 15 m^3/day;
- Infiltration in the plume for the purpose of stimulating biological degradation has to be of short duration. The flow rate and duration have to be determined in more detail and are related to the natural attenuation processes in the plume.

It is also recommended to investigate the groundwater under the funnel behind to gate in order to verify underflow of contaminants.

CHAPTER 7

WATER TREATMENT

7.1 Introduction

According to the test and monitoring programme, there would be a research during the test phase into the best possible utilisation of biological treatment. One of the constraints in this regard is a relatively constant load on treatment facilities. However, there have been no indications of a steady load whatsoever. This is due on the one hand to a number of changes to the remediation system inherent to the test phase (balancing the extraction/infiltration). On the other hand the periodic shutting down of the system resulted in concentration dips in the influent and contamination was removed in the pre-treatment step. Now the extraction and infiltration have been optimised, the implications of shutting down for the influent concentrations have been identified and the concentrations are higher, attention can be focused on optimising the biological treatment.

The test phase has provided insight into the organic load of the treatment installation and the treatment processes in the installation. The findings are addressed in this report. The findings will be used in the further optimisation during the remediation phase. The research questions are answered as good as possible.

7.2 Operation of the treatment installation

The flow chart of the treatment installation is on map 17856-F-1. The installation consists of a pre-treatment (aeration buffer and sand filtration), a biological treatment in the short and the long zone and a polishing (sand filtration). The aeration and the sand filtration are meant to remove iron and other not dissolved material. The contaminants should be decomposed in the short and long treatment zones.

The short and long treatment zones were connected in series and the second sand filter was in operation throughout the entire test period. The first sand filter and the aeration of the buffer tank and the treatment zones did not operate continuously. The settings are summarised in table 10.

The treatment unit will have an exhaust system. The exhausted air will be led through an active carbon filter. The short and long treatment zones will not be exhausted.

Table 10. Treatment settings.

Period	Component				
	Aeration buffer tank	1nd sand filter	Aeration short zone	Aeration long zone	2nd sand filter
1/1 – 22/3	+	+	-	-	+
23/3 – 15/08	-	+	-	-	+
15/08 – 30/08	-	-	-	-	-
31/08 – 26/10	-	-	-	-	+
27/10 – 27/11	-	-	+	+	+
28/11 – 7/12	+	+	+	+	+
27/11 – 31/12	+	+	-	-	+

7.3 Decomposition in the treatment installation

The concentrations BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), oxygen, nitrogen-Kjeldahl and nitrate are periodically measured in the influent, effluent and in the installation to determine whether decomposition of organic material has taken place in the installation and if so, to which extent. The last measurements were carried out on 7 July 2000.
The following sampling points are used:

- MN01: influent buffer (8 compartments a to h);
- MN02: collector pipe (for aeration buffer);
- MN03: between aeration buffer and sand filter;
- MN04: between sand filter and biological treatment zone;
- KS01 and KS04: first and fourth compartment short treatment zone;
- LS01 and LS07: first and seventh compartment long treatment zone;
- MN11: in front of sand filter;
- MN12: after sand filter;
- MN07: effluent after buffer container.

The flow scheme and sampling points are indicated on map 17856-F-1.

The presence of nitrate in the effluent is indicative of the decomposition of the major part of organic material and consequently of a far-reaching decomposition [12]. Nitrate is being formed in the installation by nitrification of organic material. Nitrification only takes place when carbon, hydrogen and other elements have decomposed into carbondioxide, water and other oxides. As long as non-oxidised organic carbon compounds are present in the water, nitrogen cannot convert into nitrate [12]. Taking into consideration the concentrations measured and the low flow rate (maximally 30 m^3/day) the COD load can be considered as low in this case.

In February and March nitrate was found in the first compartment of the short treatment zone (see figure 11). This is indicative of decomposition of organic material during pre-treatment (aeration buffer and sand filter). Besides, a clear increase in the nitrate concentration was measured in the short treatment zone, whil the nitrate concentration is not further increasing in the long treatment zone. This demonstrates the occurrence of decomposition in the short treatment during this period.

Subsequently, the treatment output of the short treatment zone has decreased, since on 29 March and 20 April no nitrate was found, although nitrogen-Kjeldahl did occur. The presence of nitrate in the effluent at these dates shows that in the second sand filter decomposition of organic matter was taking place. During the months afterwards concentrations of nitrogen-Kjeldahl and nitrate were measured in the effluent only. The presence of nitrate in the effluent is indicative of mineralisation and consequently of a far-reaching decomposition of organic material in the treatment installation. On 7 July no nitrate was measured in the effluent and decomposition of organic material was incomplete.

The chemical oxygen demand is an indication of the oxygen consumption by chemical conversion. The COD concentration in the influent varies between 20 en 40 mg/l.

The COD concentration decreases in the installation till a level of 15 to 20 mg/l in the effluent. Approximately 10 mg/l COD is decomposed or disappears from the system in some other way. The residual COD is not or hardly degradable in the installation.

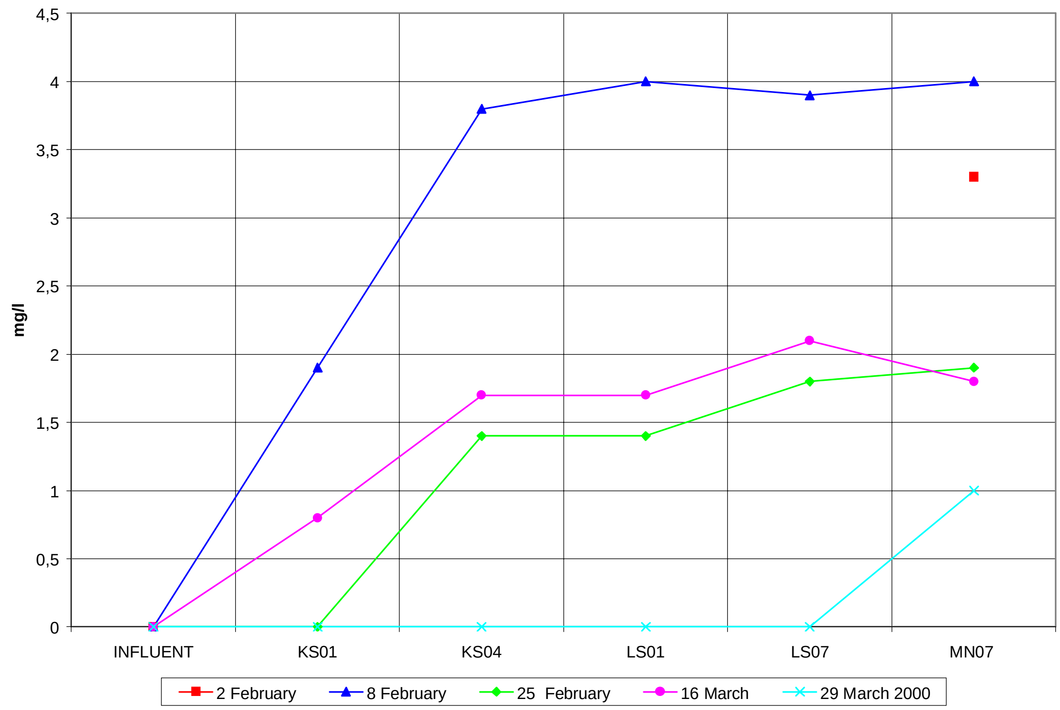


Fig. 11. Nitrate in the treatment installation in February and March.

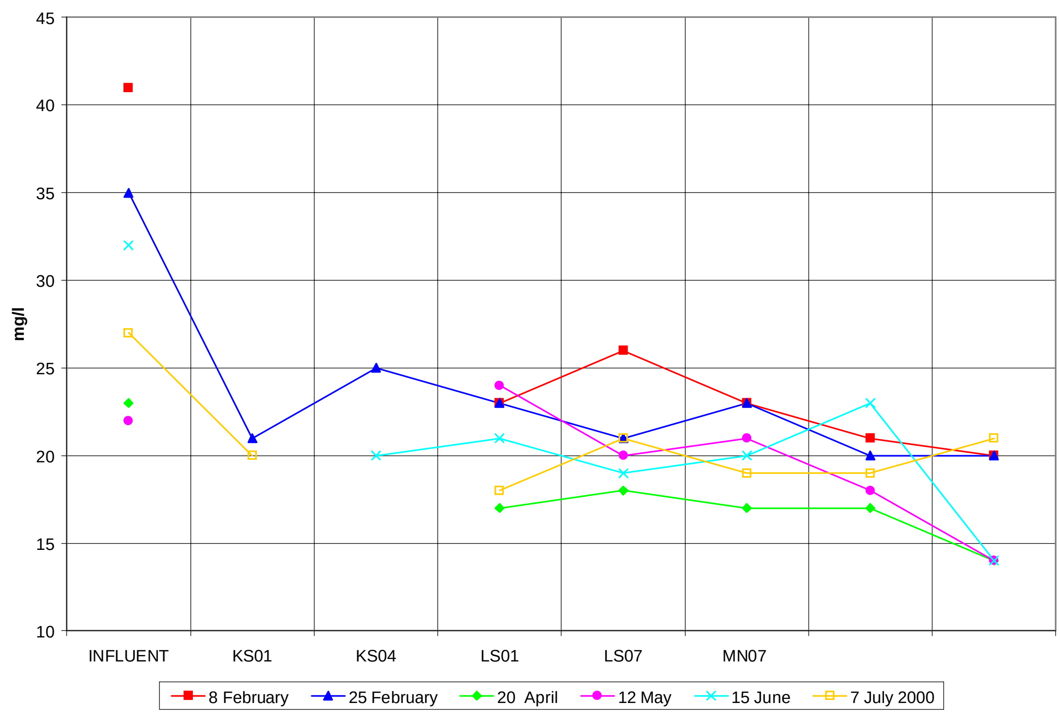


Fig. 12. COD in the treatment installation.

The major part of the COD decrease is realised in the pre-treatment zone (aeration buffer and sand filter) as shown in Figure 12. The COD decrease is thus mainly a consequence of adsorption in the sand filter and decomposition in the pre-treatment zone. Because the sand filter is frequently flushed the condition for adsorption is stayed optimal.
The COD decrease in the biological treatment zone and the second sand filter is not more than some mg/l. Also the same processes probably caused this decrease.

Based on the oxygen concentration measurements on-line the oxygen consumption in the short treatment zone is very low and thus also the biological decomposition. In the long treatment zone the oxygen concentrations are increased and thus can of biological decomposition little be expected.

The biological oxygen demand (BOD) is an indication of the oxygen consumption by biological decomposition. BOD is measured in the influent, effluent and in the installation itself. Compared to COD the concentration of BOD in the influent is low (< 10 mg/l) This means that only a limited fraction of the organic substances in the influent is biologically degradable under aerobe conditions. BTEX and part of mineral oil are easily degradable under aerobe conditions.

Consequently, the BOD in the effluent is < 3 mg/l after the first sand filter. This also indicates that biological degradation has taken place during the pre-treatment phase. It should be noticed that organic material might have been present in these water samples. Since denitrifying bacteria can degrade organic material while not using oxygen. Taking into consideration the presence of nitrate denitrifying bacteria may be present.

The concentrations of nitrogen and phosphate in the groundwater are approximately 1 mg/l. The nutrient supply may represent a restriction for biological decomposition if the concentrations remain at the same level as in the last period.

Far-reaching treatment of extracted groundwater is taking place in the gate. Removal of contamination mainly takes place during the pre-treatment phase. In the reactor with carrier material biological decomposition takes place as well. Probably, the supply of nutrients is the limiting factor for biological decomposition.

Biological decomposition does not take place in the ‘open’ bioreactor. This can be explained by the fact that the organic load of the contaminated groundwater is low and therefore insufficient sludge mass is being developed (‘thin water’).

7.4 **Removal of contaminants**

The concentrations of volatile aromatics and oil were measured in a number of places at different times. The results of the concentration measurements are given in appendices C and E.

The concentration of oil in the influent varies between 0 and approximately 1,300 µg/l and the concentration of aromatics in the influent varies between 0 and approximately 16,830 µg/l. These influent concentrations were calculated from the arithmetical average of the influent of the segments in operation. The instantaneous benzene, TEX and oil loads on the system are given in appendix C. The maximum system load is approximately 20 gram oil per day and 250 gram aromatics per day.

The concentrations of benzene, xylenes and mineral oil the most important sampling points are given in figures 13 to 14. The average concentration in the influent flow (MN01), the concentration after the aeration buffer (MN03), the concentration after the first sand filter (MN04) and the concentration of the effluent to be infiltrated (MN07) are shown for benzene, xylenes and mineral oil.

The effluent is infiltrated in the plume zone except in the third period (mid September till mid November). It can be deduced from the effluent concentration measurements (MN07) that the plume zone has loaded very little or no contamination. The effluent was only contaminated significantly in October, but in this period the effluent was infiltrated in the retention zone.

The figures show that the major part of the contamination is removed in the first sand filter. The biological treatment is only loaded significantly in the period that the first sand filter is out of duty and the concentrations in the influent are high (September till mid November).

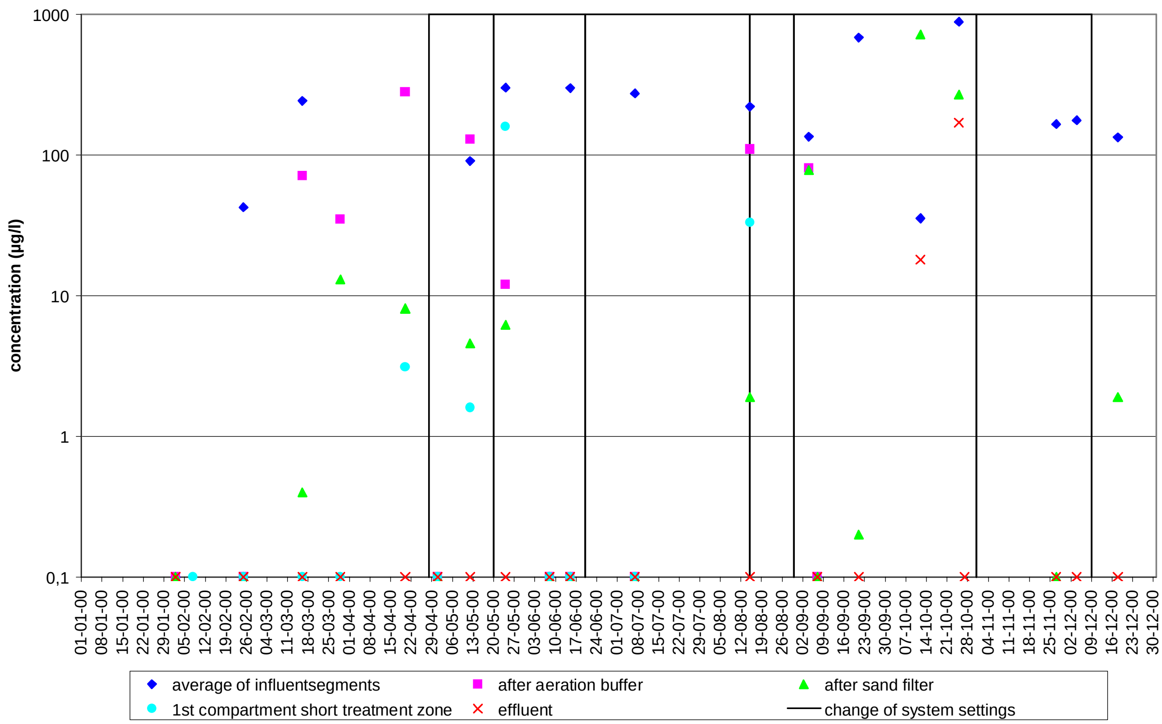


Fig. 13. Benzene concentrations in the treatment installation.

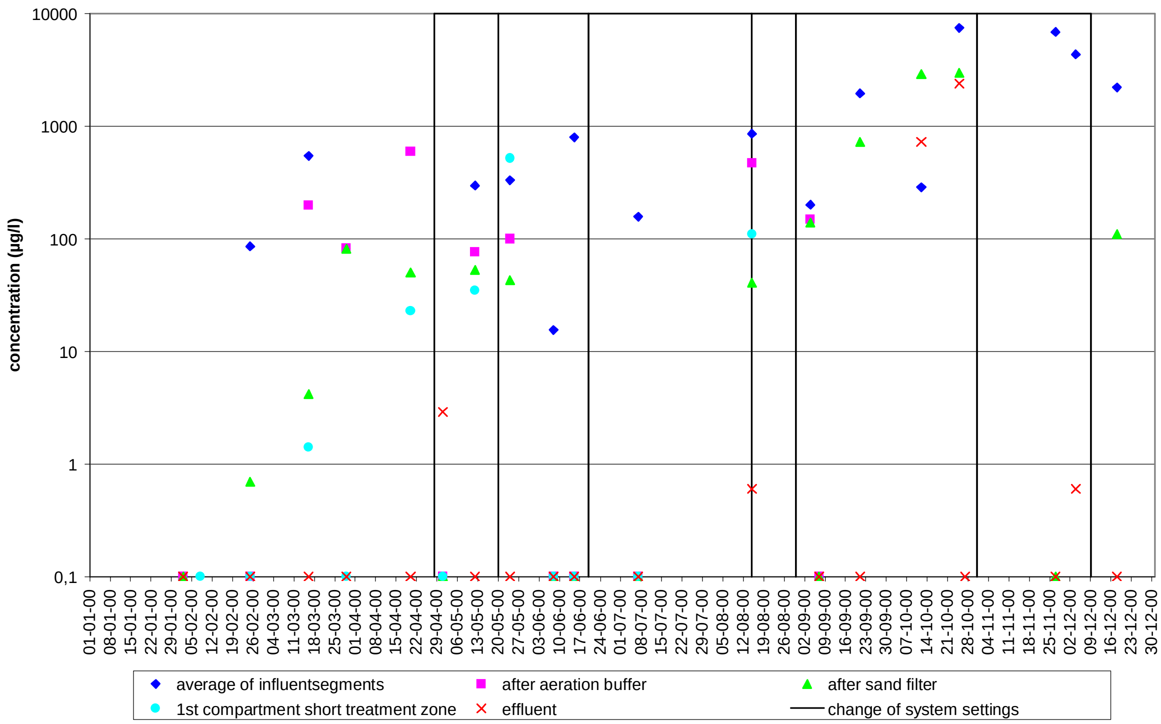


Fig. 14. Xylenen concentrations in the treatment installation.

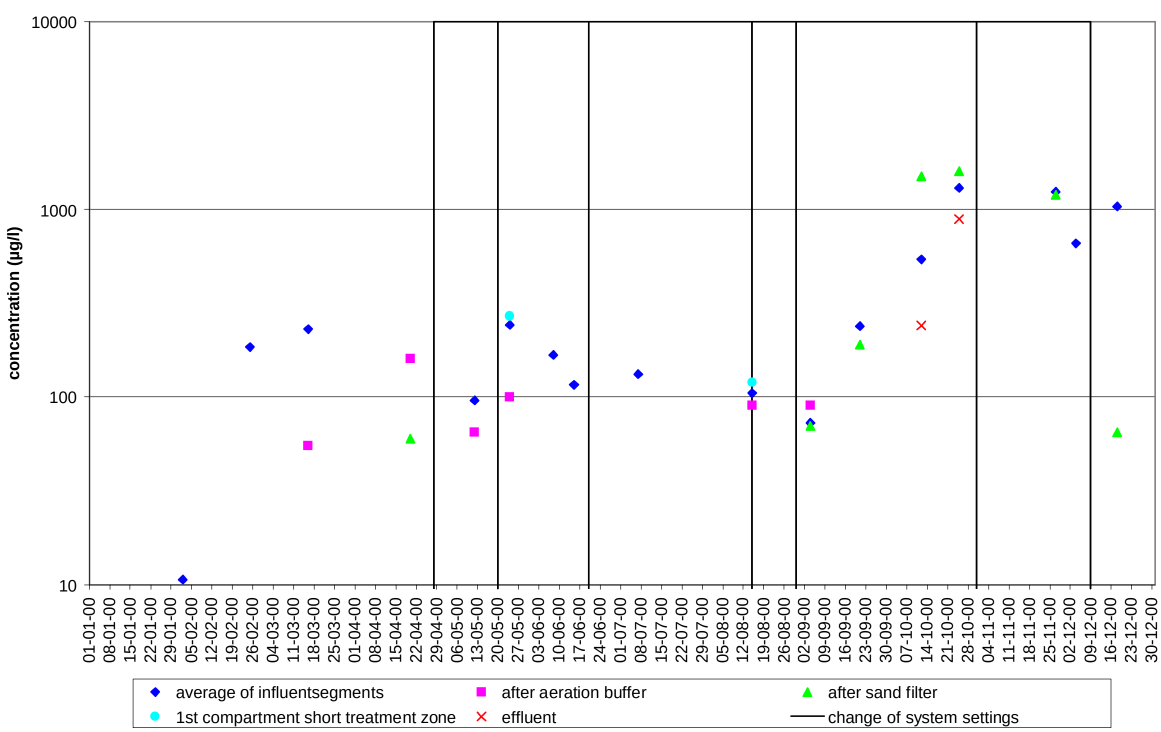


Fig. 15. Mineral oil concentrations in the treatment installation.

In October the decomposition rate in the biological treatment zones was not sufficient to get low concentrations in the effluent. The sludge mass was probably too small at that moment to decompose the contaminants.

In November the biological treatment zones are aerated and the first sand filter was out of duty to upgrade the biological decomposition in the biological treatment zones. The low concentrations of mineral oil in November and December are probably the result. Volatilisation of the contaminants has been possible, as the air injection was too high to decompose the volatilised contaminants.

On 18 October the benzene concentration was measured in the effluent of the carbon filter. The concentration was 1.4 mg/m^3. As a result the active carbon in the filter was replaced. This result means that volatilisation has been occurred.

7.5 Answering research questions

Removal rate (A3, A5, A7)

The presence of nitrate and the absence of BOD in the effluent are evident indications of far-reaching decomposition of organic substances. The far-reaching decomposition is partly the result of the low organic load of the installation. Also at a flow rate of 30 m^3/day the organic load is low and far-reaching decomposition has been demonstrated. Approximately 10 mg/l COD is decomposed or disappears from the system in some other way.

However, decomposition has been occurred mainly in the first sand filter. Decomposition has also been occurred in the short treatment zone. The removal rate in this zone cannot be deduced from the available information. Decomposition in the long treatment zone is expected to be limited.

Capacity of the biological treatment unit (A4, A6)

The organic load of the system is very low. Besides a major part is removed in the pretreatment zone. As a result of the limited concentration of COD little or no sludge deposit has taken place in the biological treatment zones. So the capacity was not sufficient enough in the period of no sand filtration and high loads of contaminants in the influent.

According to a thumb rule the organic load of a bioreactor with carrier material such as the short treatment zone is 1 gram COD/day.m^2 carrier material [13]. The total specific area of the carrier material in this case is 1,000 m^2. Thus, the decomposition capacity of the short treatment zone is approx. 1,000 gram COD/day. The load of BTEX and mineral oil is at maximum approximately 200 gram/day (see figure 10) and is equal to approx. 600 gram COD/day. Besides the COD of the other decomposable components are maximally 10 mg/l (see par. 7.3) and the organic load of these components is 300 gram COD/day at a rate of 30 m^3/day.
The hydraulic load has to be lower than 1 m^3/m^2 carrier material/day [13]. When the specific surface is approx. 1.000 m^2 the hydraulic load is approx. 1.000 m^3/day. In this case the hydraulic load of the treatment zone has been too low.

Basically the capacity of the short treatment zone could be sufficient to decompose the contaminants in this high loads. Besides the residence time in the short treatment zone is long enough.

Aeration (A1, A9, A10)
The third part of research consisted of comparing the performance of extensive methods of adding oxygen and/or nutrients (slow release compounds) with the performance of active aeration/compressed air injection. Following the development of the active 'Funnel and Gate' concept and the consortium's decision to continue with the testing and optimisation of precisely this concept, the research was abandoned. The delivery of substances by slow release compounds could not be actively regulated. As influent concentrations of contaminants and treatment rates will be constantly fluctuating, the active variant does require an oxygen supply that can be regulated (added in measured doses). For this reason aeration/compressed air injection was chosen.

An aeration tray is present in a number of compartments in the treatment system. The design capacity of the aeration trays is enough to put more than sufficient oxygen in the compartments. The aeration trays are not tested in the perspective of possible emissions of volatile components to the atmosphere.

Volatile oil compounds, such as benzene, vaporise as a result of aeration of the treated water. At low air to water flow ratios benzene will be stripped according to the theory of gas transfer.
However, several references give evidence in practise the emission of benzene to the atmosphere is low or not detectable. Reason for this has to be found in biological decomposition of vaporised components. Thus, not alone the water phase is treated, but also the injected air. Aeration becomes stripping if the biological decomposition in the reactor is insufficient.

The air has to be injected in the lower part of the reactor in order to make optimum use of the decomposition capacity of the reactor. In order to avoid evaporation as much as possible the water has to be lead through the reactor from the top to below; in case of co-current flow the stripping effect is less than in case of current flow. According to [13] the ratio of air flow and water flow ranges from 1:1 to 5:1 [13].

Co-current flow occurs in the compartment with carrier-material in the short treatment zone. Only in November the biological treatment zones were aerated in order to increase biological activity. At that moment the decomposition rate was probably too low to avoid emission. During the remediation phase concentration measurements will be carried out within the framework of optimisation of the aeration. During emission the air will be circulated. The exhausted air will be re-entered into the reactor.

Differentiated treatment (A8)
Differentiated treatment has not so far been addressed because of the low load. The use of the short treatment zone has to be sufficient for the treatment of the water.

Differentiated treatment in the short and long treatment zones can be applied in order to optimise the treatment. At the same time the water can be treated at two regimes. The added value of the addition of nutrient can be investigated for instance.

7.6 Conclusions and recommendations

The test phase has provided insight into the organic load of the treatment installation and the treatment processes in the installation and also into the costs of exploitation. It is recommended to optimise the water treatment by leaving out the pre-treatment and the 'open' reactor. As a result exploitation costs will get lower and the environmental output higher (lower use of energy, less waste, reduction of emission). At a later stage the effluent of the bioreactor can be aerated

as well in order to infiltrate water rich in oxygen and thus increasing the biological activity in the retention zone and in the plume, if necessary.
The presence of nitrate and the absence of BOD in the effluent are evident indications of far-reaching decomposition of organic substances. Far-reaching decomposition is partly the result of the low organic load of the installation. Decomposition has mainly occurred in the first sand filter. Decomposition has also occurred in the short treatment zone. Approximately 10 mg/l COD is decomposed or disappears from the system in some other way. The nutrient supply may represent a restriction for biological decomposition if the concentrations remain at the same level as in the last period.

It can be deduced from the concentration measurements that less volatile oil components are decomposed or adsorbed in the sand filters. In addition to this volatile oil components also volatilised and were captured in the active carbon filter (air treatment).

CHAPTER 8

ASSESMENT OF PLUGGING RISK

8.1 General

There is a risk of plugging during the abstraction and infiltration of groundwater. The plugging may be mechanical, chemical or biological. Plugging of the system can be caused by a number of different processes. The most common form of plugging is the result of iron precipitation that occurs when different types of water are mixed. The phreatic water flowing in contains some oxygen, but water from greater depths does not. The dissolved iron then oxidises in and around the filter. Iron precipitation is often accompanied by accretion of biomass. There is also often mechanical plugging.

Indicative limit values have been defined for the occurrence of plugging [4]. These limit values are given in table 11. The chance of plugging must be borne in mind if a limit value is exceeded.

Table 11 Indicative limit values for the occurrence of plugging.

Process	Limit value
precipitation of manganese, iron and/or biomass	Mn > 0.1 mg/l, Fe > 0.1 mg/l, CH_4 > 0.1 mg/l, O_2 > 0.01 mg/l
Lime	$SI_{lime} > 0$
Biomass	AOC > 10 µg ac-C eq/l
Particles	MFI > 3 s/l^2

8.2 Description of processes

Chemical processes

Iron precipitation

Iron is present in a reduced form in anaerobic groundwater. After contact with oxygen, iron is readily converted to the oxidised form. A part of the dissolved iron can also precipitate in the form of iron hydroxides (see the chemical equation below).

$$4Fe^{2+} + O_2 + 10H_2O \rightarrow 4Fe(OH)_3 \downarrow + 8H^+$$

Manganese precipitation

Dissolved manganese in the presence of oxygen can precipitate as manganese oxides (see the chemical equation below).

$$2Mn^{2+} + O_2 + 2H_2O \rightarrow 2MnO_2 \downarrow + 4H^+$$

Lime precipitation

Differences in pH and/or the concentration of dissolved carbonic acid in two groundwater flows, combined with a situation whereby groundwater is saturated with lime, can result in lime precipitation (see the chemical equation below).

$$Ca^{2+} + HCO_3^- \rightarrow CaCO_3 \downarrow + H^+$$

Carbonic acid can be formed in the soil as a result of all sorts of processes. When groundwater is extracted the pressure decreases and degassing can occur at ground level. A side effect of the CO_2 degassing is an increase in the pH as a result of the consumption of acid (H^+). This can shift the lime/carbonic acid equilibrium such that lime precipitates (see the chemical equation below).

$$Ca^{2+} + 2HCO_3^- \rightarrow CO_2 \uparrow + CaCO_3 \downarrow + H_2O$$

The lime saturation index (SI_{lime}) indicates whether lime will precipitate from the groundwater. Lime will precipitate from the groundwater if the lime saturation index is greater than 0. The lime saturation index depends on the concentrations of calcium and carbonate, and on the pH:

$$SI_{lime} = pH - 11{,}84 + \log\left[Ca^{2+}\right] + \log\left[HCO_3^-\right]$$

The concentrations must be in meq/l.

Biological processes

If there are components present in the groundwater that can be biologically decomposed aerobically and if the groundwater comes into contact with oxygen, accretion of biomass will occur. The growth of bacteria depends on the quantity of nutrients in the water. Bacterial growth where abstraction and infiltration takes place can lead to plugging. The assimiliable organic carbon (AOC) is a yardstick for the quantity of nutrients. It has been found in practice that at values of AOC < 10 µg/l the accretion is so slow that no problems are to be expected. The parameters associated with biological accretion and their critical limit values are given in table 12. The parameters should not be evaluated individually but in relation to one another.

Efforts should be made to achieve the above in order to prevent plugging by biological activity during infiltration.

Table 12. Critical concentrations in groundwater for biological plugging problems.

Parameter	Critical limit value (mg/l)	Critical in combination with
AOC	0.01	oxygen or nitrate
iron (II)	0.1	oxygen or nitrate
manganese (II)	>0.1	oxygen or nitrate
oxygen	0.1	AOC, iron (II) or manganese
nitrate	1	AOC, iron (II) or manganese
sulphate	1	AOC, iron (II) or manganese

Colloidal processes

If the water to be infiltrated has too high concentrations of suspended particles, plugging can occur. This is also referred to as colloidal plugging. The yardstick for this type of plugging is the membrane filter index (MFI). The MFI is the increase in the resistance of the filter cake that builds up on the membrane filter per litre of infiltrated water at a water temperature of 10 °C, at an overall pressure drop of 2 bar and when using Millipore membrane filters of 0.45 µm in an appropriate Millipore filter holder. The unit of the MFI is seconds per litre^2.

8.3 Assessment in terms of limit values

Abstraction

The iron concentration in the influent is 4 mg/l on average. The maximum concentration measured is 6 mg/l. The concentration of manganese is not higher than 1 mg/l. The measured iron and manganese concentrations in the groundwater are given in table 13.

The iron and manganese concentrations of the influent and in the groundwater upstream are significantly above the limit value. The calcium and carbonate concentrations in the influent are approximately 200 mg/l and 500 mg/l respectively. The pH is 7 to 7.5. Therefore the lime saturation index is exceeded. The lime saturation index in the groundwater is also greater than zero (see table 13). This means that lime will precipitate from the groundwater.

Table 13. Overview of critical parameters in the groundwater.

Piezometers	Filter positioning m below ground level	Date	pH	Fe mg/l	Fe^{2+} mg/l	Mn^{2+} mg/l	Ca^{2+} mg/l	HCO_3^- mg/l	SI_{lime}
upstream									
pbA01	3.0-4.0	08-11-99	7.40	9.7	5.3	0.41	180	510	0.8
pbA02	3.0-4.0	08-11-99	7.02	2.4	1.6	0.56	230	800	0.7
pbB01	7.0-8.0	08-11-99	7.50	13.0	9.5	0.42	190	600	1.0
pbB02	7.0-8.0	08-11-99	7.39	0.85	0.7	0.22	120	580	0.7
pbC02	10.0-11.0	08-11-99	7.39	0.80	0.7	0.30	130	380	0.5
downstream									
pbA09	3.0-4.0	28-03-00	8.17	0	0	-	-	-	-
pbA11	3.0-4.0	28-03-00	7.64	0.05	0	-	-	-	-
pbA13	3.0-4.0	28-03-00	7.88	0	0	-	-	-	-
gravel coffers									
SL04	air lance	16-03-00	8.27	0.34	0	-	-	-	-
SL06	air lance	16-03-00	7.95	7.6	0	-	-	-	-
SL07	air lance	16-03-00	7.90	2.9	0	-	-	-	-

However, the type of inlet design is such that plugging, as a result of iron and lime precipitation is very unlikely because the groundwater is extracted from below the groundwater table by means of a riser (and not a filter). Moreover there is a reasonable chance of oxygen entering the gravel bed and consequently possible precipitate formation in the gravel bed but the gravel bed is very generously sized. The chance of mechanical plugging is also slight because of the large gravel bed.

Infiltration

Generally speaking the iron and manganese concentrations in the effluent - the water that is infiltrated - are below the set limit value. Iron and manganese are almost completely removed in the treatment system. Iron is captured primarily in the first aeration buffer tank and the sand filters. The drain is above the groundwater table and therefore the drain does not come into contact with possibly anaerobic groundwater, and so plugging via this route is not possible.

Lime precipitation is taking place in the treatment installation. The lime saturation index in the effluent is still being exceeded. Therefore, lime precipitation in the drain system is possible.

It has been demonstrated that biologically degradable organic material in the extracted groundwater is being degraded in the treatment installation. Besides, the quantity of nutrients is low. As a result significant biological accretion in the drainage system is not to be expected.

It is expected that the MFI value of the infiltration water has been low because sand filtration was employed. The MFI has yet to be determined.

Furthermore so far there have not been indications of plugging in the soil of any type whatsoever. It is evident that the infiltration capacity will decrease in the course of time as a result of the aforementioned processes.

8.4 **Conclusions**

The chance of plugging of the inlet is slight because of the abstraction method (riser) and the dimensions of the gravel bed. Furthermore, the concentrations of the iron and lime decrease further with time as a result of the groundwater being pumped around and treated.

Furthermore so far there have not been indications of plugging in the soil of any type whatsoever.

CHAPTER 9

FOLLOW-UP SOIL REMEDIATION AT LIJNBAAN/WESTEINDE

9.1 Introduction

After completion of the test phase the Lijnbaan/Westeinde location in The Hague will be decontaminated using the active ‘Funnel and Gate’ system. A description of how this is done is given in [5]. The remediation plan anticipates the government’s position with regard to updating the soil remediation policy of September 1997. It was decided to re-examine the remediation version proposed for the Lijnbaan/Westeinde location at the time for two reasons. The first reason was the fact that the test phase generates supplementary information about the local geohydrological situation and the properties of the soil contamination at the location. As can be seen from the preceding chapters, the field data depart with regard to some points from the situation expected on the grounds of laboratory experiments and model calculations. The second reason for re-evaluating the remediation version that had been worked out at the time is that the government stance has been defined in more detail in the meantime and this has resulted in a new process for setting remediation objectives.

This chapter describes where it has been necessary to adapt the approach to soil remediation at the Lijnbaan/Westeinde location as a result of the developments referred to above. In particular, there needs to be greater focus on how progress of the remediation is monitored and how the remediation process can be adjusted during implementation in order to achieve a stable end situation. The following sections address the subjects below in the order indicated:

- the remediation version proposed in the remediation plan (section 9.2);
- link to recent policy developments (section 9.3);
- assessment of the duration of the remediation (section 9.4);
- recommendations and conclusions (section 9.5).

9.2 Soil remediation in accordance with the order issued

9.2.1 *Function-oriented remediation of the retention zone*

The ‘Funnel and Gate’ method is used to separate the retention zone from the retardation zone in accordance with the remediation plan. The objective of this approach is the removal of mobile residual contaminants that have entered the groundwater. The residual contaminants are transported by natural or induced runoff to the reactive zone of the ‘Funnel and Gate’ system. In this zone the collected groundwater contaminants are removed. After sufficient biologically reactive substances (oxygen and in so far as necessary nutrients) have been added, the treated groundwater is infiltrated into the soil.

The ‘Funnel and Gate’ method prevents further dispersion of residual contaminants from the retention zone. Consequently the total quantity of contaminants in the retardation zone will not increase further. Remediation continues until a situation without active follow-up is reached. On the grounds of the field research, laboratory experiments and model calculations, it is expected that all mobile contaminants will have disappeared after about 30 years of active flushing. The question of expansion of the system might come up earlier. The groundwater flowing is no longer need to be treated as soon as the influent quality of the Gate under natural flow complies with the intervention value. From that moment groundwater pumping is stopped and the only action taken is to monitor the ground-water quality at the location and the influent quality of the Gate (passive follow-up). The funnel and the gate can both be removed as soon as the influent quality of the Gate complies with the intermediate value.

9.2.2 *Anticipatory remediation of the retardation zone*

In the first place the behaviour of the retardation zone is monitored. The monitoring has two goals. Firstly the monitoring has to supply enough data to actively intervene as soon as there is a threat that the retardation zone will disperse to an unacceptable degree. Secondly the monitoring plan serves as an instrument for determining whether natural decomposition takes place and, if so, to what extent. Natural decomposition is defined here as: a decrease in the concentrations of contaminants in the groundwater as a result of naturally occurring:

- physical processes; diffusion, dispersion, volatilisation etc.;
- chemical processes; sorption and abiotic reactions etc.;
- biological processes; mineralisation, oxidation etc.

There are three possibilities for the retardation zone:

a) the extent of the groundwater contamination increases
b) the extent of the groundwater contamination remains the same
c) the extent of the groundwater contamination decreases

a) If the groundwater contamination continues to increase, this means there is too little natural decomposition. On the grounds of private law considerations alone this is not permissible. This type of change is also undesirable from the point of view of soil remediation.

b) If the extent of the groundwater contamination does not increase, there is natural decomposition. If the extent remains steady, the effect of natural decomposition is the same as the effect of dispersion under natural runoff conditions.

c) There is also natural decomposition if the extent of the groundwater contamination decreases. Here the effect of natural decomposition is greater than that of dispersion under natural runoff conditions.

Since the retention zone is cut off from the retardation zone, the overall contamination load in the retardation zone will not increase. It is expected the retardation zone will shrink ultimately as a result of the natural processes referred to above. In any event the concentrations in the retardation zone will decrease with time.

The retardation zone will be decontaminated in anticipation. The status of the groundwater contamination is tracked on the basis of a monitoring plan. If the extent of the groundwater contamination grows unacceptably, active intervention is essential. The groundwater contamination can be restored to its original extent by bringing the oxygen content up to the desired level (for example by aeration or the addition of oxygen release compounds) or by temporary abstraction. If the extent of the retardation zone remains the same or decreases, only the decomposition process is monitored. Active intervention is then not necessary.

9.3 **Link to policy developments**

Shortly after the publication of the government position with regard to updating the soil remediation policy of September 1997, a start was made in the context of BEVER with working out the first strategic spearhead-making soil remediation cheaper. This was accomplished in project A ‘Process for defining remediation objectives’.

The final report 'Van trechter naar zeef; afwegingsproces saneringsdoelstelling' ('From funnel to screen; process for defining remediation objectives') was published in October 1999. The basis for this document was established by the 'government's position with regard to the function-oriented and cost effective approach to soil contamination' (September 2000).

In accordance with the methodology in 'Van trechter naar zeef', the soil contamination at Lijnbaan/Westeinde is considered as contamination of the subsoil. As regards the way to tackle the subsoil, the updated policy is based on achieving a 'stable end situation' (standard approach), whereby both the retention zone and the plume are removed as much as possible in order to reach the point where 'active follow-up' is no longer necessary. From the point of view of cost effectiveness, this goal should be reached within 30 years after the start of the remediation. Calibration moments should be built into the schedule in order to compare the actual progress of the remediation with the expected progress and, if necessary, to make adjustments.

Fixed calibration moments have been defined in the remediation at Lijnbaan/ Westeinde in The Hague in line with the philosophy of BEVER. Periodically the concentrations of BTEX en mineral oil in the influent will be measured. A trend analysis will be made and by extrapolation the remediation time will be figured.

There can be several reasons for adjusting the remediation in the interim:
- A remediation duration of longer than 30 years is calculated using extrapolation;
- The quantity of contamination removed is found to be substantially lower than the quantity expected on the basis of extrapolation from the last calibration moment;
- The geohydrological situation is changed by unforeseen circumstances such that proper operation becomes impossible;
- Part or all of the location is redeveloped as a result of which part of the contamination is excavated and/or disposed of.

The adjustments to the remediation may involve additional technologies that can enhance the flushing out of the contaminants (surfactants etc.). It may also be decided to tackle the contaminants locally in another way (for example through a combination of other in-situ technologies or through partial excavation).

9.4 Assessment of the remediation duration

The design is determined primarily by the maximum duration of the remediation of 30 years and the residence time in the treatment system. The flow rate through the retention zone was derived from the first of these requirements. The desired flow rate through the retention zone (within the target value contour) was maintained at 4 m^3/day. The flow rate through the retention zone under the short Lijnbaan calculated at the time was approximately half this.

The flow rate through the retention zone under the short Lijnbaan is approximately 1 m^3/day, some 50% of the design flow rate. The remediation duration would double according to the design calculation method. However, the points of view are changed.

Interaction between retention zone and plume
The interaction between the retention zone and the plume is rather complex. The oil products in the retention zone forms a source, emitting BTEX and mineral oil into the unsaturated soil by evaporation and into the saturated zone by dissolving, forming the contamination plume. The emission process towards the groundwater is determined by the diffusion processes in the pure product and the transfer processes at the interface between pure product and groundwater. In

the source the contaminants are distributed over several zones, determining by the diffusion, dissolving and emission processes:

- The residual zone with small blobs distributed well over the soil particles and thus forming a big interface between product and ground water. This residual zone can be situated in the unsaturated or saturated zone, depending on the site specific circumstances and the history of the leakage;
- The floating layer, floating on the water table and going up and down with the season. It is a continuous pure product zone (big blob) with less interface and thus a limited emission towards the plume;
- The smear zone formed by the seasonal variation of the water table with residual oil from the floating layer.

The distribution of the pure product over the distinguished zones in relation with the groundwater flow and groundwater table determines the interaction between source and plume. This has also its influence on the permeability of the retention zone.

Estimated remediation period

Understanding of the leaching behaviour of product has further developed in the meantime (NOBIS 95-3-11, Restrisk, SKB SV-415, Model Code), showing that the flow rate is not the only determining factor for the remediation period. The leaching of a source is complex with a mix of diffusion, dispersion, dissolution, adsorption and dissorption and geo- and biochemical reactions.

In phase 1 of the flushing process contaminants are dissolved at the interface pure product-groundwater. This emission is high in the mobile zones of the source, especially where pure product is finely distributed over the soil, so in the residual contaminant zone. Increasing of the groundwater velocity will increase the mass of contaminants removed.

Gradually in phase 2 the more mobile components are removed, the mobility of the components gets less and mobile zones are flushed. For mineral oil first the short chain aliphates (C8-C12) will get dissolved and gradually the longer chains (>C12) turn up slowly. The emissions towards the groundwater will get diffusion limitated; components will have to migrate through diffusion towards the interface and via stagnate zone towards the mobile zone of the saturated zone. The characteristics of the source is changing; “weathering” is taking place. Increasing the groundwater flow doesn’t increase the mass removal. The emissions will decrease to such a degree that active pumping is no longer effective and needed. Hopefully the load in the plume is small enough to meet the remediation target and natural attenuation processes will eliminate the residual components downstream. Further migration of contaminants will no longer occur. This means that a stable final situation has been achieved, which is an important criterion in the new Dutch soil policy.

During the test phase a decrease of the concentrations was expected in view of the described processes above. A decrease of the concentrations is not determined, on the contrary. The retention zone is yet flushed merely approximately two times. The expectation was the flushing factor should be a lot more resulting in an identifiable decrease of the concentrations. During the test phase it becomes clear that the retention zone is not so permeable as was supposed in the design phase. As a consequence the flow rate is smaller as well.

Not a decrease, but an increase is identifiable in the measured concentrations. The increase of concentrations is caused by the increase of the flow during the test phase and the mobilisation of contaminants from the vadose zone as a consequence of the rising groundwater level.

No reliable estimate can be made of the duration of the remediation on the basis of the results of the test phase. There is no question of decrease of the concentrations and so extrapolation is not possible. Against that it may be supposed the expected concentration curve will be identifiable after flushing the retention zone 10 till 20 times and than the most of the mass in the mobile zones is removed. It is proposed the first evaluation should be at that moment, about three years later if the actual flow rate is not changed.

Subjects for evaluation are for instance the expected concentration curve in the next period and an analysis of a more extensive strategy of pumping. At that time probably a mathematical model is present which can be used for the purposes of these predictions.

CHAPTER 10

STATE OF THE ART OF PERMEABLE REACTIVE BARRIERS

10.1 Introduction

Efficiently and cost-effectively engineered in situ bioremediation may be required to attenuate groundwater plumes of regulated petroleum hydrocarbon components such as benzene, toluene, ethylbenzene, and xylenes (BTEX). For petroleum hydrocarbons, this usually involves the manipulation of physical, chemical, and/or biological properties within the subsurface to eliminate factors limiting the rate of biodegradation. Typically electron acceptors, usually oxygen, and perhaps such as nitrogen, are added to the subsurface. Even then, success is often limited by low oxygen solubility and limited in situ dispersion leading to incomplete mixing of remedial chemicals with the contaminants. Various pilot and full scale projects have now demonstrated the successful in situ treatment of a wide range of contaminants using in situ permeable reactive barrier (PRB) technology [USEPA, 1998; RTDF, 2001].

This chapter summarises field experiences outside of the NOBIS project with in situ permeable reactive barriers as applied to treating groundwater contaminated by petroleum hydrocarbons. Some basic designs are illustrated in figure 16.

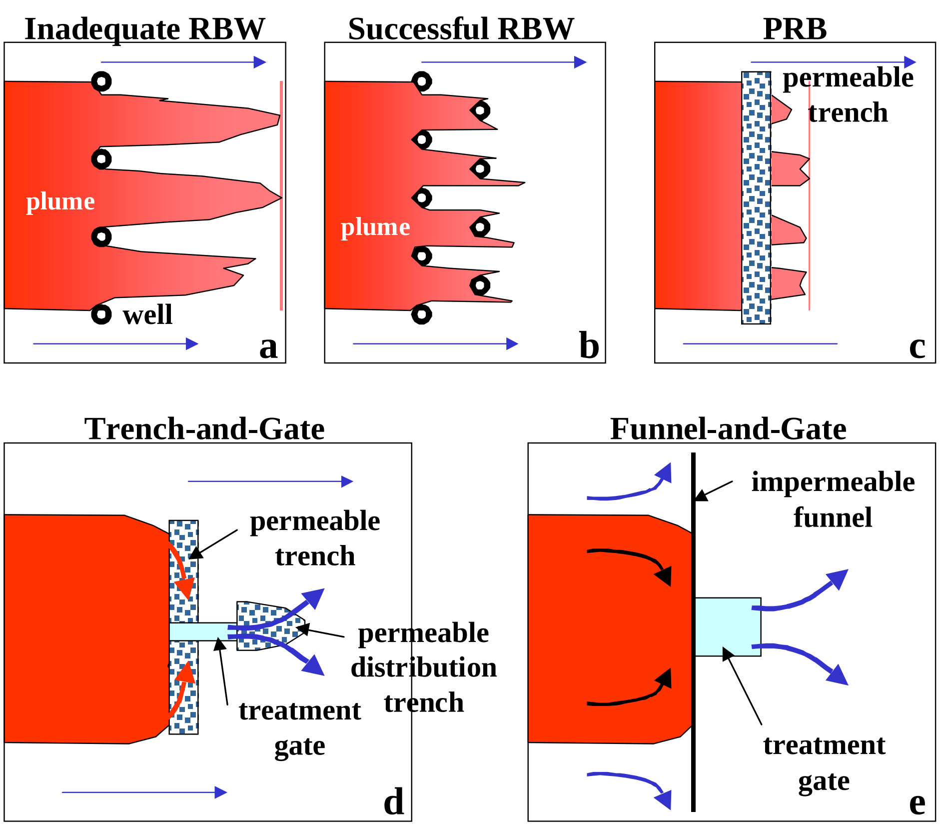


Fig. 16. Schematic plan views of various in situ systems used to treat groundwater contaminated by petroleum hydrocarbons.

The simplest, lowest cost PRBs use a line of wells transverse to the groundwater flow direction, termed reactive barrier wells or RBWs. These are used to introduce remedial agents (oxygen gas, [Gibson et al., 1998]; oxygen from oxygen-releasing magnesium peroxide compound, ORC®, [Borden et al., 1997] and [Chapman et al., 1997]) into the contaminated groundwater. RBWs make minimal effort to control the reactive zone and depend on the usually weak lateral dispersive mixing to spread the remedial addition into the contaminated groundwater flowing between the wells (figure 16 a). Consequently, the wells need to be sufficiently close for lateral dispersion to deliver remedial chemicals to the plume (figure 16b). A more controlled or engineered approach is to introduce the remedial additions across the width of the contaminant plume, by periodically injecting remedial solutions and pumping them across the plume width, either through the natural aquifer material [Devlin and Barker, 1999] or through a trench of permeable material (a true Permeable Reactive Barrier or PRB) installed across the width of the plume (figure 16c).

The more expensive and highly-engineered PRBs use groundwater flow barriers and engineered in situ treatment zones (e.g., [Bowles et al., 2000]; [Morkin et al., 2000]). The 'funnel' or permeable 'trench' direct groundwater to an in situ, semi-passive treatment system termed the 'gate' (figure 16d and 16e). Table 14 provides a summary of the PRBs used with petroleum hydrocarbon contamination and that are reviewed here.

Table 14. Summary of Permeable Reactive Barriers (PRBs) used with petroleum hydrocarbons.

Case no	Reference	PRB system	Contaminant	Treatment
1	[Gibson et al., 1998]	Wells	BTEX	Oxygen addition via diffusing tubing
2	[Borden et al., 1997]; [Chapman et all., 1997]	RBW	BTEX	Oxygen addition using ORC[R]
3	[Gorman, 1995]; [Austrins, 1997]	F&G	BTEXS	Oxygen (+ammonia) sparging of gravel-filled gate
4	[Bowles et al, 2000]; [Granger, 1997]	T&G	Natural gas condensate (BTEXS)	Oxygen sparging; ammonia addition via diffusing tubing; P via dissolution of phosphates
5	[Lauzon, 1998]; [Kerr, in prog.]	F&G	Naphthalene	Nitrate addition in cassette gate
6	[Morkin et al, 2000]	F&G	BTEX and chlorinated ethenes	Fe^0 for reduction of Cl-ethenes followed by oxygen sparging to volatilize/biodegrade BTEX

10.2 **Description case 1: Oxygen Addition into Wells**

The paper by Gibson et al. [1998] established that oxygen added to water in a well within a coarse sand injection area can support aerobic BTEX biodegradation in and down-gradient (2.3 m) of the well. The oxygen addition was via silicone tubing coiled in the well. Well water attained high concentrations of oxygen (39 mg/L) since pure oxygen was flushed through the tubing. What remained uncertain was how efficiently such wells would deliver oxygen across the total width of the BTEX groundwater plume (see figure 16a and 16b). Also, the long-term diffusion of oxygen through the silicone tubing was not demonstrated.

10.3 **Description case 2: Reactive Barrier Well (RBW) systems using ORC®**

Borden et al. [1997] and Chapman et al. [1997] used a proprietary oxygen-releasing compound produced by Regenesis Bioremediation Products. When contacted by water the magnesium peroxide reacts with water to release half of its oxygen as oxygen gas:

MgO_2 (solid) + H_2O == Mg^{2+} + 2 OH^- + 0.5 O_2 (gas)

Borden et al. [1997] noted clogging of delivery wells apparently by iron precipitates formed by the oxidation of Fe^{2+} present in the reduced BTEX-contaminated groundwater. Chapman et al. [1997] found limited success with the RBWs using ORC® placed in closely spaced treatment wells (figure 17). Maximum treatment was about 70% of the influent BTEX at fence 1, judging from concentration declines at fence 2. These fences contained multilevel wells placed about 0.3 m apart, each have vertical sampling ports at 15 cm intervals. BTEX flux probably increased and oxygen release apparently slowed within two months. However, along flow paths where BTEX was < 5 mg/L, nearly complete removal was noted for the 132 day experiment. They also noted that much more oxygen was consumed than needed to degrade the BTEX removed between fences 1 and 2. This was attributed to high biological oxygen demand (BOD) exerted by uncharacterised, non-BTEX organics and dissolved Fe^{2+}.

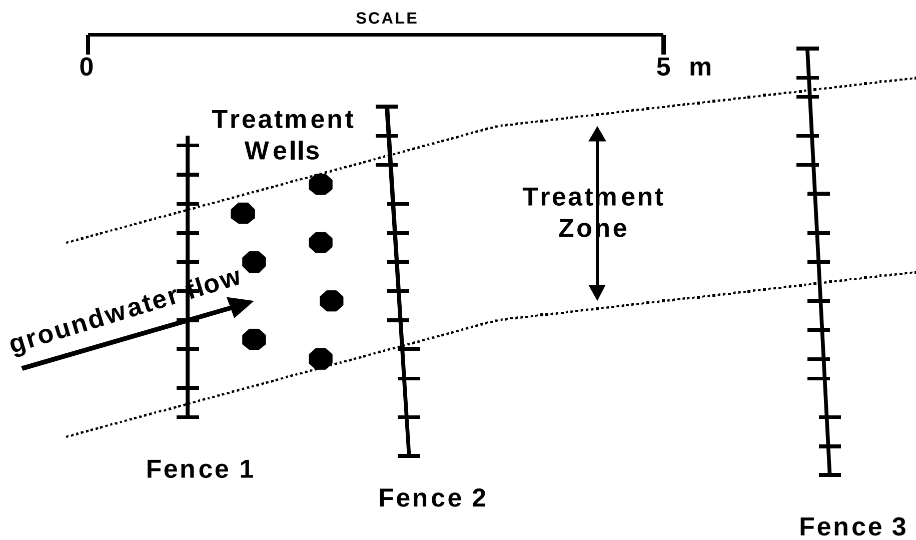


Fig. 17. Plan view of the RBWs and multilevel monitoring wells used to treat a BTEX plume through in situ oxygen addition using ORC®.

In designing in situ oxidation, this field case demonstrates the need to insure sufficient oxygen is delivered to satisfy the total Biological Oxygen Demand (BOD). ORC® was demonstrated to deliver oxygen to water with minimal formation of bubbles. This should minimise the release of potentially harmful organic contaminants to the air. However, the ORC® system had a potentially short time for delivering oxygen and so its use in PRBs must be assessed on economic grounds. It may be a particularly attractive oxygen delivery system where other methods to deliver oxygen (compressed gas tanks or compressors) are not possible.

10.4 Description case 3: Controlling a Recurring BTEXS Plume

A pilot-scale 'Funnel and Gate' system was installed at an operating industrial plant in Alberta, Canada. Most of a dissolved BTEX and styrene (BTEXS) plume was captured using sheet piling cut-off walls (the funnel) and directed through a high permeability gravel 'gate' where oxygen and ammonia were added by sparging. BTEXS aerobic biodegradation was found to be nitrogen limited in a microcosm study using site materials [Gorman, 1995] and so providing nitrogen was desired. Since an oxygen gas delivery system was to be employed at this site, nitrogen was also

delivered by sparging a gas (ammonia, NH_3). Nitrogen will become bio-available upon NH_3 hydrolysis to ammonium (NH_4^+). Target NH_4^+ concentrations were 10 – 15 mg/L as N.
At the 'Funnel and Gate' site groundwater contamination occurs in the upper 5 m of an unconfined aquifer with a shallow water table 0.5 to 1.5 m below ground surface (bgs). The unconfined aquifer consists of local silty sand backfill overlying a layer of clayey silt (0.2 to > 3m thick). A hydraulic conductivity of 2.6×10^{-6} m/s was estimated for the unconfined aquifer. The groundwater flow direction is quite variable with the average local groundwater velocity being about 1 m/yr towards the northeast. During testing, a pumping well was operated down gradient to enhance the groundwater and BTEXS flux through the gate.

Design of the 'Funnel and Gate' system was based on initial characterisation of the site in the fall of 1992. Then, groundwater concentrations were < 60 mg/L BTEXS and about 5 mg/L BTEXS was anticipated to enter the treatment gate. The plume had induced anaerobic conditions as evidenced by measured dissolved oxygen (DO) values of approximately 0.5 mg/L within the aerobic aquifer. In uncontaminated groundwater DO was typically 1 to 2 mg/L. The groundwater pH remained about 7, with a relatively low iron concentration (0.1 to 6 mg/L). But upon installation of the system in the fall of 1993, maximum concentration in the plume was found to be 560 mg/L BTEXS, with benzene accounting for about 78% by mass. The average BTEXS concentration entering the gate was now 60 mg/L. This emphasises the need to assess both spatial and temporal contaminant distributions when designing a PRB.

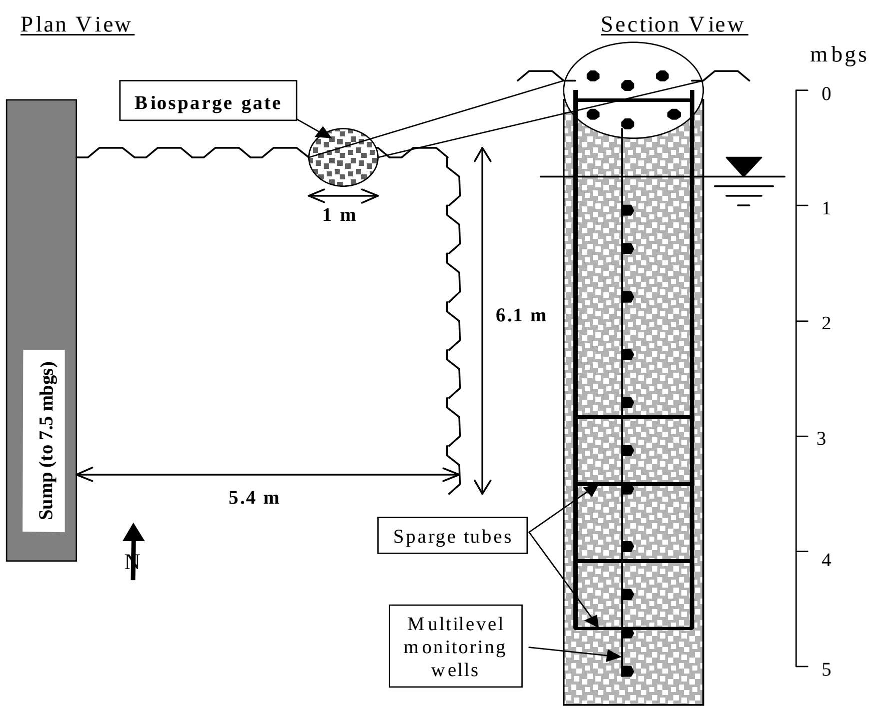


Fig. 18. Plan and section view of the case 1 'Funnel and Gate'™ treatment system.

Figure 18 shows a plan-view of the 'Funnel and Gate' layout. Details of the design and installation methods can be found in Gorman [1995]. The funnel is composed of steel sheet piling sections driven just to or into the confining layer. The gate itself consists of a 1.07-m diameter, 5.3m deep zone of backfilled pea-gravel (average grain diameter of 13 mm and a porosity of 0.38) installed with the aid of a removable caisson. Embedded within the gravel are a series of five 'u'-shaped, 2.5-cm OD diameter steel pipes. Each extends above ground surface, and has two injection ports on the west and the east side. The horizontal sections of pipe have 3.2 mm diameter holes spaced every 25 mm to release the carrier fluids along the width of the gate, in a plane perpendicular to groundwater flow. The injection system could use either air from the chemical plant or O_2 gas or NH_3 gas cylinders. Within the gate are a series of six, eleven point multilevel monitors.

The exceptionally high BTEXS concentrations precluded the success of the original design. This design had been to deliver enough oxygen via a single air sparging event to attenuate the total BTEXS load within the hydraulic residence time of the gate. The concept was that most of the sparged gas would remain as residual gas in the gravel and so be available as contaminants flowed through the gate. With the much higher BTEXS concentrations, at least 500 g of O_2 (350 L of O_2 at STP) now had to be delivered within the hydraulic residence time of the gate (about 50 days) for complete attenuation of the BTEXS. It was felt that the residual, sparged air occupying an estimated 7% of the porosity (i.e., 115 L of 1640 L) of the gravel-filled gate would provide the bulk of this O_2 (20% of 115 L or 23 L). Thus, less than 10% of the required 350 L O_2 could be provided by one sparge event using air. About 50 g of O_2 were estimated to have been provided in a single sparge event using 100% oxygen gas; 80% of this was as residual gas phase in the pea gravel [Austrins, 1997]. At least 10 O_2 sparge events every 50 days would be required to meet the BOD. More frequent sparging would increase volatilisation, and would only be useful if biodegradation was sufficiently rapid to utilise the additional O_2 provided. It was found that DO in gate groundwater dropped to below 2 mg/L within about 5 days when ammonia was also sparged into the gate groundwater. This suggested that the N-amended biodegradation rates were sufficient to use up available O_2 within 5 days. It was also apparent, however, that sufficient O_2 was not being provided since residual BTEXS, typically > 10 mg/L was still found in gate groundwater. Clearly, with the unexpectedly high BTEXS concentrations, even sparging with oxygen and enhancing biodegradation rates through NH_3 sparging, were not able to remove the BTEXS completely.

The carrier gas(es) was applied to the subsurface in a pulsed manner using the horizontal injection lines. Air injection [Gorman 1995] was followed by a phase using O_2 gas and then NH_3 gas sparging [Austrins, 1997]. The subsurface sparged gas distribution was inferred from the bubble distribution expressed on the water table surface. The most intense bubbling on the water table occurred directly above the sparge lines and the majority of the gas flow escaped within 20% of the plane area of the gate, near the injection port. Continual bubbling lasted about 3 minutes after gas injection ceased and the water level rose slightly. Preferential flow paths had development within the east side of the gate. Groundwater mixing during and for up to 2 hours after sparging was indicated by elevated DO (> 12 mg/L) at monitors that did not experience any bubbling in the immediate vicinity (i.e., primarily on the west side of the gate).

Applying Henry's law with measured sparge gas volumes, suggested a maximum potential volatilisation loss of only 2% of the gate BTEXS per sparge. This estimate seems reasonable based on direct gas phase measurements by Gorman [1995], where up to 60 ppm (v/v) total hydrocarbons were detected in a single pipe installed near the center of the gate, 1.6 feet bgs (0.5 mbgs) after a 12 hour equilibration time following a sparge event. This measurement suggests a maximum of 8% of the hydrocarbons in the gate may have been volatilised during each sparge event.

Periodic ammonia sparging produced an arithmetic average gate concentration of 14 to 25 mg/L NH_3-N that is very close to the desired concentration. NO_3^- remained at background levels. The average increase in pH for monitors that experienced concentrations of about 25 mg/L NH_3-N were only 0.27 pH units above a background value of 6.9.

Because of the slow groundwater velocity in the gate, changes in gate concentrations were considered to reflect biochemical reactions much more than advective groundwater flushing. Parameter trends observed at individual monitoring locations revealed a surprisingly heterogeneous response, both spatially and temporally (see [Austrins, 1997]). The overall gate response was estimated by calculating an arithmetic average concentration of the various monitors sampled and then by concentrating on temporal trends in this average concentration. The expected trend of decreasing BTEXS was typically found at least until Day 4, accompanied by a decrease in DO and an increase in alkalinity, suggests that biodegradation of BTEXS occurred. Furthermore, a plot of ethylbenzene:benzene ratios shows a decreasing trend which is consistent with the preferential biotic degradation of ethylbenzene compared to benzene that was seen in the laboratory microcosm study (details in [Austrins, 1997]).

Over 4 days of one test, the apparent biodegradation rate of 2.8 mg BTEXS/L/day compares well with the average biodegradation rate determined in the microcosm study of 4.2 mg BTE/L/day. This mass loss was equivalent to a gate O_2 demand of 42.5 g. It was estimated previously that the sparge event supplied 49 g of O_2. This suggests that O_2-coupled biodegradation was capable of supporting the observed BTEXS decrease.

The apparent biodegradation rate calculated for an NH_3 plus O_2 sparge test was only 1.0 mg BTEXS/L/day. However, the majority of monitoring points had a significantly greater DO loss rate (one-tailed, paired t-test, α=0.05, n=9) than during O_2-only sparging. This suggests some enhancement of aerobic degradation was gained by NH_3 addition. However, based on the data available it is unclear whether nitrogen addition enhanced biodegradation in the field. The variable response to amendment is comparable with observations by other workers (e.g. [Swindoll et al., 1988]).

This experiment demonstrated that:

1. during gas sparging, direct gas phase contact was limited to about 20% the gate, probably because of the development of preferential flow paths within the pea gravel. Sparge-induced groundwater mixing occurred mostly within the first day after the injection and significantly increased the volume of gate groundwater to which O_2 or NH_3 was provided. It did not, however, greatly enhance the residual gas volume that was the largest proportion of O_2 provided.
2. the chemical and inferred biological response to a sparge event within the gate was highly heterogeneous both spatially and temporally.
3. nitrogen was successfully delivered to the gate using pure NH_3 gas. NO_3^- production was minimal, and excessively high pH and NH_3 concentrations were not experienced. The aqueous NH_3 was distributed more widely than the DO because it is highly soluble, but the distribution was still bias to the east side.
4. however, based on similar gate average BTEXS loss observed between the nitrogen and non-nitrogen amended tests, nitrogen-enhanced biodegradation in the field was not demonstrated.

Subsequent studies (cases 4,5, for example) where aerobic biodegradation is to be enhanced have left the bioreactor essentially open or have overdesigned the length of the sparged zone. While useful for storing oxygen, the porous media filled gate is unlikely to provide the mixing of contaminants and remedial chemicals required to attain remedial objectives.

10.5 Description case 4: A 'Trench and Gate' (T&G) System

An essentially full-scale 'Trench and Gate' system was installed at an operating gas plant in Alberta in September 1995. Details of the construction, operation and general performance is provided by Bowles and Bentley [2000] and references therein. A thin (< 5 m) veneer of till overlies a sedimentary bedrock aquitard at the plant. Where the 'Trench and Gate' was constructed, the till is a 'cobble till' overlying a grey clay-rich sandy till. A < 1m thick, relatively permeable weathered bedrock regolith lies between the tills and bedrock. Hydraulic conductivity of these units is heterogeneous, ranging from 10^{-10} m/s for shale bedrock to 2 x 10^{-5} m/s in fractured or sand-stringer tills.

Shallow groundwater is contaminated with up to 10 mg/L BTEX locally, but typical concentrations entering the 'Trench and Gate' were < 0.2 mg/L. The challenge here was to induce groundwater to flow from a low conductivity aquifer into a treatment zone and then distribute the treated water back into the low conductivity aquifer. Rather than an impermeable funnel, a permeable trench was used to control the groundwater flow into the treatment gate. Thus the system is termed a 'Trench and Gate'.

Construction called for two, 30 m long, gravel-filled collection trenches to about 5m depth just into bedrock to be installed at right angle approximately corresponding to the down gradient property boundary corner. The cobble till could not be penetrated by continuous trenching and so conventional trenching with considerable excavation was employed. Trenches were equipped with slotted PVC pipe to act as drains to the gate and backfilled with screened gravel. The gate, at the junction of the collection trenches, consisted of 3, 1.8 m diameter by 6 m high cylindrical galvanised culverts set vertically into a concrete base. These connect to the large diameter PVC pipes from the collection trenches, to each other, and to the infiltration gallery PVC pipes via welded steel pipes.

Shut-off values were installed in the connecting pipes and flow meters were installed at the entry to the third culvert. Treated groundwater flows from the last culvert into an infiltration gallery, which has about 1.5 times the infiltration area as the collection gallery to ensure no mounding within the 'Trench and Gate' system. The first culvert was equipped with an air sparging system, a spiralled micropore hose anchored to the base, the second culvert could be divided into two parallel compartments and the third culvert could also be equipped with a biosparge system. The benefits of using open gates are threefold:

1. a more flexible, easily-modified treatment zone,
2. the residence time of the groundwater within the gate is longer, allowing more time for the treatment method to be effective,
3. the gate has a higher hydraulic conductivity which may lead to an increase in the capture zone of the funnel [Starr and Cherry, 1994].

One potential drawback is the lack of surface area for bacterial attachment. Figure 10.4 shows the gate system schematically.

The high permeability trench collection system focuses groundwater flow from the less-permeable tills into the 'Trench and Gate' system, minimising underflow and lateral bypass, both being greater potential problems in conventional 'Funnel and Gate' systems. Perhaps fortuitously, the more permeable cobble till lessened the chance of mounding caused by inadequate re-infiltration. Hydraulically, the 'Trench and Gate' worked as designed, even when fluxes into the system increased substantially after rain events.

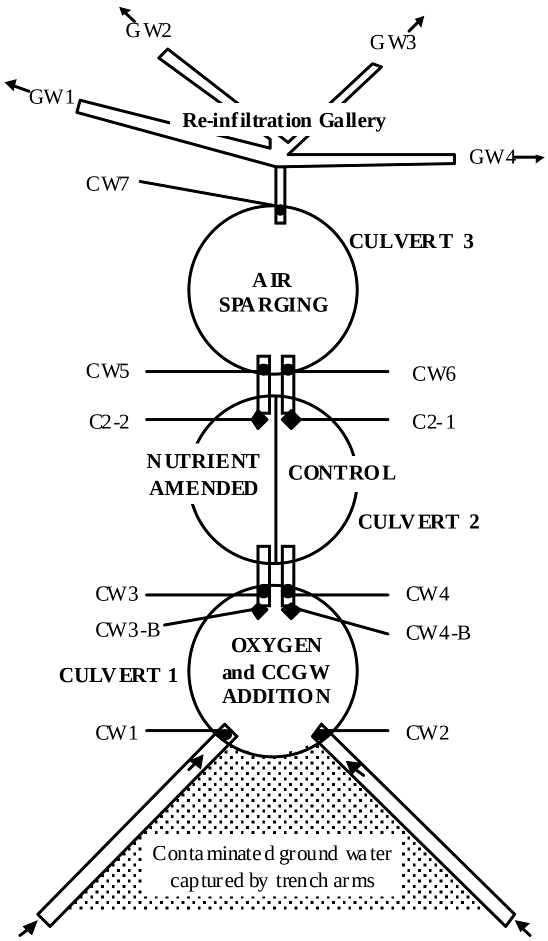


Fig. 19. A schematic diagram (not to scale) of the gate treatment system as used for enhanced treatment experiments. The right side of the middle (second) culvert was used as a control and the left side as the active treatment zone to demonstrate treatment efficacy.

Flow through the culverts varied from 80 to 240 L/hr. In terms of treatment of BTEX, effluent, treated water usually contained < 1 µg/L BTEX. Occasionally µg/L concentrations were found exiting the third culvert along with mg/L DO, but no BTEX was detected in monitors at the end of the infiltration trenches. Based on an average flux through the treatment zone of 100 L/hr, a total BTEX concentration of 0.15 mg/L, the total mass removed was about 130 g/year [Bowles and Bentley, 2000].

To evaluate methods to enhance the treatment capacity in the 'Trench and Gate' so as to handle higher fluxes, the natural contaminant levels entering the gate system were artificially increased [Granger, 1997; Granger et al. in press]. Laboratory microcosm experiments had demonstrated long adaptation times and slow, phosphorous-limited biodegradation rates in groundwater at this site [Granger et al., 1999]. The groundwater influent to the first culvert was spiked with natural gas condensate contacted groundwater (CCGW) having total BTEX of about 70 mg/L BTEX. An O_2 gas sparging unit in the first gate was operated at low pressure (35kPa to 55kPa gauge pressure) to oxygenate the water while minimise contaminant volatilisation. The sparging unit in the third gate was operated at a higher pressure (170kPa to 240kPa gauge pressure) to strip any

volatile organic contaminants remaining in the groundwater prior to discharge to the aquifer via the infiltration gallery (figure 19).
The first experiment compared the addition of N and P to no addition. Identical 'containers' (well screens 5.5 m long and 10 cm diameter, wrapped with microporous (15 – 45 micron pore size) membrane) were hung at the influent pipe discharges on both sides of the partitioned second culvert. The amended side container was filled with BIOFOS™ (mono- and di-calcium phosphate) and phosphate rock (carbonate-substituted fluorapatite) and the control side container was filled with silica sand. Two tubing emitter devices [Wilson and Mackay, 1995] were installed, one on each side. These consist of about 300 m of 3 mm OD LDPE tubing with 12mm wall thickness held by a stainless steel support. On the amended side, the tubing was kept pressured (about 3 atm) with ammonia gas which would diffuse through the tubing into the groundwater, while the tubing on the control side was kept filled with groundwater.

BTEX concentrations influent to the second culvert increased to perhaps 3 mg/L after day 6 during this 10 day test, as the proportion of CCGW mixed into the first culvert was increased. Some BTEX was lost in the first culvert, due to biodegradation and volatilisation. There was no significant difference in influent and effluent NH_4^+-N concentrations and no differences between the amended and control sides in culvert 2. The effluent on the control side has significantly enhanced PO_4^{3-} -P (see table 15).

Table 15. Mean concentrations and pH in culvert two, experiment 1.

Chemical	Mean Concentration (mg/L)			
	Control		Amended	
	influent	effluent	influent	effluent
PO_4^{3-}-P*	0.32	0.45	0.36	0.93
NH_4^+-N	0.43	0.41	0.41	0.52
NO_3^-N	0.15	0.14	0.16	0.26
PH	7.26	7.37	7.28	7.81
Benzene, days 1-6	0.137	0.073	0.132	0.039
Benzene, days 7-10	1.173	1.137	1.038	0.111
Toluene, days 1-6	0.079	0.075	0.074	0.049
Toluene, day 7-10	0.864	0.835	0.689	0.112
Oxygen, day 1-6	25.5	21.4	25.7	18.7
Oxygen, days 7-10	24.2	24.4	24.2	11.0

* concentrations averaged over day 2-18, excluding day 1 data.

Very little BTEX biodegradation and oxygen reduction occurred in the control side, while significant oxygen consumption and BTEX biodegradation apparently occurred on the amended side of culvert two.

The mass loss rates of benzene and toluene within the second culvert during the course of experiment 1 are calculated as the difference in influent and effluent concentrations multiplied by the estimated mean flow rate (one half of: 5 m^3/day of groundwater per side). Throughout the experiment, the mass loss rates for benzene and toluene in the control side fluctuated around zero. For example, for day 7 to day 10, the rate for benzene averaged 0.1 g/day and for toluene averaged 0.08 g/day. In contrast, average mass loss rates of 2.9 g/day benzene and 1.8 g/day toluene were observed in the nutrient amended side. Note that an apparent benzene mass loss rate of 5.3 g/day is attributed to benzene biodegradation in the first culvert [Granger et al., in press]. This suggests that, while considerable benzene biodegradation can occur without nutrient addition, when BTEX loading is raised to > 90 g/day nutrient limitations are reached. Further degradation is not apparent over a few days, unless nutrients are added.

In a second experiment, NH_3 was added to both sides of culvert 2 via the emitter tubing and phosphate was added as in the first experiment to the 'amended' side only. No significant increase in NH_4^+-N or P were noted on either side, but again oxygen consumption and BTEX biodegradation was enhanced on the PO_4^{3+}-side relative to the 'control' side (see results in table 16).

Table 16. Mean benzene, toluene and dissolved oxygen concentrations in culvert two, with NH_4^+-N provided to both sides and PO_4^{3+} provided only to the amended side.

sample	mean concentration (mg/L)					
	Benzene		toluene		Dissolved oxygen	
	Influent	effluent	influent	effluent	Influent	effluent
N added	0.522	0.543	0.333	0.248	16.7	16.7
N+P added	0.474	0.022	0.291	0.001	16.7	10.4

While up to 200 µg/L of benzene and toluene persisted through the third culvert during these tests, excess oxygen (mean 12 mg/L) also persisted, such that biodegradation within the infiltration gallery kept concentrations there consistently below detection (0.001 mg/L).

The 'Trench and Gate' system proved to be an effective means to capture and treat a dissolved BTEX plume in lower permeability material. Ammonia and phosphorous could be added rather passively to enhance biodegradation rates, if necessary, using solid-sources of P and ammonia gas. Fouling of ammonia diffusing tubes by calcite was noted, likely due to the locally high pH produced by ammonia hydrolysis. Long-term performance remains an issue and monitoring this system continues.

10.6 **Description case 5: Naphthalene Plume Control – CFB Borden**

Coal tar creosote emplaced below the water table in the sand aquifer at CFB Borden in 1991 has created a dissolved plume in this well-characterised aquifer [King and Barker, 1999]. While very mobile constituents like phenolics and xylenes have been essentially completely removed by natural attenuation, the plume of naphthalene continued to expand. Therefore, a pilot-scale 'Funnel and Gate' was installed in 1997 to limit its extent.

The 'Funnel and Gate' is comprised of Waterloo Barrier™ sealable sheet piling and the gate makes use of a novel cassette system with four, removable sections. This is shown schematically in figure 20.

A hydraulically aggressive design was used to evaluate the prediction of plume capture derived from simple modelling. The hydraulic parameters of this aquifer are very well known [Sudicky, 1986] and so it was anticipated that the plume capture by the 'Funnel and Gate' could be reasonably predicted using simple flow models (Visual MODFLOW, in this case). The 'Funnel and Gate' was 'hanging'; that is, it wasn't keyed into an underlying aquitard. In many cases this can produce considerable cost saving, but does allow a plume to flow underneath the system. The modelling suggested the section (across flow) of groundwater captured would be triangular (see figure 20). The hydraulic performance of this system, especially the anticipated movement of a segment of the naphthalene plume around the funnel (see figure 20), is still being evaluated (Kerr, M Sc, in progress). As predicted, the naphthalene plume is generally not plunging but proceeds directly into the gate at a similar depth as it occurs in the aquifer.

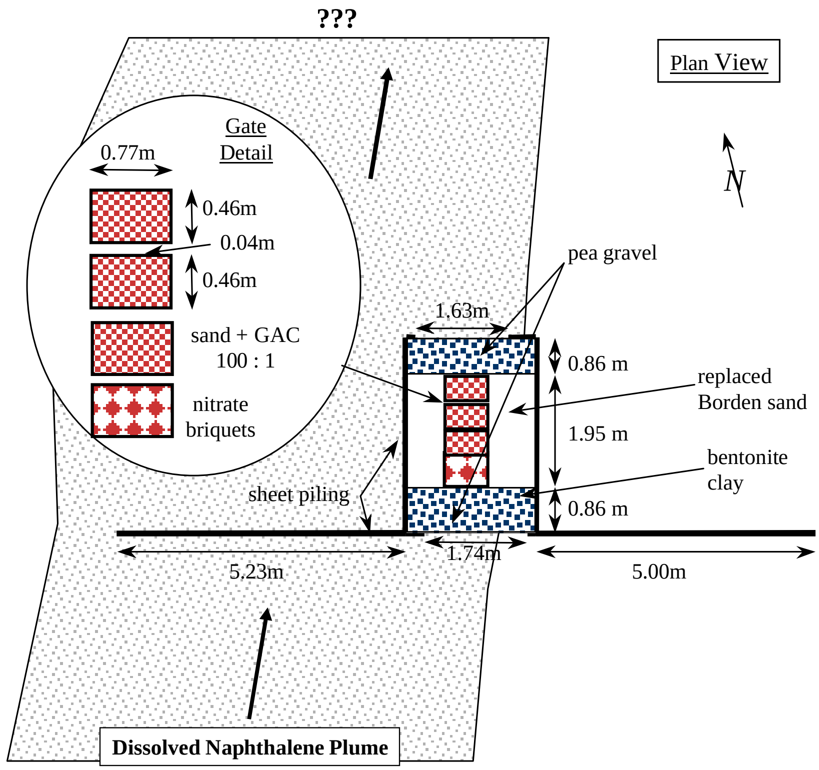


Fig. 20. Plan view of the 'Funnel and Gate' system treating the naphthalene plume, CFB Borden.

A novel aspect of treatment was the use of denitrification for naphthalene removal in the gate. Following the work by Kao and Borden [1997], nitrate release was from concrete briquettes that had been manufactured with inclusion of ammonium nitrate. These were placed into cassette 1 and were shown to release nitrate into the passing groundwater [Lauzon, 1988], as anticipated from lab studies. Cassettes 2 to 4 contained coarse sand with about 1% granular activated carbon (GAC). The GAC was thought to be a preferred site for microbial colonisation. Having a small proportion would encourage the microbes to be distributed throughout the cassette and so minimise biofouling. GAC would also enhance retardation of naphthalene and so would provide more residence time for degradation. A microbial consortium, developed from Borden aquifer material and capable of degrading naphthalene under denitrifying conditions, was inoculated into cassettes 2 to 4.

The naphthalene plume entered the cassette system directly from the aquifer and was initially persistent into the third cassette. Naphthalene concentrations declined from 2.2 – 0.3 mg/L upgradient of the briquettes, to 0.9 – 0.2 mg/L immediately after the briquettes, to < 0.2 mg/L after the second sand:GAC cassette, and naphthalene was not detected (< 0.01 mg/L) after the last cassette. Eventually in 1998, neither nitrate nor naphthalene persisted beyond the first cassette and the nitrate-releasing briquettes were found to have developed a biofilm at the depth of maximum naphthalene concentration. It appears that denitrifying, naphthalene degraders had become established in the first cassette and produced essentially complete remediation there. Smaller briquettes of a slightly different mix were manufactured and replaced the original briquettes in the gate, in early July 1998. They released more nitrates than the original briquettes, as evidenced in a parallel laboratory study.

Further characterisation of microbes in the pea gravel zone upgradient of the cassettes and within the briquette cassette implicates aerobes as mainly responsible for naphthalene attenuation (Drs. C. Greer and R. Roy, Biotechnology Research Institute, National Research Council, Canada, pers. com.). Somehow, oxygen-bearing groundwater within/above/below the naphthalene plume is apparently mixing with oxygen-poor, naphthalene-bearing plume water and naphthalene degradation is sufficient for complete attenuation even before cassette gate treatment. Currently, additional field sampling is assessing this.

The design modelling suggested the hanging design would produce an essentially triangular plume capture area. That is, the modelling predicted that the portion of groundwater well upgradient of the 'Funnel and Gate' that would be directed through the treatment gate was limited to that groundwater within a triangle bounded by the mid-points of the funnels and by the bottom of the gate (see figure 21). Kerr (M Sc thesis, in progress) is evaluating this prediction, using the migration of naphthalene around the funnel.

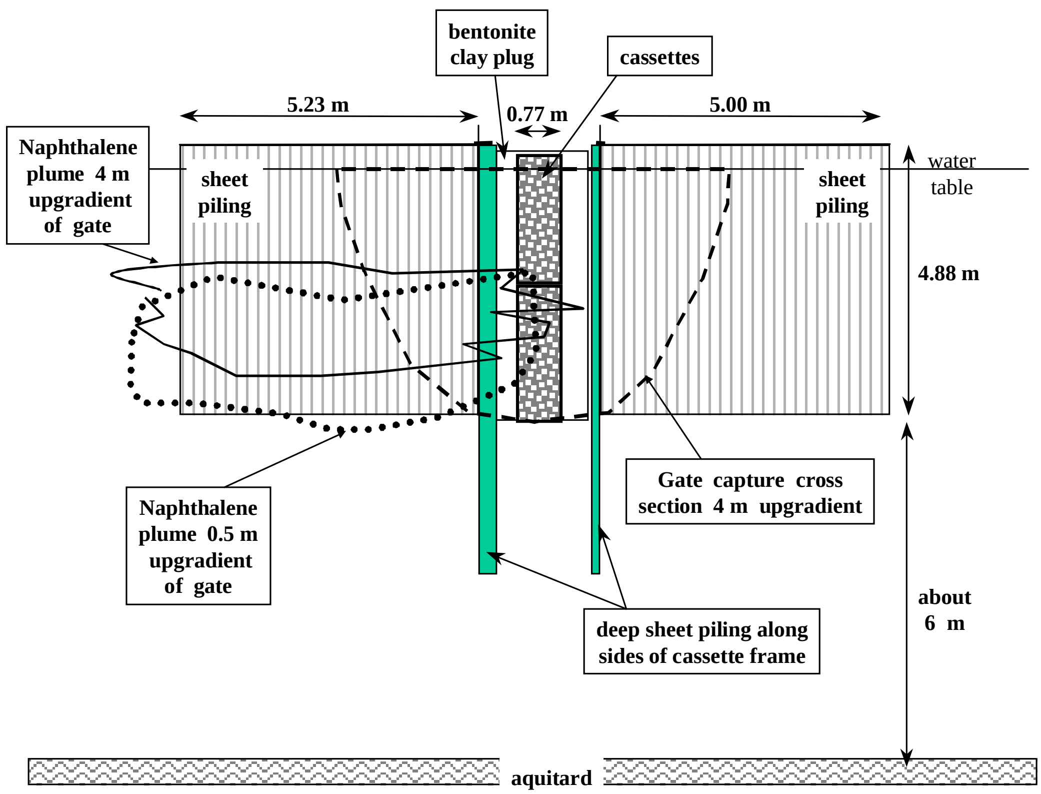


Fig. 21. Schematic section across groundwater flow showing the predicted groundwater capture zone and the shape of the naphthalene plume 4 m upgradient of the gate and immediately upgradient of the gate.

The naphthalene plume is not centred on the gate, but rather is centred on the west funnel (figures 20 and 21). Initial field sampling suggests the naphthalene plume is plunging slightly at the mid-point of the funnel. This feature was predicted by the MODFLOW modelling but only when actual hydraulic conductivity values for the aquifer and for the cassettes were used. Also as predicted, the naphthalene plume beyond the capture zone was pushed around the west funnel with some plunging.

Kerr (M Sc thesis in prog.) has also conducted a tracer test in the gate and has derived an estimate of the groundwater flux through the gate. It appears consistent with the design prediction. In this case, the gate is capturing about 35% of the naphthalene mass found in groundwater about 4 m upgradient of the 'Funnel and Gate'.

The experience with groundwater capture with this 'Funnel and Gate' is encouraging. It would appear that for at least simple aquifers with a simple gate design, the hydraulic behaviour can be reasonably anticipated by modelling using measured hydraulic properties. The gate treatment was also encouraging. Initial results suggest that denitrifying bacteria can be used to remove simple polynuclear aromatic hydrocarbons such as naphthalene. While long-term testing is still required, the use of solids such as concrete as the medium from which nitrate is slowly released in the gate appears viable.

10.7 **Description case 6: Sequential Gate Treatment, Alameda NAS, CA**

Information about this pilot-scale 'Funnel and Gate' is provided to illustrate four aspects:
1. installation of a sequential treatment system
2. design and operation of a unique biosparge design potentially useful for treating simple petroleum hydrocarbon plumes
3. analysis of the biosparge zone performance assuming it acted as a completely mixed bioreactor
4. overall performance in a highly contaminated aquifer.

Further information can be found in Morkin et al. [2000] and Barker et al. [2000].

The field demonstration was performed on the northwestern tip of Alameda Island, adjacent to San Francisco Bay, California. Contamination occurs in a silty sand fill unit about 6 m thick, which overlies the clayey Bay Mud unit, approximately 4 to 6 m thick. The contaminant plume likely originated from unlined waste pits excavated in the fill unit which, beginning in the 1940s, received cleaning solvents and waste petroleum hydrocarbons. Based on multilevel groundwater sampling data, the highest concentrations of the chlorinated ethenes, and BTEX occurred together and within the upper portion of the fill unit, 3.7 m below ground surface (bgs), slightly below the water table (located at 1.8 m bgs).

The treatment gate, 3.0 m wide, 4.5 m long and 6.0 m deep, was designed to funnel contaminated groundwater first through a sand/iron mixture (3-5% by weight of iron) followed by a 100% granular iron medium, then a well sorted gravel and the biosparge zone. Finally, the treated water passed into a second gravel zone, downgradient of the biosparge zone. The purpose of the sand/iron section was to ensure that the gate entrance was more permeable than the native aquifer and to initiate the reductive dechlorination reactions. The first gravel section was included to provide a separation distance between the anaerobic and aerobic treatment zones and the second gravel section served as the final monitoring zone (figure 22).

For the purpose of experimentation, the treatment gate was operated under controlled groundwater flow conditions. To achieve this, the gate was sealed downgradient of the last gravel section, and two pumping wells were used to draw groundwater through the gate at a specified flow rate.

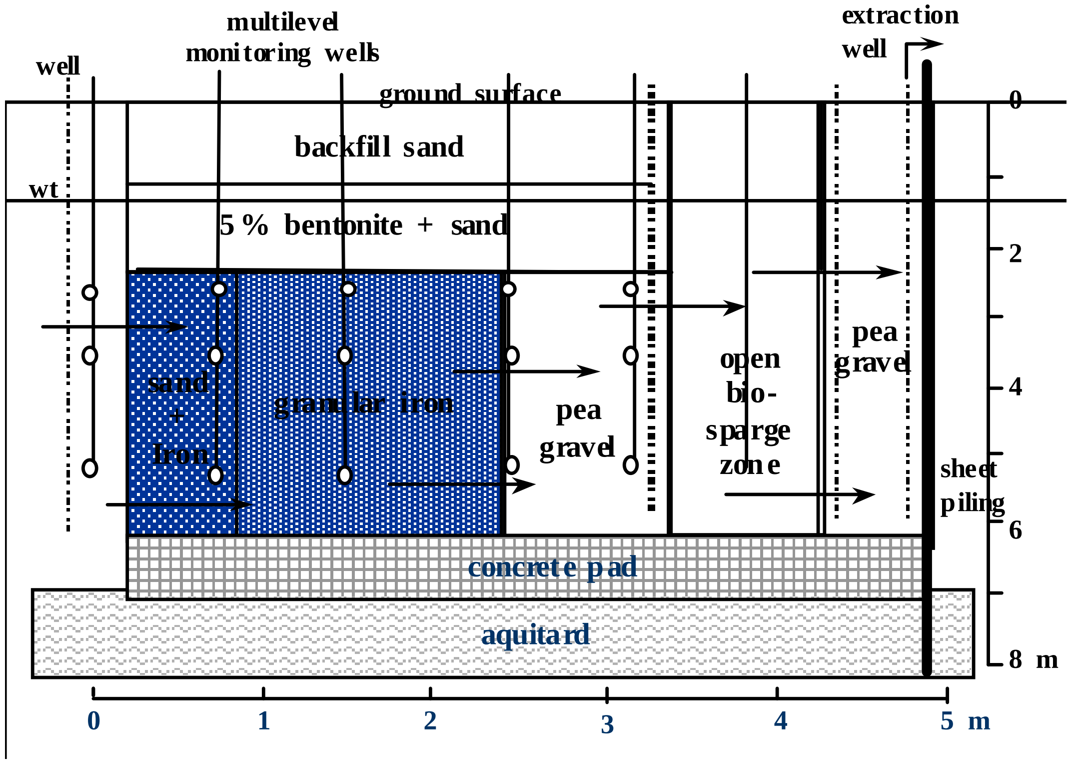


Fig. 22. Schematic layout of the Alameda sequential treatment gate in section along the groundwater flow direction through the gate.

Morkin et al. [2000] and Barker et al. [2000] describe details of the design, layout and construction. The biosparge system is emphasised here. The funnels and the treatment gate were constructed using Waterloo Barrier™ Sealable Joint Sheet Piles [Starr et al., 1994], extending into the underlying aquitard. A 'box' of sheet piling was installed and the fill inside excavated. Then a 0.6 m thick cement floor was poured on the bottom of the excavation to limit the vertical flow of groundwater within the gate, to support the weight of the iron, and to provide a bottom for the sparging system. The frame for the biosparge unit was then lowered into the open excavation. The frame consisted of five, hollow steel boxes, stacked one on top of the other. Each box was 0.9 m wide, 3.1 m long and 1.2 m high. The up and downgradient sides of the bottom 3 boxes were perforated (expanded metal lattice, ¼" centered holes on Gauge 11 steel) to permit unobstructed groundwater flow but retain gravel outside. The top two boxes were not perforated.

Once the frame was in place and sealed to the sheet piling, the monitoring wells were positioned throughout the treatment gate by strapping them to wooden beams laid down across the top of the open excavation. A total of 13 fully screened, stainless steel wells (5 cm ID) and 18 bundle multilevel piezometers were installed. The sand, iron and gravel units were then back-filled simultaneously to 2.4 m bgs. The 3 units were then covered with a geotextile liner, followed by a 100% bentonite layer (~5 cm thick), followed by fill mixed with 5% bentonite (1.2 m thick) and finally clean sand (1.2 m thick) was added to complete the cover. The gravel section, downgradient of the biosparge unit, was back-filled from 6.1 m bgs up to grade.

Two sparge units were lowered into the biosparge zone and placed side by side on the cement floor. The two units consisted of porous rubber/synthetic 1.58 cm ID hose that were mounted in a spiral configuration on the upper side of an expanded metal frame with dimensions of 81 cm by

122 cm. Gas inputs were located at each end of the hose as well as in the middle to provide a consistent air pressure throughout the hoses. The elliptical spirals were positioned approximately 5.1 – 12.7 cm apart leading to approximately 15.2 – 18.3 m of hose in each unit. The ports on the sparge hose were 1-2 mm wide. The hollow biosparge frame was then partially filled with low-volume, rigid, bacterial growth support material (Yeager Tri-Pac™, 8 cm diameter, hollow PVC balls resulting in approximately 90% porosity in the biosparge zone) with the remaining space left as open water. Because the PVC balls were significantly less dense than water, they were placed in steel cages and forced below the water surface. A cover/seal was placed over the bio-sparge unit to minimise the escape of any off-gas. The space overlying the water table, but below the biosparge cover, was also packed with the PVC balls that served as an unsaturated, headspace bioreactor where excess oxygen, perhaps containing traces of organics, could reside for a period of time sufficient to further degrade the contaminants.

The aerobic treatment method for this field demonstration consisted of sparging oxygen and carbon dioxide into the contaminated groundwater via the 2 sparge units. To maintain target DO and pH levels in the biosparge zone (DO ~20 mg/L and pH ~ 7-8), oxygen and carbon dioxide gas were sparged at regular intervals using automated timers. It was estimated, from prior field experience, that oxygen should be sparged at a delivery rate of 4.7 L/min, 6 times in 24 hours with each event lasting 15 minutes, leading to a total injected oxygen volume of 423 L in 24 hours. Carbon dioxide was sparged once every 3 weeks for 10 minutes at a delivery pressure of 10 psi, with a flow rate of 4.7 L/min. Infrequent sparging with carbon dioxide was sufficient for pH control considering that the liquid residence time in the biosparge zone was approximately 28 days.

Once construction was complete, the upgradient sheet piles were removed and the two pumps in the extraction wells were activated to draw groundwater through the gate. Continuous pumping was initiated on February 3, 1997 at an initial flow rate of 1.27 m^3/day and continued until April 21, 1997. The extraction rate was then reduced and maintained at 0.34 m3/day until June 27, 1998. On June 27, 1998, the extraction pumps were disconnected, the downgradient sheet piles were removed and the groundwater was allowed to flow through the treatment gate under the natural gradient. Field sampling and analytical methods are provided by Morkin et al. [2000].

A microcosm experiment was conducted to investigate the potential for contaminant biodegradation in the biosparge unit. Details are in Morkin et al. [2000].

After April 1997, benzene and toluene began to appear downgradient of the iron wall in the concentration range 10-4,000 µg/L. However, neither compound was consistently detected as far as the biosparge zone in concentrations above the limit of quantification (LOQ = 0.5 µg/L to 12 µg/L, depending on dilution and laboratory used). The attenuation of these compounds was probably due to some combination of aerobic biodegradation and volatilisation in the gravel upgradient of the biosparge zone. Both of these processes are reasonable assumptions since dissolved oxygen as high as 20 mg/L was detected in this gravel zone immediately upgradient of the biosparge zone. Insufficient data were available to resolve the relative contributions of these two mechanisms to the overall rate of BTEX mass removal. The only two organic contaminants that consistently reached the biosparge zone in concentrations above their LOQ were cDCE and VC.

It was anticipated at the outset of the experiment that both cDCE and VC would be susceptible to aerobic biodegradation and microcosm experiments confirmed this with micro-organisms from the biosparge section of the gate. Vinyl chloride was readily biotransformed from 300 to 400 µg/L to below detection within 8 days and cDCE was partially biotransformed (34% removal) at similar levels within 15 days. Toluene, added to the microcosm, was degraded to below detection limits 1 day after set up. Due to the high porosity of the biosparge system (porosity >90%), and the frequent mixing of the groundwater during sparging events (6 oxygen sparges every 24 hours, each lasting 15 minutes), the biosparge zone is perhaps best described as a mixed bioreactor rather than a porous medium. In a mixed bioreactor, the concentrations of solutes are consistently homogenised.

This seemed to be the case in the biosparge zone where there was little variation in organic contaminant concentrations from the influent to the effluent sides at any given time. Contaminant concentrations did, however, decline with increasing time (figure 23) suggesting biodegradation rate increases over that period.

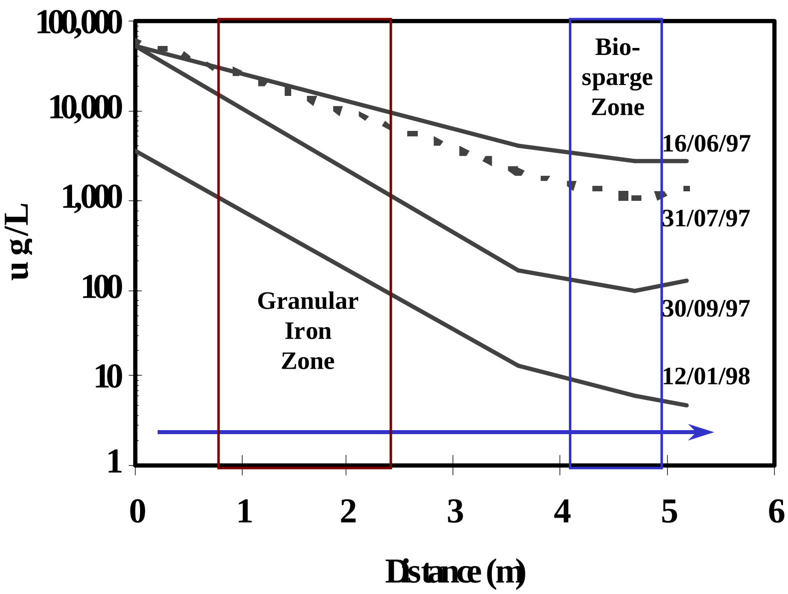


Fig. 23. Changes in average concentration of cis-1,2-dichloroethene in multilevel monitoring wells through the Alameda gate at four different times. Distance is measured from monitors immediately upgradient of the gate. The location of the granular iron and biosparge zones is indicated.

Modelling the mass removal in the biosparge zone assumed the biosparge zone to be a completely mixed bioreactor. The processes accounted for were (see [Morkin et al. 2000] and [Barker et al. [2000] for details):

1. biodegradation
2. partitioning of the organic contaminants into the sparge bubbles (assumed instantaneous) and the headspace
3. flux into the biosparge zone via advective groundwater flow
4. flux out of the biosparge zone via advective groundwater flow, and headspace gas release.

Calculating a percent mass loss using concentrations from just in front of the gate to concentrations in the final gravel zone assessed the overall performance of the 'Funnel and Gate'. The 'Funnel and Gate' removed > 99.6% of the total organic contaminants when the influent concentrations were high, as in September 1997, and the performance improved to > 99.9% when the influent concentrations decreased, in January 1998.

Much of the BTEX mass that entered the treatment gate (total BTEX ~8000 µg/L) did not break through the iron wall during this experiment, possibly due to sorption. However, the mass that finally broke through (total BTEX up to 5000 µg/L), was removed in the gravel section separating the iron wall from the biosparge zone, likely through a combination of aerobic biodegradation and volatilisation. Of the two chlorinated contaminants to reach the biosparge zone, VC and cDCE, modelling suggested that 66% of the total mass that entered the biosparge zone over a six-month period (June 1997 – November 1997) was removed due to a combination of biodegradation and volatilisation. In addition, of the total mass removed, it is estimated that 65% of cDCE mass was biodegraded with only 35% being volatilised.

The dominant removal process for VC was volatilisation (70% of the mass) with biodegradation amounting to 30%. Further monitoring may reveal that mass removal could be improved once a more efficient biomass is established in the biosparge zone.

The experience from other field studies indicated the potential for a high pH to develop in the granular iron zone. The periodic sparging of the CO_2 appeared to be successful in neutralising the elevated pH levels hence there were no discernible adverse effects to the aerobic microbial processes in the biosparge zone.

In general, this field demonstration has shown that treatment of mixed contaminant plumes (chlorinated solvents and petroleum hydrocarbons) by sequential use of granular iron with a biosparge zone is a viable option for controlling this type of groundwater contamination.

10.8 **Activating the system creates new possibilities**

The emphasis of the Canadian experiments with 'Funnel and Gate' lies on cutting off the contamination plume in a passive way when source cleanup is technically difficult or needs to be postponed. Within the framework of the NOBIS-project the possibilities were investigated of applying the original 'passive' concept for enhanced flushing/bioremediation. This investigation resulted in an 'active' system whereby downstream of the retention zone a low capacity pumping well is installed and upstream the extracted water is infiltrated. By the presence of a 'Funnel and Gate' system the direction and velocity of the groundwater movement in the captured zone is being influenced. As a consequence the 'captured' area will be flushed more intensely in comparison with 'Pump and Treat' systems having the same extraction and infiltration configuration and so the mobile components are more quickly leached leading to a decrease of the total remediation duration. The velocity in the captured zone is higher since because the funnel channels the water that is pumped through only the captured zone. On the contrary, in comparable 'Pump and Treat' systems the soil outside the retention zone will be flushed as well and as a result the velocity in the retention zone is lower. An illustration of the flow pattern is given in figure 24.

Re-infiltration in or upstream of the captured zone is not only necessary to enhance flushing but also to prevent lowering of the groundwater level. As a consequence of lowering of the groundwater level part of the contaminants cannot be flushed and remediated. Therefore, the extraction point should preferably be situated outside the retention zone.

Besides, infiltration on the downstream side of the gate may cause dispersion of the contaminants in de plume zone up to an unacceptable level. In case of Lijnbaan the down infiltration caused a radial flow from the gate which makes the plume zone fan out, mainly perpendicular to the natural direction of flow. An additional advantage of re-infiltration upstream of the gate in the case of Lijnbaan was the convergence of the streamlines upstream of the gate the streamlines and consequently the narrowing of the width of the plume zone.

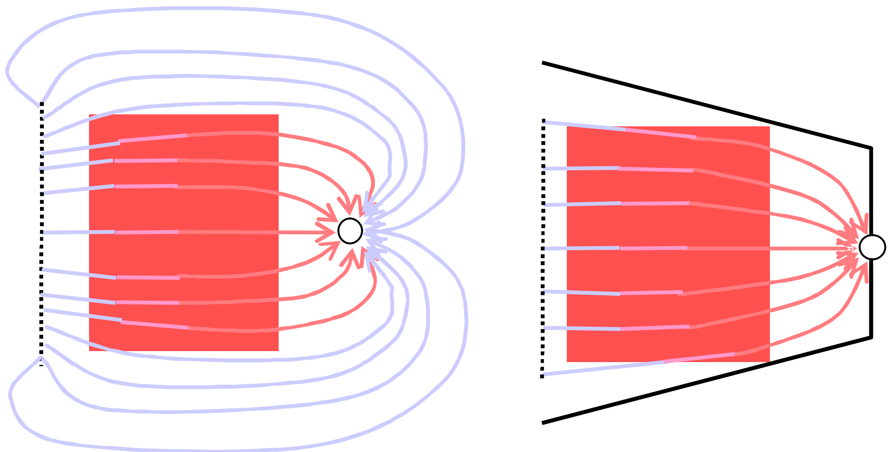


Fig. 24. Groundwater flow in a 'Pump and Treat' system (left) and 'Funnel and Gate' system (right)

In fact, one could say 'Pump and Treat' is uniquely combined with the original ‘Funnel and Gate’ concept. Not only the smaller duration of remediation is an advantage but maybe more important is the flow is channelled and therefore the flow and the remediation are controlled and managed more easily. Besides, the retention zone is physically separated from the plume by the 'Funnel and Gate' system. As a result the load of the plume is minimised and the failure risk of Monitored Natural Attenuation of the plume is lower. The active system thus is capable of remediation of the retention zone (increased leaching of the pure product from the soil), as well as of the plume zone (decomposition of the contaminants in the groundwater).

Also in an active 'Funnel and Gate' system the flushed and contaminated groundwater can be treated in a reactive zone in the gate. Different techniques can be used in the in situ reactor (see the foregoing chapters). Of course the abstraction point must be situated downstream of the reactor (see figure 25). During the course of the remediation, it even can become interesting to (temporarily) cease the groundwater abstraction and continue with the passive (original) concept. A flexible design of the system (dimensions of the funnel and the construction of the gate) then is, of course, a first prerequisite.

An alternative can be to treat the extracted water ex situ. In that case the groundwater is pumped up nearby the gate and is treated in a subsurface or aboveground installation. Basically, the output of an ex situ reactor is higher than in case of an in situ reactor. Highly contaminated water can be remediated completely in a well designed ex situ reactor. Sufficient know-how is available of the process of ex situ treatment while PRB technology now moves from the demonstration stage to maturity and remains with uncertainties in the long-term performance. On the other hand in an active system the effluent will be infiltrated again upstream of the retention zone. Complete remediation in the reactor is not absolutely necessary, while in the next cycles the remaining contaminants can be removed in the reactor.

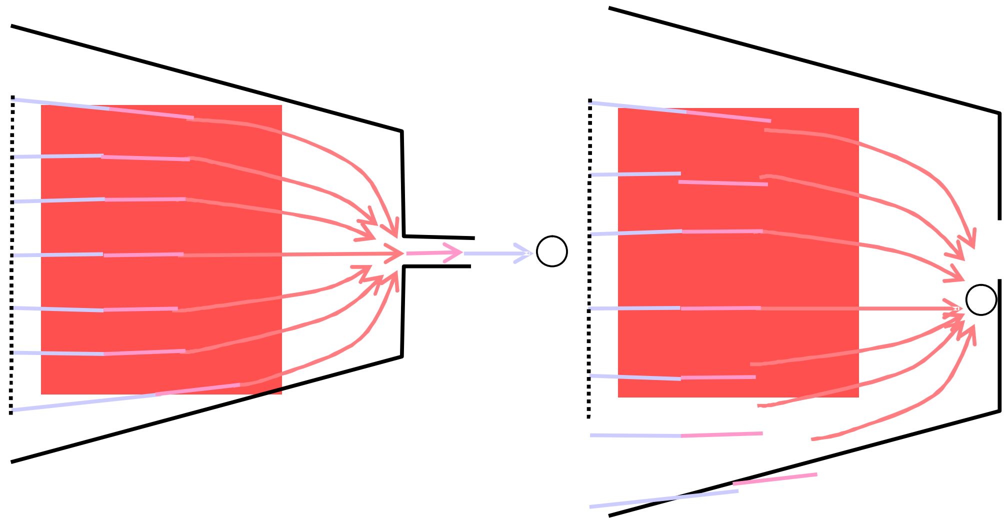


Fig. 25. Active system with reactive zone in gate or ex situ treatment

In the case of the Lijnbaan a subsurface installation has been opted for, partly because of the lack of space for an aboveground ex situ installation and an in situ reactive zone. Basically, in case of the Lijnbaan the 'Funnel and Gate' system is used for channelling the flow and for a physical separation between the retention zone and the plume zone.

Except for the possibility of cleaning up oil spills, an active 'Funnel and Gate' system still has other advantages compared to passive systems. By installing a pumping well, the location and depth of the funnel can be adjusted to the local situation. This can prove to be convenient when faced with infra-structural limitations (cables and conduits, buildings, roads etc.). Also, more flexibility is achieved when changes or adjustments are required (uncertain local geo-hydrological situations).

Naturally, the cost-effectiveness of an active system will vary from site to site. Determining factors are, amongst others, the technical feasibility to remediate by flushing and sub- and supra-surface obstacles (buildings, roads, cables, etc.). The choice between an active or passive variant therefore should be site-specific.

10.9 Comparisons and overview of PRBs for petroleum hydrocarbons

The five RBW/'Funnel and Gate'/'Trench and Gate' systems reviewed in this chapter have provided a reasonable measure of treatment success. The active 'Funnel and Gate' system at Lijnbaan (case 7) is described in the foregoing chapters. Table 17 draws some comparisons.

All cases dealt with typical petroleum hydrocarbon contaminants: BTEX, styrene and naphthalene. Both O_2 and NO_3^- were used as electron acceptors and novel methods to provide N and P nutrients were demonstrated in cases 3 and 4. The 'Funnel and Gate' systems were installed in sand aquifers, while the 'Trench and Gate' was used in a less permeable till setting. The 'Trench and Gate' was by far the largest, with a capture zone cross section of about 480 m^2. While the 'Funnel and Gate' systems were much smaller, they were typical of full-scale systems that could be employed on small retention zones or plumes. Case 5 permits assessment of a hanging system. Costs of design, materials, and construction are actual costs. In future applications, cost savings would be realised, as these systems had enhanced treatment gates to support the research studies. On the other hand, other sites may have conditions that make these systems inappropriate and/or more expensive. Both reduction in average concentrations entering the gate and reduction in contaminant flux out of the gate are estimated. The flux reduction is rather uncertain, as only in case 5 is the groundwater flux reliable measured, and then on only one occasion.

Table 17. Comparison of five PRBs.

	Case 1	Case2	Case 3	Case 5	Case 6	Case 7
Target compounds	BTEX	BTEX	BTEXS	Naphthalene	BTEX, Chlor. ethenes	BTEX
Electron Acceptor	O_2 from ORC®	Sparged O_2	Sparged O_2	NO_3^- from cement	Sparged O_2	O_2 in reactor ex situ
Nutrients	none	Diffused NH_3, solid PO_4^{3-}	Sparged NH_3	none	none	none
Aquifer K (m/sec)	10^{-4}	10^{-7} (est.)	3×10^{-6}	7×10^{-5}	2×10^{-5}	8×10^{-5}
Capture cross section, m2	5	480	25	20	40	250
Cost of design & installation	US$ 12,000	US$ 60,000	US$ 25,000	US$ 67,000	US$ 140,000	Hƒ 1.600.000
Treatment: Conc. reduction Flux reduction (g/yr)	 10 $mgL^{-1} \rightarrow$ 3 mgL^{-1} --	 2.5 $mgL^{-1} \rightarrow$ < 1 ugL^{-1} 2,200	 60 $mgL^{-1} \rightarrow$ 45 mgL^{-1} 200	 1 $mgL^{-1} \rightarrow$ < 10 ugL^{-1} 320	 1.5 $mgL^{-1} \rightarrow$ 0.3 mgL^{-1} --	 20 $mgL^{-1} \rightarrow$ < 1 mgL^{-1} 20,000
Major remaining uncertainties	Long-term performance	Long-term cost & performance	Treatment capacity, long-term cost & performance	Treatment mechanism, long-term performance	Long-term performance	Remediation duration
Potential application in the petroleum industry	Cut off a small plume in a shallow aquifer	Contain a large retention zone in a shallow, low K aquifer	Contain a small retention zone or plume in a shallow aquifer	Contain a small retention zone or plume in a shallow aquifer	Contain a small retention zone or plume in a shallow aquifer	Source cleanup
Challenges for cost-effective, full scale application	Longevity and cost of ORC®	Variable ground water flux	Non-uniform oxygen delivery	Uncertain reaction, expensive cassette system	Construction costs and longevity of sparge K	Construction costs of bioreactor

The 'Funnel and Gate' system presented in case 3 was not able to treat the unexpectedly high BTEXS flux at the site. This points out the need for good site assessment and for a conservative 'Funnel and Gate' design, especially near recurring sources when essentially-NAPL saturated groundwater might be encountered. Using a pea gravel sparge zone had the advantage of storing O_2 in the gate, but non-uniform distribution of gas is such a common occurrence that great care would be required to ensure sufficiently broad distribution of this stored residual gas to oxygenate all groundwater emanating from the gate. It was demonstrated that NH_3 could also be provided to the gate by sparging, if required to enhance biodegradation rates. Successful treatment at this site would have required almost continuous air sparging, with an increased reliance on volatilisation, and better distribution of residual O_2 in the pea gravel gate.

The 'Trench and Gate' system (case 4) demonstrated the use of permeable trenches to move groundwater into and out of the in situ treatment zone. Plume capture is inherently more effective than with 'Funnel and Gate' in which about half of the flow towards the barrier is diverted around the funnel and does not pass through the gate. Bowles et al. [2000] indicate the 'Trench and Gate' system requires that the trenches only be one order of magnitude more permeable that the aquifer/aquitard.

However, a system to re-infiltrate the treated groundwater is also required, and this must have at least the capacity of the collection trench system. This system would have been even cheaper to install if site conditions were as expected from initial site assessment. This highlights the need to address constructability issues during site assessment if reactive barriers are to be considered.

This site is somewhat unusual in that PO_4^{3-} was found to be a nutrient limiting biodegradation of higher loading of BTEX. The research demonstrated this could be overcome by passive PO_4^{3-} release from solids. The 3-culvert treatment system continues to operate successfully with only air sparging into the first culvert.

Sparging oxygen, used in cases 3, 4, and 6, has an added advantage for gate treatment, in that it promotes homogenisation of often heterogeneous influent groundwater concentrations. In many reactive barriers, groundwater follows slightly distorted flow lines through the porous treatment medium (e.g., granular Fe0). Where a small proportion of the influent flow is of much higher concentration, the thickness of such a reactive barrier must be designed for the highest concentration. If influent groundwater was mixed, as by gas sparging, before entering the remedial system, a thinner and less costly treatment zone would be possible.

The fifth case, the 'Funnel and Gate' at Borden, is the focus of continuing research. Considerable cost savings could have been realised if the sophisticated cassette gate system had not been used. On the other hand, it has proved invaluable for evaluating the gate treatment. While stimulation of naphthalene degradation by denitrifying bacteria was demonstrated through NO_3^- addition from solids, the longer term competition with aerobes is as yet unclear. Plume capture appears to be at least as good as predicted. This is the only 'hanging' barrier system we are aware of and so this is the first demonstration that plume 'dive' under the system need not be significant.

Recent work by Kerr (M Sc in progress) has used tracer tests to demonstrate the groundwater flux through the Borden 'Funnel and Gate' system. There does not appear to be independent measurement of groundwater flux through any current reactive barrier system and so the designs have not be completely verified. The other 'Funnel and Gate' and the 'Trench and Gate' were plagued by problems with measuring this important treatment design parameter and so this tracer test approach is a useful technique.

The ongoing research at this site focuses on assessing the accuracy of the hydraulic design predictions of flux through gate and plume capture. If these systems cannot be demonstrably well designed in the highly-characterised Borden aquifer, there would be little confidence in designs at geo-hydrological more complex sites, potentially leading to failures or gross over-designs with cost penalties.

All three systems focus contaminated groundwater to a small, in situ treatment zone. Simple reactive barriers simply treat the groundwater as it flows through the permeable 'barrier'. The potential advantage of the more-engineered 'Funnel and Gate' or 'Trench and Gate' systems would be lower costs for funnels/trenches with only a small in situ treatment zone versus higher costs for continuous, in situ treatment within the whole permeable barrier.

This advantage is usually realised only if treatment requires expensive processes or frequent adjustment/service. While passive, in situ treatment by Fe^0 appears to be more economically conducted in permeable reactive barriers [US EPA, 1998], the more active support required for in situ biodegradation of petroleum hydrocarbons makes a small, flexible, easily accessed gate more attractive. A minor advantage of 'Funnel and Gate'/'Trench and Gate' systems may be that compliance monitoring may be focused on a smaller area (i.e., down gradient of the gate), providing more confidence at lower cost.

For petroleum contamination, *in situ* reactive barrier systems are mainly for long-term containment and as such are typically compared to 'Pump and Treat' techniques. 'Funnel and Gate' and 'Trench and Gate' are typically characterised by higher initial costs with potentially lower operation costs than 'Pump and Treat'. In all the three systems discussed here, cost advantages over 'Pump and Treat' or recurring excavation of sources were predicted, but are very dependent on ongoing operational costs. While considerable experience with 'Pump and Treat' has accumulated, the long-term operating costs for 'Funnel and Gate' and 'Trench and Gate' systems are just now being developed. Certainly these systems will be selected and designed on the basis of site specific assessment and remedial goals. Design variants continue to appear and longer-term performance information is accumulating as this technology moves from the demonstration stage to maturity.

All of these PRBs have been used for plume cut-off, not remediation of the retention zone. The NOBIS system is unique in also trying to shorten the time that the retention zone would remain as a source of significant groundwater contamination. Also, all other systems avoid pumping groundwater except for experimental control while the NOBIS 'Funnel and Gate' uses pumping and groundwater recirculation to enhance the dissolution/desorption of contaminants in the retention zone.

The choice of cleanup remedy will be situation-specific. One screening approach is to identify the 'drivers' for cleanup. These are often one or more of: time, cost and distance. If time is the driver for remediation, neither MNA and traditional permeable reactive barriers (PRBs) are likely appropriate. The NOBIS system presents an alternative 'Funnel and Gate' approach in which remedial objectives need to be attained within a 30-year time. The NOBIS 'Funnel and Gate' attempts to combine plume control ('Funnel and Gate') with enhanced flushing/bioremediation of the retention zone. While necessitating a more sophisticated gate, it provides for outstanding control of subsequent groundwater collection using the 'Funnel and Gate'. When cost becomes the driver, MNA should be the general choice. Where time is available but MNA is not technically feasible or is too risky (e.g., plume will be too close to receptors), then traditional in situ PRBs are possible remedies.

For plume cut-off or control, PRBs typically have higher initial costs with potentially lower operation costs than 'Pump and Treat'. Cost advantages over 'Pump and Treat' are very dependent on ongoing operational costs and financial discount rate. PRB design variants continue to appear, so technically better and lower cost systems are anticipated. While considerable experience with 'Pump and Treat' has accumulated, longer-term performance/cost information for PRBs is still needed.

10.10 **References**

Austrins, C. D.,1997, Enhanced in situ bioremediation of hydrocarbon contaminated groundwater using oxygen and ammonia gas injection in a funnel & gate scheme, M Sc Thesis, University of Waterloo, Waterloo, ON.

Barker, J. F. and 9 other authors, 2000. Sequenced reactive barriers for groundwater remediation. Fiorenza, S., Oubre, C. L., Ward, C. H. (eds.). Lewis Publishers (ISBN 1-56670-446-4).

Borden, R. C., Goin, R. T., Kao, C. M., 1997. Control of BTEX migration using a biologically enhanced permeable barrier. Ground Water Monitor. Remed., 17(1), 70-80.

Bowles, M. W., Bentley, L. R., Hoyne, B., Thomas, D. A., 2000. In-situ ground water remediation using the Trench and Gate system, Ground Water, 38(2), 172-181.

Chapman, S. W., Byerley, B. T., Smyth, D. J. A., Mackay, D. M., 1997. A pilot test of passive oxygen release for enhancement of in-situ bioremediation of BTEX-contaminated ground water. Ground Water Monitoring and Remediation, 17(2), 93-105.

Devlin, J. F. and Barker, J. F., 1999 . Field demonstration of permeable wall flushing as a method of introducing solutions to an aquifer for bioremediation. Ground Water Monitoring & Remediation, 19(1):75-83.

Gibson, T. L., Abdul, A. S., Chalmer, P. D., 1998. Enhancement of in situ bioremediation of BTEX-contaminated ground water by oxygen diffusion from silicone tubing. Ground Water Monitoring & Remediation, 18(1), 93-104.

Gorman, J.K. 1995. Bioremediation of Hydrocarbon Contaminated Soil and Groundwater using an In Situ Funnel-and-Gate Strategy. M.Sc. Project. Department of Earth Sciences, University of Waterloo, Waterloo, ON.

Granger, D. 1997. Nutrient Amendment to Enhance Aerobic Biodegradation within a Funnel-and-Gate System, M.Sc. Project, Department of Earth Sciences, University of Waterloo, Waterloo, ON.

Granger, D.A., Butler, B.J., and J.F. Barker, 1999. A case of phosphorus limiting monoaromatic hydrocarbon biodegradation in groundwater, Bioremediation Jour. 3(3), 213-221.

Granger, D. A., Barker, J. F., Bowles, M. W., (in press). Field demonstration of nutrient amendment and BTEX bioremediation in a trench and gate system. Submitted to Ground Water Monitoring & Remediation.

King, M. and Barker, J. F., 1999. Migration and natural fate of a coal tar creosote plume 1. Overview and plume development. J. Contam. Hydrol., 39, 249-279.

Kao, C. and Borden, R.C., 1997. Enhanced TEX biodegradation in nutrient briquet-peat barrier system, Jour. Environ. Engin., Jan., 1997, 18-24.

Lauzon, F.,1998, In Situ Biodegradation of a Naphthalene Plume in a Funnel-and-Gate System, M.Eng. thesis, Department of Civil Engineering, Royal Military College of Canada, Kingston, ON.

Morkin, M., Devlin, J. F., and Barker, J. F., 2000. In situ sequential treatment of a mixed contaminant plume. Jour. Contam. Hydrology, 45(3-4):283-302.

RTDF, 2001. www.rtdf.org/public/permbarr/barrdocs.htm.

Starr, R.C., and Cherry, J. A., 1994. In situ remediation of contaminated ground water: the funnel-and-gate system. Ground Water 32, 465-476.

Sudicky, E. A., 1986, A natural gradient experiment on solute transport in a sand aquifer: spatial variability of hydraulic conductivity and its role in the dispersion process, Water Resour. Res., 22, 2069-2082.

Swindoll, C.M., Aelion, C.M., and F.K. Pfaender., 1988, Influence of inorganic and organic nutrients on aerobic biodegradation and on the adaptation response of subsurface microbial communities, Applied and Environmental Microbiology 54, 212-217.

USEPA, 1998. Permeable reactive barrier technologies for contaminant remediation. EPA/600/R-98/125.

Wilson, R. D. and D. M. Mackay, 1995, A method for the passive release of solutes from an un-pumped well. Ground Water 33, 936-945.

CHAPTER 11

GUIDELINES FOR APPLICATION AND DESIGN OF ACTIVE 'FUNNEL AND GATE' SYSTEEM

11.1 Guidelines for application of active 'Funnel and Gate' systems

With the ‘Funnel and Gate’ technology contaminated groundwater is channelled under the influence of the prevailing groundwater flow and isolation walls (funnel) through a controlled reactive zone in the soil (gate) in which the groundwater is remediated. This makes ‘Funnel and Gate’ suitable for:

- The cut-off of retention zone from plume zone, thus preventing further ‘loading’ of the plume zone and trapping all contaminants coming from the retention zone (source clean-up and source control).
- Controlling the plume zone and – in this way – preventing a further increase of the groundwater contamination (plume control)

Source clean-up and source control

With ‘Funnel and Gate’ it is possible to cut-off the retention zone from the plume zone. This aims at the removal of the mobile contaminants that are released into the groundwater by the contamination source. To meet this objective, the system should contain the retention zone. In that case all contaminants released from the retention zone are directed towards the reactive zone of the ‘Funnel and Gate’ system (by either natural or induced flow). In this reactive zone, the contaminants are biologically degraded. After administering sufficient amounts of biological-reactive compounds, the groundwater is re-infiltrated into the soil system.

‘Funnel and Gate’ prevents a further spreading of contaminants by preventing the retention zone to ‘add’ new contamination to the plume. The bulk of contaminants in the retardation zone will then cease to increase. Remediation proceeds until a situation is reached in which - without active after-care – all mobile contaminants have disappeared. This point generally will be reached after considerable time in passive variants. One could name it, therefore, groundwater control instead of groundwater remediation.

To decrease remediation duration, the system can be activated in the way described earlier. Based upon the required duration, literature data and laboratory research, calculations can be made about the number of pore volumes ‘soil flushing’ required in order to meet the remediation objectives. The calculated number of pore-volumes of groundwater that must be abstracted will be a parameter in setting the correct pumping quantity. Since an intensive in-situ flushing of the retention zone aims at an increased removal of the contaminants, such a concept also meets the objectives of a variant aimed at removal of the contaminants.

A shorter remediation period not necessarily forms the sole and only reason for the choice to activate the system. Requirements in flexibility, anticipating changes in the geo-hydrological situation and (telemetric) controllability can also form important aspects.

Also in an active 'Funnel and Gate' system the flushed and contaminated groundwater can be treated in a reactive zone in the gate. Different techniques can be used in the in situ reactor. An alternative can be to treat the extracted groundwater ex situ. In that case the groundwater will be extracted nearby the gate and treated in a subsurface or aboveground installation by way of proven technology.

Generally speaking, an active 'Funnel and Gate' system will be applied when:

- the retention zone is remediated by way of enhanced flushing/bioremediation and other remediation techniques are not suitable or feasible or are more expensive
- an active 'Funnel and Gate' system has strong advantages compared to a 'Pump and Treat' system.

Plume control

As follows from chapter 10 former pilot tests usually involved passive ‘Funnel and Gate’ variants, which were installed downstream groundwater contamination. In this way a further increase of the plume-size was prevented. If the retention zone is not removed, the groundwater contamination will be continuously ‘feeded’ by dissolution from the pure product in the retention zone.

The remediation will end finally once all mobile components are dissolved from the retention zone, and the groundwater contamination as a whole has disappeared by natural groundwater flow through the gate.

To decrease remediation time the retention zone can be removed (e.g. by biosparging or bioventing). Then the process of dissolution can practically immediately be halted. Activation of the system is in this situation less effective as compared to a system in which the ‘Funnel and Gate’ would be installed directly downstream of the retention zone (to prevent further dissolution into the plume). An active system can however be effective in the following situations:

- An unstable geo-hydrological situation, e.g. by other pumping-activities in the direct neighbourhood of the system;
- Limited natural groundwater flow;
- If the costs of extra abstraction and infiltration systems do not counterbalance the cost-reduction resulting from a shorter and probably also shallower funnel construction;
- If a long oval plume is present, the gate will be relatively far away from the retention zone, rendering the system more sensitive to small changes in the direction of the groundwater flow.

Conditions for the application of active F&G are:

- The source approach of an active F&G (flushing, bioremediation), possibly combined with other techniques, has to be competitive compared to alternative approaches.
- Active F&G also has to be competitive in relation to P&T. The higher initial costs of active F&G compared to P&T have to be earned back during the exploitation phase by way of lower exploitation costs. Profits can be achieved by way of a short remediation period; the presence of a F&G system allows for higher flow rates in the source zone. A second advantage can be found in a simple in situ treatment compared to a more expensive (aboveground) installation in case of P&T.
- It has to be possible to install a solid F&G system. This means that the funnel encloses the source zone with sufficient space between it and can be installed on a separating layer situated at a limited depth.
- It will have to be possible to deal with the plume in a different way than applied in case of P&T. P&T in the plume comes into conflict with active F&G of the source, since the advantage of active F&G has to be achieved by avoiding the use of an expensive aboveground treatment installation.

11.2 **Guidelines for design of active 'Funnel and Gate' systems**

The most important guidelines for the design and operation of an active F&G system are:
- A solid F&G system has to be installed. Preferably, the funnel will be installed on a layer with a low permeability and the retention zone(s) will enclose the funnel with sufficient space in between.
- The reactor in the gate has to be simple and cheap in order to be competitive with other techniques. Preference is given to an active soil zone.
- The infiltration facilities have to be installed in the retention zone in order to achieve an effective remediation.
- The groundwater extraction has to take place downstream of the gate. In this way resistance to groundwater flow as a result of the treatment in the gate will be neutralised.

An active 'Funnel and Gate' system is combined with enhanced flushing/ bioremediation. The design of the 'Funnel and Gate' system is attuned to the process of flushing/bioremediation. Two phases should be distinguished in this remediation approach. In the first phase the mobile components are removed faster. The groundwater velocity in the retention zone determines the duration of this phase. In the second phase the solute of contaminants is no longer determined by the flow rate, but the removal rate is determined by slow processes such as diffusion and desorption. During the course of the remediation therefore, it can become interesting to cease (temporarily) the groundwater abstraction and continue with the passive (original) concept. A flexible design of the system (dimensions of the funnel and the construction of the gate) then is, of course, a first prerequisite.

The design of a 'Funnel and Gate' system is determined by:
- the location of the construction
- the length and depth of the funnel
- the depth of the gate
- the construction of the water inlet
- the treatment installation
- the infiltration and monitoring systems

Location of the system

The system can be situated downstream of the retention zone or in front of the plume. For this choice the following aspects must be taken in consideration:
- temporal variability of the direction of the groundwater flow
- (future) abstractions within the project area
- presence of obstacles (underground structures, buildings etc.)

Funnel length

The retention zone needs to be closed in by the funnel in a sufficient way in order to prevent back flow. The results of the test phase have shown that the short funnel of the system limits the remediation extent of the retention zone. The length and also the depth of the funnel depend on the abstraction rate. Besides, the rate and the place of infiltration may determine the length of the funnel. The abstraction depth also determines the depth of the funnel. The abstraction depth needs to be situated at the level of the retention zone to prevent under flow.

Another condition for the dimensions of the funnel that the groundwater flowing through the retention zone also passes the gate under natural flow conditions. The assumption for the determination of the funnel length is that all groundwater contaminants originating from the retention zone are 'caught' in 'Funnel and Gate'. In case the objective is source control the horizontal track of the funnel will follow the contours of the retention zone. In the event of a possible little fluctuation of the direction of flow, minimal leakage could be accepted. Using the groundwater model created, the length of the funnel wall will be determined by means of iterative calculations.

Funnel depth

The depth of the funnel influences the amount of contaminants leaking out under the structure. There are two possibilities for the funnel depth:

- a funnel reaching into an aquitard, a complete funnel
- a funnel not reaching into an aquitard, a so-called 'hanging' funnel

Obviously, for shallow aquifers (< 10 m -gl) a complete funnel will be chosen. For deeper aquifers complete funnels lead to high costs and, possibly, construction problems. For example sheet pile walls (steel vertical impermeable walls) have a maximum length of 25 m. If the contamination does not reach the aquitard the groundwater model can be used for determining the optimum depth.

Depth of gate

One of the criteria to determine whether it is possible to apply 'Funnel and Gate' is the maximum depth of the gate. A maximum depth of the gate of 10 m is stated. In most cases this depth will not coincide with the depth at which the aquitard can be situated. Then a hanging gate has to be applied. Two options for a hanging gate can be investigated, namely:

- the space under the gate is open, which means that clean groundwater can flow out under the gate
- the space between the bottom edge of the gate and the aquitard is confined.

Of course, the second option will lead to a shallower situated gate than with the first option. The experiences with the project Lijnbaan/Westeinde show that the second option is preferable for hydrological as well as constructional and financial reasons.

Construction of the water inlet

The location and number of abstraction points may influence the groundwater flow in the retention zone. Location and number of abstraction points are determined on the condition that the groundwater velocity shall be as high as possible in that part of the retention zone where the highest load of mobile components occurs. Furthermore, the number of points is determined by the absorbing capacity of the abstraction point and the design flow rate. Preference is given to a limited number of miniwells.

In the design attention has to be paid to the depth of the abstraction points. The abstraction point has to be installed well below the lower side of the funnel and gate in order to prevent under flow.

The construction of the water inlet has to be designed by way of a detailed groundwater model.

Treatment installation

Proven technology can be applied for ex situ water treatment. Biological treatments in a sludge-on-carrier system or intensive aeration systems are obvious techniques for the treatment of oil contaminants. Differentiated treatment can be applied to optimise the treatment.

The design of the treatment system can be influenced by the presence of natural substances:

- precipitation of iron and manganese oxides within the treatment system could be undesirable, thus making removal necessary (aeration and sand filtration)

- the precipitation of iron and manganese and accumulation of small particles within the infiltration system could make removal of these components necessary

On the other hand, the treatment process itself can influence the quality of the effluent that will be infiltrated. For example, if during the treatment process too much oxygen is added, the residue could lead to problems at the infiltration system (precipitation, bacterial growth etc).

The results of the test phase show that the output of an active sludge system without using carrier material (open gate) is low. In general, the organic load of (contaminated) groundwater is too low to develop sufficient mass of sludge in a reactor.

The method of in situ groundwater treatment in a reactive zone was described in detail in chapter 10.

Infiltration
With an active 'Funnel and Gate' system the extracted groundwater has to be infiltrated upstream of the gate in order to flush the retention zone as intensive as possible (in vertical direction) and at the highest velocity. The location of the infiltration depends on the location of the mobile zones and the possible presence of pure product in the unsaturated zone. Horizontal infiltration means are preferred (drains in gravel) since flushing of the retention zone will be more effective than in case of vertical systems.

The location of the infiltration also influences the groundwater flow in the plume zone. Infiltration on the downstream side of the gate may also cause dispersion of the contaminants in de plume zone up to an unacceptable level. In case of the Lijnbaan project the down infiltration caused a radial flow from the gate which makes the plume zone fan out, mainly perpendicular to the natural direction of flow. If natural attenuation is insufficient the shape of the retardation zone will alter which may cause legal problems. Corrective measures may be taken.

Re-infiltration upstream of the gate resulted in the case of Lijnbaan in converging streamlines upstream the gate and therefore the width of the plume zone will be smaller.

Monitoring system for source clean up and control
In the retention zone monitoring wells are installed to monitor the remediation. These monitoring wells will also be used for the determination of the groundwater movement in the retention zone in order to optimise the flushing of the retention zone.

At critical points (ends and lower part of the funnel) the groundwater quality will be monitored as well. The abstraction and infiltration system will be attuned the moment the concentrations at these critical points are higher that the action values determined in advanced and as a result undesired back flow or up flow has occurred.

During the synchronising phase groundwater measurements will be carried out frequently to determine the correct tuning of the system. During the exploitation phase the number of measurements of the groundwater level will be reduced and monitoring will focus on monitoring of the groundwater quality inside and outside the retention zone. The measuring frequency in the retention zone corresponds with the changes to be expected in the concentration level. The measuring frequency at the aforementioned critical points corresponds with the groundwater velocity at this location and the remediation capacity of the soil in the plume zone.

During the synchronising phase PLC control of the groundwater movement may be of use for the determination of the right tuning of extraction and infiltration rates, but during the remediation phase PLC control of the groundwater movement will not be necessary.

Monitoring system for plume control

As a first step, the behaviour of the retardation zone is monitored. The objective of the monitoring is twofold. On the one hand, the monitoring must provide sufficient data to allow active intervention as soon as the retardation zone threatens to spread beyond permitted limits. On the other hand, the monitoring plan is a tool for ascertaining whether natural attenuation is already taking place and if so, to what extent. In this case, natural attenuation is defined as a decrease in the concentrations of contaminants in the groundwater due to naturally occurring.

For the determination of the dimensions the groundwater model must be used. An infinite number of combinations of abstraction rates and funnel length can be achieved. So the design is an iterative process in which the cost must also be taken into account.

The costs of ‘Funnel and Gate’ is affected by the remediation period, the capacity of the gate, and the length and depth of the funnel. Other costs are not directly related to the structural dimensions. The cost variables depend on the flow rate through the retention zone. Obviously, the duration of the remediation and therefore the monitoring costs are linked to the abstraction rate.

11.3 Groundwater modelling, a tool for design

From a hydrological point of view the 'Funnel and Gate' system is such complex it makes the use of advanced calculation techniques necessary. Therefore, the use of a groundwater model is indispensable for the design process of 'Funnel and Gate' systems.

Groundwater modelling has the following objectives:

- design of 'Funnel and Gate' systems
- comparison of 'Funnel and Gate' systems
- determination of influence on the surroundings

Groundwater models always are an aid in designing. A groundwater model is inadequate for engineering a remediation. Groundwater level measurements and also groundwater quality measurements are of primary importance in getting insight into the groundwater flow.

Type of model

At the start of the design process it is not clear which remediation options are involved, so it is important to use a model which is flexible and easily adaptable. For instance funnels must be easy to model and quick to change. Modelling of 'Funnel and Gate' systems requires a certain amount of detail (interdistances of knobs of a few meters) so the model should have a sufficient capacity of both cells and calculation speed.

Model size

The first step to take is to establish the project area or speaking in terms of geo-hydrology: determine the rate of influence of the future remediation system. Based on studies elaborated at the University of Waterloo in Canada, a radius of 2 to 3 times the size of the future system can be chosen. In the Lijnbaan project the radius of influence is four times the width of the system. In case of active 'Funnel and Gate' systems the rate of influence of the abstraction and infiltration system determines the model size.

Geo-hydrological data

Next is to establish the geo-hydrological situation in the project area. Among others this includes the determination of the following aspects:

- stratification and schematisation of the soil
- permeability of various layers (horizontal and vertical)
- groundwater heads (possibly in various layers)
- direction of groundwater flow

Especially for active 'Funnel and Gate' systems it is of importance to consider the retention zone as a separate layer in the model, since the permeability of the retention zone is influenced by the presence of oil.

Also it is important to have insight into the temporal variety of the direction of the natural groundwater flow. Eventually, more than one situation has to be modelled and calibrated. Furthermore, attention should be paid to present or future abstractions in the vicinity of the project area.

CHAPTER 12

FINAL CONCLUSIONS AND RECOMMENDATIONS

12.1 General

In the first instance the original 'Funnel and Gate' concept was designed to control groundwater plumes of regulated petroleum hydrocarbon components such as benzene, toluene, ethylbenzene and xylenes. The Funnel and Gate technique can also be applied for the attenuation of groundwater plumes. In that case a Funnel and Gate system prevents a further spreading of contaminants by preventing the retention zone to add new contamination to the plume. The mobile components are decomposed in a reactive zone and do not reach the plume zone. Various pilot and full scale projects have now demonstrated the successful in situ treatment of a wide range of contaminants using in situ permeable reactive barrier (PRB) technology [USEPA, 1998; RTDF, 2001]. Design variants continue to appear and longer-term performance information is accumulating as this technology moves from the demonstration stage to maturity.

The choice of cleanup remedy will be situation-specific. One screening approach is to identify the 'drivers' for clean up. These are often one or more of: time, cost and distance. If time is the driver for remediation, neither MNA and traditional permeable reactive barriers (PRBs) are likely appropriate. In that case an active 'Funnel and Gate' system would be an optional technique. When cost becomes the driver, MNA should be the general choice. Where time is available but MNA is not technically feasible or is too risky (e.g., plume will be too close to receptors), then traditional in situ PRBs are possible remedies.

For plume cut-off or control, PRB technology typically has higher initial costs with potentially lower operation costs than 'Pump and Treat'. Cost advantages over 'Pump and Treat' are very dependent on ongoing operational costs and financial discount rate. PRB design variants continue to appear, so technically better and lower cost systems are anticipated. While considerable experience with 'Pump and Treat' has accumulated, longer-term performance/cost information for PRBs is still needed.

The case of Lijnbaan presents an alternative 'Funnel and Gate' approach in which plume control ('Funnel and Gate') are combined with enhanced flushing/ bioremediation of the retention zone. The velocity of the channelled flow is higher than in passive 'Funnel and Gate' and 'Pump and Treat' systems and so the remediation time will be decrease. Furthermore and maybe of more importance is the increased degree of control and management of a flushing system by the presence of the funnel. Also in an active 'Funnel and Gate' system the water can be lead through a reactive zone and be treated in situ. In the case of Lijnbaan proven technology in a ex situ reactor has been chosen for.

Conditions for the application of active F&G are:

- The groundwater flow is manageable; without to much detrimental effects and costs it is possible to canalise the flow through the source and between the funnel walls into the gate. Canalisation always requires energy; water table is rising before the gate and is dropping behind the gate to provide the energy to cope with the resistance in the system. In case of a passive system the natural groundwater system should allow this draw down In case the water table has its limitations, limited unsaturated zone and limited possibilities to draw down the water table, than a passive system is no longer feasible and pumping is required. By applying pumps in combination with infiltration drains and the valves in the gate it is possible to manage the flow and enhancing the leaching processes in the source;

- The source is leachable; solubilisation of (the mobile fractions of) the contaminants is possible. This means that the permeability of the soil is reasonable, also in the source, and adsorbtion forces are not too high;
- The contaminants in the plume are treatable in the gate. For aliphatic and aromatic compounds this is no problem by applying bioreactors. For chlorinated compounds like Tri and Per iron walls are feasible solutions;
- Infrastructure on the site allows the construction and exploitation for a longer period of the F&G system;
- The source approach of an active F&G (flushing, bioremediation), possibly combined with other techniques, has to be competitive compared to alternative approaches;
- Active F&G also has to be competitive in relation to P&T. The higher initial costs of active F&G compared to P&T have to be earned back during the exploitation phase by way of lower exploitation costs. Profits can be achieved by way of a short remediation period; the presence of a F&G system allows for higher flow rates in the source zone. A second advantage can be found in a simple in situ treatment compared to a more expensive (aboveground) installation in case of P&T.

Guidelines have been drawn up for the application and design of active 'Funnel and Gate' systems in [3]. The test phase resulted in a number of additional design criteria for active 'Funnel and Gate' systems.
The most important guidelines for the design and operation of an active F&G system are:

- A solid F&G system has to be installed. Preferably, the funnel will be installed on a layer with a low permeability and the retention zone(s) will enclose the funnel with sufficient space in between;
- The reactor in the gate has to be simple and cheap in order to be competitive with other techniques. Preference is given to an active soil zone;
- The infiltration facilities have to be installed in the retention zone in order to achieve an effective remediation;
- The groundwater extraction has to take place downstream of the gate. In this way resistance to groundwater flow as a result of the treatment in the gate will be neutralised;
- The system will also have to function in accordance with the original principle.

12.2 **Groundwater flow**

- The retention zone has an intrinsically isolating capacity. The natural groundwater flow rate is low (3 – 5 m/year) and the permeability of the retention zone has decreased by at least 50% as a result of the presence of oil. Therefore, the retention zone offers resistance to groundwater flow.

- It can be concluded that the hydrology in a retention zone influences the supply of contamination to a plume and the spreading of the contamination in the plume. A retention zone has an intrinsically isolating capacity and fluctuations in the water table make that the supply of contamination to a plume and the spreading of contamination in the plume have a dynamic nature.

- Partly because of the isolating capacity of the retention zone the plume is limited in size.

- It is very likely that short-circuit flow below the funnel (under flow) has taken place. The chance of under flow would be reduced, when the funnel is longer and the inlet point is situated higher.

- As a result of remediation in the retention zone (drain 6) pass flow along the funnel will occur.

- The F&G system influences the groundwater flow in the surrounding area up to some tens of metres outside the system or 4 times the width of the system.

- By means of the groundwater model the infiltration capacity of the drains has been fixed at maximally at 2 m^3/dag.m^1. There are no indications yet of clogging of the drains.

- By geohydrological standards the differences in calculated and measured water tables can be considered as limited (< 0.25 metre). These differences are too high to be able to give a clear picture of the groundwater flow at the location of an active F&G system.

12.3 **Remediation**

- Three retention zones were distinguished in the soil investigation. The first zone was excavated during the installation of the gate. The results of the test phase show that the supply of contaminants from the retention zone at the location of drain 1 to the groundwater is limited compared to the supply from the retention zone at the location of Westeinde, which was beyond expectations. By far the highest concentrations were measured in the last-mentioned retention zone. Based on this information the extraction strategy was adjusted. The four segments receiving water from this retention zone, were kept open, while the other four segments were closed off.

- The highest load is being removed when infiltration in the retention zone is applied. This can be explained by the fact that by way of infiltration in the retention zone firstly the hydraulic gradient is getting higher and consequently the groundwater flow rate and secondly the water table is increasing and as a result the contact area between the oil and the groundwater is getting larger as well. Infiltration outside the retention zone is less effective, because the retention zone forms a barrier for the groundwater flow.

- The drains 3 and 6 have to be used for an effective flushing of the retention zone. In view of pass flow it is recommended not to use drain 6. Taking into consideration the aforementioned infiltration capacity, the flow rate for the remediation if using drain 3 cannot be much higher than 15 m^3/day. The flow rate through the most important retention zone has been calculated at about 1m^3/day.

- During the test phase the retention zone was renewed only twice. The load in the gate can be called high and is fluctuating as a result of changes in the flow rate in the retention zone. Besides, no shift in the concentrations in the retention zone and the influent of the gate was observed. Consequently, the flushing process is still in an initial phase and an estimate of the contamination period is hard to provide.

- Infiltration of treated water in the plume has caused spreading of the contamination. The flow rate and duration of infiltration have to be attuned to the purifying capacity of the soil.

12.4 **Water treatment**

- Far-reaching treatment of extracted groundwater is taking place in the gate. Removal of contamination mainly takes place during the pre-treatment phase. In the reactor with carrier material biological decomposition takes place as well. Probably, the supply of nutrients is the limiting factor for biological decomposition.

- Biological decomposition does not take place in the 'open' bioreactor. This can be explained by the fact that the organic load of the contaminated groundwater is low and therefore insufficient sludge mass is being developed ('thin water').

- Targeted research of the ideal options for biological treatment was found to be impossible. One of the boundary conditions in this regard is a relatively constant load on treating facilities. However, there have been no indications of a steady load whatsoever. This is due on the one hand to a number of changes to the remediation system inherent to the test phase (balancing the abstraction/infiltration). On the other hand the regular shutting down of the system resulted in concentration dips in the influent and contamination was removed in the pre-treating step.

12.5 Recommendations for operation

The test phase has made clear the preconditions for an optimum operation of the F&G system. The optimum extraction and infiltration strategy has been determined and are made still concrete:

- Drain 3 is used for an effective flushing of the most important retention zone;
- The segments which receiving water from the most important retention zone, are still operational, the others are not;
- The flow rate is limited by the infiltration capacity of drain 3 and is not higher 15 m^3/day;
- Infiltration in the plume for the purpose of stimulating biological degradation has to be of short duration. The flow rate and duration have to be determined in more detail and are related to the natural attenuation processes in the plume.

It is recommended to optimise the water treatment by leaving out the pre-treatment and the 'open' reactor. As a result exploitation costs will get lower and the environmental output higher (lower use of energy, less waste, reduction of emission). At a later stage the effluent of the bioreactor can be aerated as well in order to infiltrate water rich in oxygen and thus increasing the biological activity in the retention zone and in the plume, if necessary.

It is also recommended to investigate the groundwater under the funnel behind to gate in order to verify underflow of contaminants.

It is proposed that there should be a calibration moment of the remediation after three years. After 3 years the retention zone will have been replaced approximately 10 times at a flow rate of 15 m^3/day and the concentration changes at that time will provide insight into the further concentration changes and the possible end concentration. At that time a mathematical model that describes the most important remediation processes can be used for the purposes of these predictions. It is also recommended that the mobile fraction of the oil and the efficiency factor should be determined using the oil characterisation method.

LITERATUUR

[1] Funnel & Gate test phase, Lijnbaan/Westeinde; Testing and monitoring programme, 'Oranjewoud', projectnr. 9929-17856, revisie 00, September 1999.

[2] Funnel & Gate test phase, Lijnbaan/Westeinde; Evaluation 1^{e} period test phase, 'Oranjewoud', projectnr. 9929-17856, revisie 01, September 2000.

[3] In Situ Bioremediation of contaminated groundwater by application of 'Funnel and Gate', CUR/NOBIS, 97-1-13, May 2000.

[4] Implementatie beslissystematiek ontwerp en onderhoud van infiltratie en onttrekkingsmiddelen, CUR/NOBIS, mei 2000.

[5] Aangepast saneringsplan proefproject 'Trechter en poort', 'Oranjewoud', projectnr. 81289, revisie 01, 23 december 1998.

[6] Systeemontwerp Funnel & Gate, Lijnbaan/ Westeinde Den Haag, 'Oranje-woud', projectnr. 81289, revisie 00, 23 december 1998.

[7] Restrisk; verspreiding en risico's van restconcentraties in bodem en grondwater, CUR/NOBIS 95-2-11, juni 1997.

[8] Voortgangsnotitie, Actualisatie verontreinigingssituatie, Funnel & Gate, Lijnbaan/Westeinde; 'Oranjewoud', projectnr. 3273-81289, revisie 01, December 1998.

[9] Nader onderzoek Voormalig Benzinestation aan de Lijnbaan/Westeinde Den Haag, De Ruiter Milieutechnologie B.V., PWN/PZT/A950716.108860, 13 juli 1995.

[10] DNAPLKAR, eindrapportage: dynamische monitoring Tilburg, CUR/NOBIS, 1998.

[11] Infiltratie van water in de bodem, Technische Universiteit Delft, Faculteit der Civiele Techniek, juni 1998.

[12] Behandeling van afvalwater (Technische Hogeschool Delft, Afdeling der Civiele Techniek, november 1980).

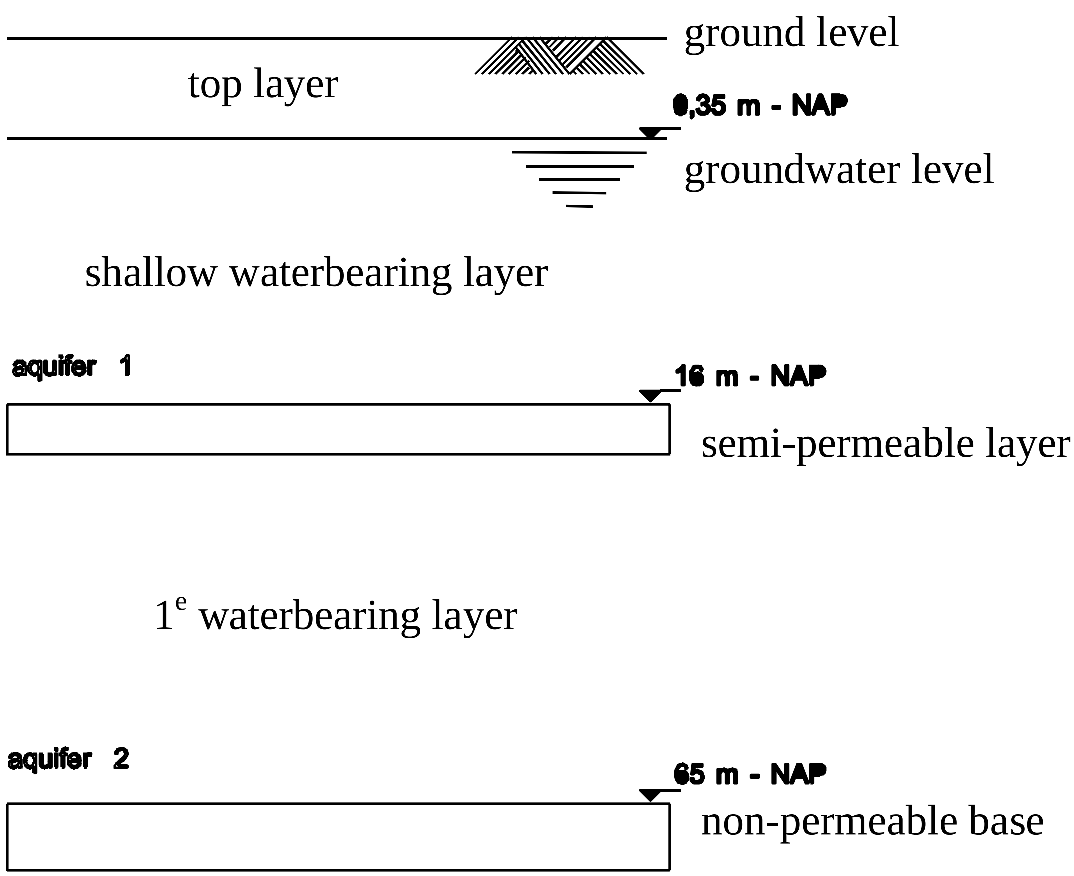
[13] Handboek Bodemsaneringstechnieken (Sdu, afl. 16, november 2000).

APPENDIX A

GROUNDWATER MODELLING

A.1 Schematisation

The soil layering has been schematised using geohydrological unit layers (see figure below). The main model of choice consists of three water-bearing layers and two poorly permeable layers. The sandy layer above the Basis Peat (shallow water bearing layer) is permeable and is defined as shallow water bearing layer (aquifer no. 1). Since at approx. NAP -7 m a thin resisting, impermeable layer is present, the shallow water-bearing layer has been subdivided into two water bearing layers. The upper part of the water-bearing layer is further subdivided into three layers (amongst which the retention zone).



The basis of the Holocene sand layer (a.o. Basis Peat) can be defined as an aquitard that forms the poorly permeable upper part of aquifer no. 2. The sand layer beneath NAP –20 m can assumed to be well permeable and it forms the first water bearing layer (aquifer no. 2). The non-permeable basis of the model is assumed to be present at a depth of NAP -65 m.

Surface water

The surface water (West Singelsgracht) is schematised in the model by using the available 'RIVER'-module of Groundwater Vistas. The water level was set to NAP -0,4 m.

A.2 Geohydrological parameters

Permeability of the retention zone
The retention zone is modelled by a separate layer (layer no. 2). To this layer a horizontal permeability was attributed equalling 2 m/day (as measured).

Permeability outside the retention zone
For the shallow sand layers outside the boundaries of the location as well as for the zone beneath the retention zone, a permeability of 7 m/day was chosen.

Resistivity of the intermediate layer shallow water bearing layer
The clayey intermediate layer within the shallow water-bearing layer possesses a vertical resistivity of 35 days. This value was deduced by correlating probing results at the location (Joustra Geomet B.V., February 1998) with data of the VVI-location (Soil Investigation near the VVI-location, FUGRO, May 1998) and the formerly mentioned pumping experiment at the Tripstraat. This resistivity value is confirmed by groundwater level measurements conducted at the location.

Resistivity of the Basis Peat
The resistivity of the Basis Peat was estimated by assuming that all of the precipitation surplus (0.5 mm/day) flows into the first water bearing layer. At a waterlevel difference of 0.1 m, a c-value results of 200 days.

A.3 Subregional flow pattern

Flow patterns of the phreatic water-bearing layer were produced for two periods:
- summer 1999
- winter 1999/2000

Summer 1999
In the spring of 1999 monitoring wells were installed into the shallow water-bearing layer, at a distance of several hundreds of meters. These wells were periodically monitored. The results of 1999 were transformed into an iso-water level chart (Map 17856-I-1). The groundwater level at the location equals approx. 0.70 m -NAP, the level gradient is approx. 0.0007 m/m and the flow velocity equals approx. 6 m/year. The groundwater flows in southeastern direction.

Winter 2000
The winter measurements (November 1999) are indicated on Map 17856-I-2. When comparing to the summer situation, the following difference become apparent:
- higher water levels (approx. 0.05 m)
- larger level gradient (0.001 m/m)
- south/south-eastern flow direction

A.4 Calibration of the groundwater model - subregional scale

A.4.1 Adjustments to the model of 1998

Detail/refinement
In 1998 a groundwater model was developed used for design of the ‘Funnel & Gate’-system. Since the finally installed system and the original design differed to some extent, the model has been adjusted. The adjustments lead to a refinement of the model at the location of the system. A model was developed with 231 rows and 218 columns.

The right locations of the funnel and the gate have been incorporated into the model, as was the gravel bed around the gate. At the upstream side infiltration drains and wells are located and about the gate the influent and effluent segments were placed.

Change of model assumptions

In the 1998 flow model a strong influence (drainage) of the sewer system close to the location was accounted for. The predicted local flow pattern, however, was at that time a result of a relatively small set of groundwater level data. Since then additional data was acquired (see sub-regional flow patterns; Maps 17856-I-1 and 17856-I-2), leading to a different insight. Consequently, the sewer system was removed from the model.

A.4.2 Calibration

The model was calibrated using the flow image of summer 1999. Since this period no input of precipitation into the model was given. In figure 17856-I-1 the measured and calculated flow patterns are given, which are quite comparable for each of the parameters (1) groundwater level, (2) level gradient, as well as for (3) the flow direction.

A.4.3 Validation

The measured flow pattern of winter 1999 has been used for validation of the model. In this time period the system had already been installed, therefore the system was incorporated into the model as well. Also precipitation was accounted for. Again the calculated flow pattern agrees reasonably well with the measured flow pattern, the calculated flow direction however slightly differs from the real direction.

A.5 Area of influence of the system

In 1998 the boundaries of the model area were determined based upon existing experience at the University of Waterloo in Canada. At the occasion of earlier model studies performed by this institute, it had been concluded that any hydrological influence of a funnel and gate no longer exists at a distance of 2 to 3 times the width of the system. For the location at the Lijnbaan, at a supposed length of the system of approx. 30 m, the distance of influence therefore was assumed to be max. 70 m and the dimensions of the model were set to 250 x 250 m.

Using the revised model, for the design situation of 15 m^3/day with downstream infiltration, a range of influence of approx. 100 m was established. This equals approx. four times the width of the system. For future modelling we therefore advise to use as a basic rule: area of influence = 4x the width of the system, instead of the previous rule: area of influence = 2 to 3x the width of the system.

APPENDIX B

PRINCIPLE OF DYNAMIC MONITORING

The concept of dynamic monitoring for characterisation of groundwater pollution is based upon the enlargement of the scale of support of point measurements. With a limited amount of measuring points, a significantly more reliable picture of the pollution can in this way be developed.

The scales of support can be increased by – when interpreting concentration measurements - taking the origin of the groundwater sampled from a well into account. The origin of the groundwater can be varied by groundwater abstraction.

Groundwater flowing past zones containing free phase product, is strongly contaminated with oil components by dissolution from the free phase into the water phase. Downstream this secondary source a 'plume' of polluted groundwater develops. The dissolved components thus function as a 'clue' for the presence of secondary source areas upstream the monitoring well. By interpreting the measurements in various monitoring wells in that way, indications can be obtained about the presence of a secondary source zone.

The scale of support of a point measurement (a monitoring well) can be further enhanced by actively changing the direction of the groundwater flow during the monitoring period, in such way that one monitoring well can be used to sample groundwater originated from different directions. In theory it is possible to obtain information about the presence of pollution within a circular area with radium of several tens of meters about the co-ordinate of the monitoring well (a soil volume of some hundreds to thousands of cubic meters!). A frequent change of the groundwater flow direction will be prerequisite for such deductions.

Figure B1 illustrates the above mentioned principle as well as the added value of dynamic monitoring. In this figure the groundwater flow direction towards the monitoring wells is depicted for 5 wells (view from above), for two flow patterns. Also the location of pollution is indicated with the corresponding plume of polluted groundwater, migrating from the polluted zone towards the location of the groundwater abstraction. During abstraction no. 1 only wells no. 2 and 5 will show elevated concentrations. At the point where the flow paths to both wells intersect upstream, the presence of pollution is expected. In monitoring wells 1, 3 and 4 no elevated concentrations will be detected, upstream these wells an area can be defined in which, most probably, no pollution is present. Then the flow direction is changed, by quitting abstraction no. 1 and starting abstraction no. 2.

Now concentrations in well 5 will gradually drop to zero, since now groundwater from a 'clean' area is being sampled. This is not the case for well no. 2, which will remain polluted, even in the current case of changed direction of groundwater flow. This results in new information about the whereabouts of pollution upstream. Groundwater sampled from well no. 4 now also will be polluted. This is not a surprise since the water sampled here originates from the same area as the groundwater sampled in well no.2. From well no.1 still clean water will be sampled. Figure 1 illustrates how the southern boundaries of the pollution can now be deduced. In well no. 3 a temporary break-through is expected in the transition state between both groundwater abstraction situations, because some time is required before a new 'stationary' pollution situation is reached. Finally the concentrations will drop to zero again, confirming the absence of pollution upstream.

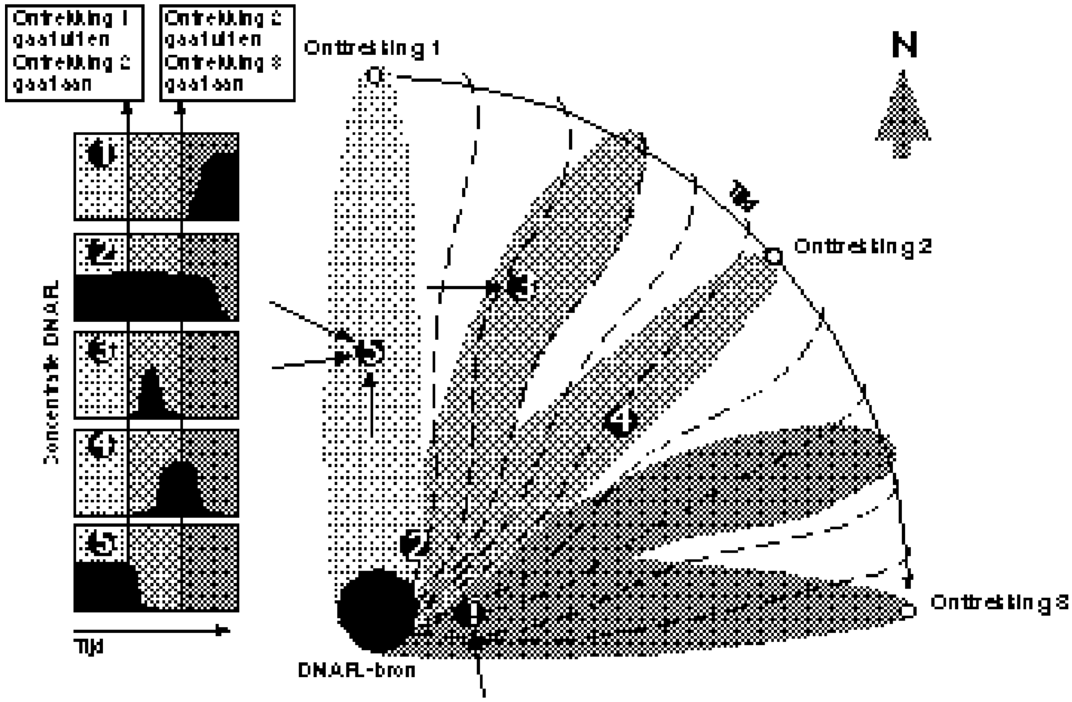


Fig. B1. Upscaling of point measurements to measurements with larger scale of support.

In figure B1 a third flow situation is depicted as well, in which abstractions 1 and 2 are ceased and abstraction no. 3 is commenced. This leads to a further increase of the scales of support of the point measurements. It now becomes clear, in this flow situation, that a contamination is present upstream well no. 1. The scale of support of the measurements has, owing to this last set of data, increased to a point possessing three ‘areas of origin’. This illustrates how the position of the pollution can be precisely determined using only a limited number of measuring point, when several measurements in time are available and per time interval a specific groundwater flow situation can be distinguished.

APPENDIX C

CONCENTRATION MEASUREMENTS IN THE GATE

APPENDIX D

CONCENTRATION MEASUREMENTS IN THE GROUNDWATER

APPENDIX E

CONCENTRATION MEASUREMENTS IN THE WATER TREATMENT

APPENDIX F

DATA GROUNDWATER LEVELS

APPENDIX G

OTHER MEASUREMENTS

APPENDIX H

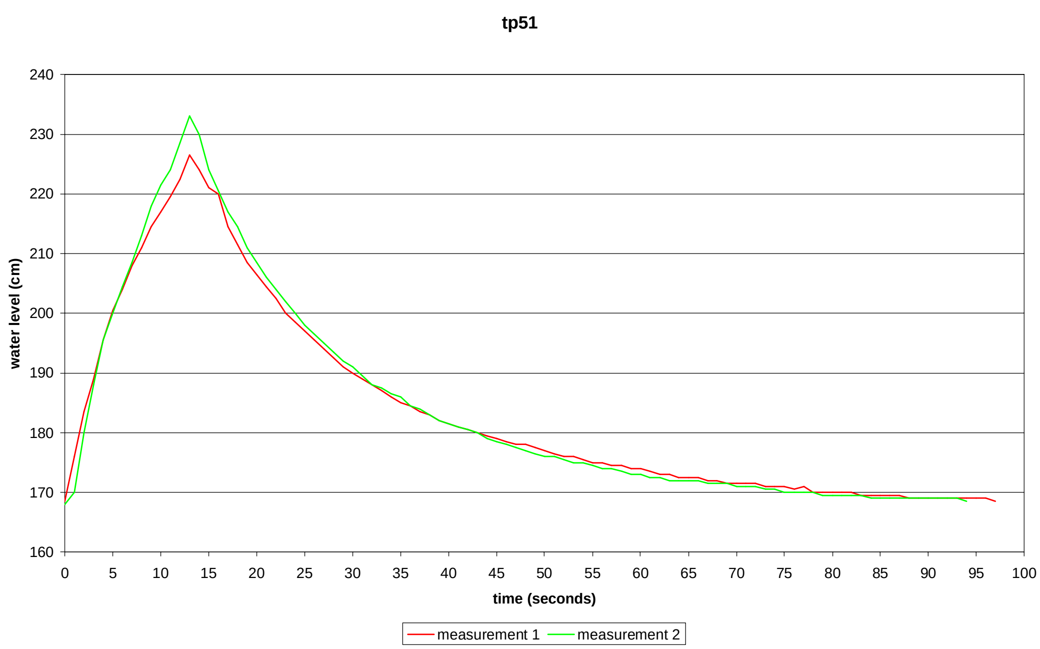
WELL TESTS PERMEABILITY

Below the method (technique and calculation) is described used for the determination of the permeability. Results of these tests are also given in paragraph 5.2.

The permeability of the soil has been measured in the field using well tests. Monitoring wells no. tp51 to tp54 were used for this purpose. Wells tp51 and tp53 have filters located inside the retention zone; the filters of well no. tp52 and tp54 are located beneath the retention zone.

The tests were conducted by quickly filling the wells with 1 l of water. The groundwater levels were at the same time continuously measured by means of a diver. Measurements were done in twofold for each well.

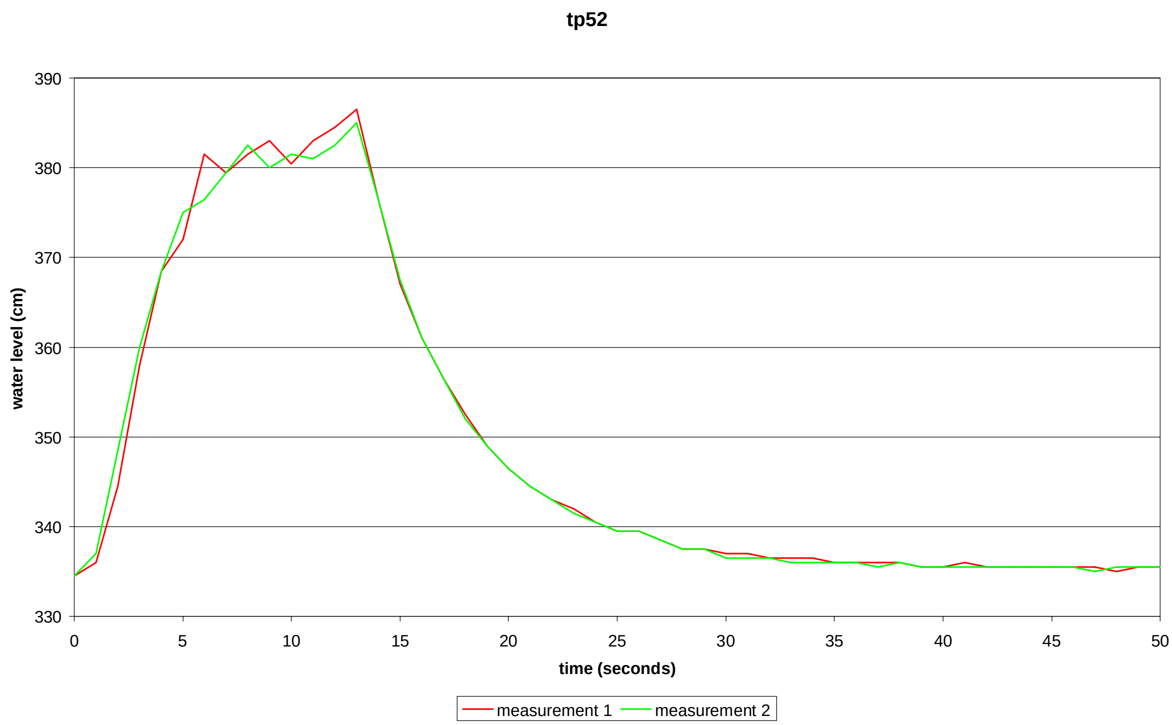
The results of the measurements are presented in the graphs below.

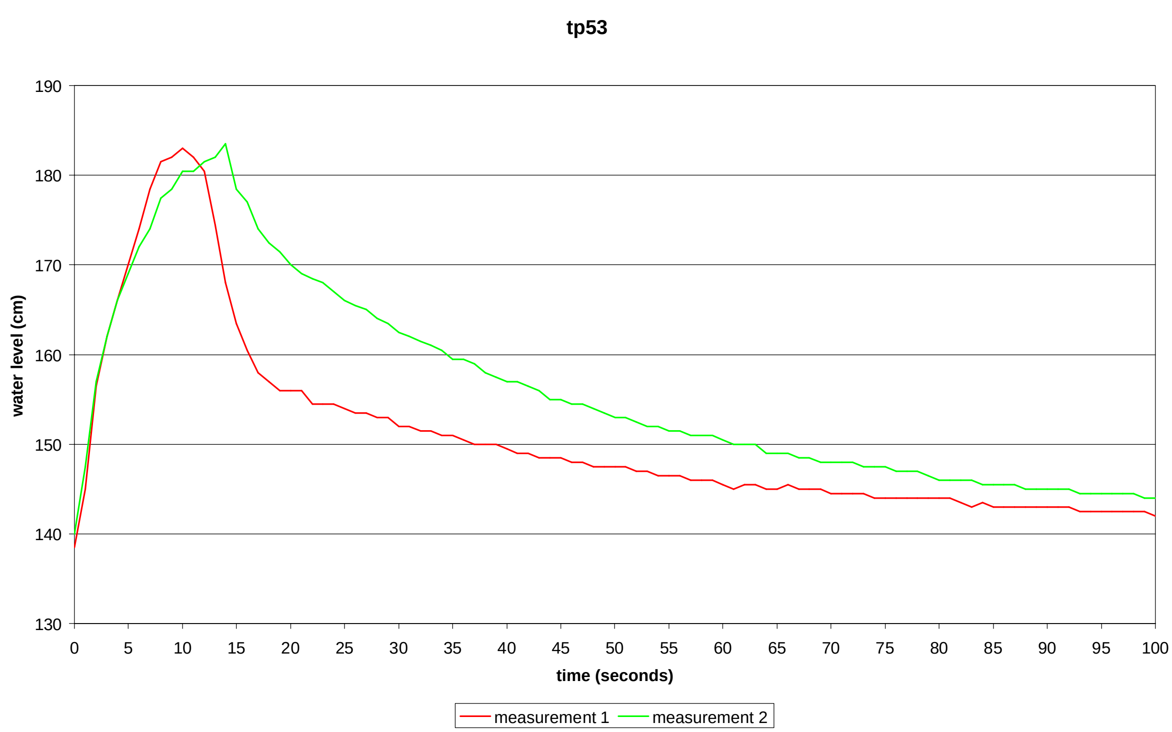


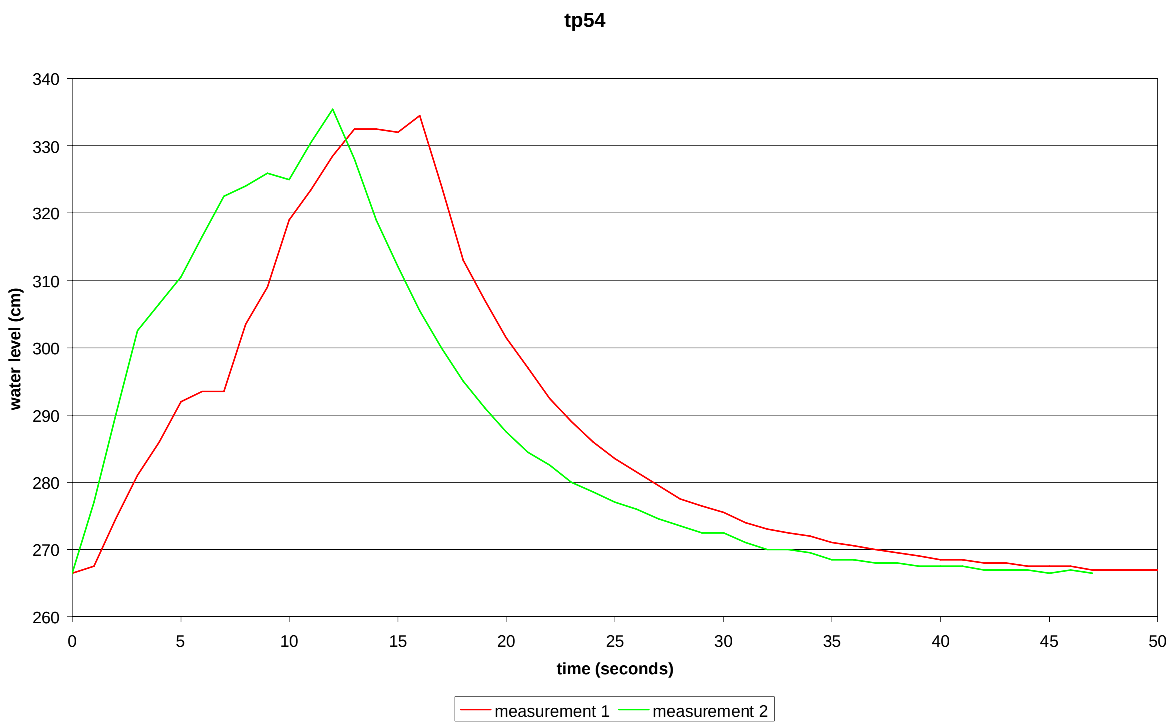
Using the field data depicted below, the permeability was calculated.

Monitoring well	Filter length (cm)	Diameter (mm)	Filling time (sec)	Time to measurement remaining height (sec)	Remaining height (cm)	k-value (m/day)
tp51	100	40	13	30	12	1.9
tp52	50	25	13	9	9	12.5*
tp53	100	40	12	42	10	1.9
tp54	50	25	14	12	11	7.5

* probably leakage past the filter took place in this case, leading to an overestimation of the permeability.


tp52
water level (cm)
390
380
370
360
350
340
330
0
5
10
15
20
25
30
35
40
45
50
time (seconds)
measurement 1
measurement 2


tp53
water level (cm)
190
180
170
160
150
140
130
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
time (seconds)
measurement 1
measurement 2



tp54
water level (cm)
340
330
320
310
300
290
280
270
260
0
5
10
15
20
25
30
35
40
45
50
time (seconds)
measurement 1
measurement 2

APPENDIX I

OVERVIEW OF MONITORING WELLS

MAPS