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IN SITU BIOREMEDIATION OF CONTAMINATED GROUNDWATER BY APPLICATION OF 'FUNNEL AND GATE'

Dr G. Lethbridge B.Sc., Ph.D. (Shell Global Solutions)
Prof. J.F. Barker (University of Waterloo)
ing. M.P.M. Koenraadt (Ingenieursbureau 'Oranjewoud' B.V.)
ir. M.H.A.M. de Nijs (Ingenieursbureau 'Oranjewoud' B.V.)

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Auteur(s)
Dr G. Lethbridge B.Sc., Ph.D.
Prof. J.F. Barker
ing. M.P.M. Koenraadt
ir. M.H.A.M. de Nijs

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Uitvoerende organisatie(s) (Consortium)
Shell Global Solutions (Dr G. Lethbridge B.Sc, Ph.D., 00-44-151-3735032)
University of Waterloo, Department of Earth Science (Prof. J.F. Barker, 00-1-519-7467484)
Gemeente Den Haag, Dienst Stadsbeheer (ir. A.A. Koning, 070-3536557)
Technische Universiteit Delft (prof.dr.ir. A. Verruijt, 015-2785280)
Ingenieursbureau 'Oranjewoud' B.V. (drs. R. Suurbier, 010-2884721)

Uitgever
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Samenvatting

Onder de naam 'In situ bioremediation of contaminated groundwater by Funnel and Gate' is in 1997 in Nederland een project opgestart dat tot doel heeft om het concept 'Trechter en Poort' verder te optimaliseren en geschikt te maken voor de Nederlandse markt. Het project wordt uitgevoerd door een consortium bestaande uit Shell Global Solutions, University of Waterloo, TU Delft, Ingenieursbureau 'Oranjewoud' B.V. en de gemeente Den Haag. Het project wordt bekostigd met onderzoeks- en saneringsbudgetten van de consortiumleden en subsidie van het Nederlands Onderzoeksprogramma Biotechnologische In-situ Sanering (NOBIS).

'Funnel & Gate' is een in situ saneringstechniek, waarbij verontreinigd grondwater onder invloed van de van nature aanwezige grondwaterstroming en met behulp van isolatiewanden (trechter) door een gecontroleerde reactieve bodemzone (poort) wordt geleid. In de reactieve zone worden de grondwaterverontreinigingen omgezet, afgebroken en/of afgevoerd.

De mogelijkheden zijn bestudeerd om het van origine 'passieve' concept zodanig aan te passen dat de saneringsduur kan worden verkort. Dit heeft geresulteerd in een 'actief' systeem, dat op een unieke wijze het 'Pump & Treat' principe combineert met het oorspronkelijke 'Funnel & Gate' concept.

Onderdeel van het project is het beproeven van het 'Funnel & Gate' concept op een proeflocatie aan de Lijnbaan/Westeinde te Den Haag. Voor deze locatie is een systeem ontworpen dat niet alleen voldoende informatie oplevert voor optimalisering van het concept, maar bovendien geschikt is voor sanering van de op de locatie aanwezige bodemverontreiniging.

Trefwoorden
Gecontroleerde termen:
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Ingenieursbureau 'Oranjewoud' B.V.
(drs. R. Suurbier, 010-2884721)

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Dr G. Lethbridge B.Sc., Ph.D.
Prof. J.F. Barker
ing. M.P.M. Koenraadt
ir. M.H.A.M. de Nijs

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Shell Global Solutions (Dr G. Lethbridge B.Sc, Ph.D., 00-44-151-3735032)
University of Waterloo, Department of Earth Science (Prof. J.F. Barker, 00-1-519-7467484)
Municipality of the Hague, Urban Management Department (ir. A.A. Koning, 070-3536557)
Technical University of Delft (prof.dr.ir. A. Verruijt, 015-2785280)
Ingenieursbureau 'Oranjewoud' B.V. (drs. R. Suurbier, 010-2884721)

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Abstract

'Funnel and Gate' is an in situ remediation technique in which contaminated groundwater is channelled under the influence of the prevailing natural groundwater flow and isolation walls (funnel) through a controlled reactive zone in the soil (gate). In this reactive zone the groundwater contaminants are remediated. The possibilities are studied for adjustment of the original 'passive' concept in such way that remediation times can be reduced. This resulted in an 'active' system, that uniquely combines the 'Pump and Treat' with the original 'Funnel and Gate'-concept. A system has been devised for a test site that not only provides sufficient information to optimize the concept, but is also suitable for remediating the soil contamination present on the site.

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(drs. R. Suurbier, 010-2884721)

This report can be obtained by: CUR/NOBIS, PO Box 420, 2800 AK Gouda, The Netherlands
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PREFACE

In 1997 a project entitled 'In situ bioremediation of contaminated groundwater by Funnel and Gate' was started in the Netherlands. The project is being carried out by 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. The project is financed by the research and remediation budgets of the consortium members and a subsidy from the Dutch Research Programme In-Situ Bioremediation (NOBIS).

The objective of the 'Funnel and Gate' project is twofold:

- the optimization of a 'Funnel and Gate' system, with attention to not only the technical aspects but also to the policy aspects of this technology;
- the development of a number of principles of scale and boundary conditions for implementing these technologies at polluted locations.

'Funnel and Gate' is an in situ remediation technique in which contaminated groundwater is channelled under the influence of the prevailing natural groundwater flow and isolation walls (funnel) through a controlled reactive zone in the soil (gate). In this reactive zone the groundwater contaminants are remediated with biological, chemical, physical and/or electro-kinetical techniques.

The possibilities are studied for adjustment of the original 'passive' concept in such way that remediation times can be reduced. This resulted in an 'active' system, that uniquely combines the 'Pump and Treat' with the original 'Funnel and Gate'-concept.

Part of the project consists of testing the 'Funnel and Gate' concept on a test site at 'Lijnbaan/Westeinde' in The Hague. A system has been devised for this site that not only provides sufficient information to optimize the concept, but is also suitable for remediating the soil contamination present on the site.

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CONTENTS

Appendix A SYSTEM DESIGN 'FUNNEL AND GATE' AT TEST SITE LIJNBAAN/WESTEINDE

Appendix B MONITORING SCHEME

SAMENVATTING

In situ bioremediation of contaminated groundwater by application of 'Funnel and Gate'

Onder de naam 'In situ bioremediation of contaminated groundwater by Funnel and Gate' is in 1997 in Nederland een project opgestart dat tot doel heeft om het concept 'Trechter en Poort' verder te optimaliseren en geschikt te maken voor de Nederlandse markt. Het project wordt uitgevoerd door een consortium bestaande uit Shell Global Solutions, University of Waterloo, TU Delft, Ingenieursbureau 'Oranjewoud' B.V. en de gemeente Den Haag. Het project wordt bekostigd met onderzoeks- en saneringsbudgetten van de consortiumleden en subsidie van het Nederlands Onderzoeksprogramma Biotechnologische In-situ Sanering (NOBIS).

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De mogelijkheden zijn bestudeerd om het van origine 'passieve' concept zodanig aan te passen dat de saneringsduur kan worden verkort. Dit heeft geresulteerd in een 'actief' systeem, dat op een unieke wijze het 'Pump & Treat' principe combineert met het oorspronkelijke 'Funnel & Gate' concept.

Onderdeel van het project is het beproeven van het 'Funnel & Gate' concept op een proeflocatie aan de Lijnbaan/Westeinde te Den Haag. Voor deze locatie is een systeem ontworpen dat niet alleen voldoende informatie oplevert voor optimalisering van het concept, maar bovendien geschikt is voor sanering van de op de locatie aanwezige bodemverontreiniging.

SUMMARY

In situ bioremediation of contaminated groundwater by application of 'Funnel and Gate'

Background of the project
In 1997 a project entitled 'In situ bioremediation of contaminated groundwater by Funnel and Gate' was started in the Netherlands. The project is being carried out by 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. The project is financed by the research and remediation budgets of the consortium members and a subsidy from the Dutch Research Programme In-Situ Bioremediation (NOBIS).

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- the optimization of a 'Funnel and Gate' system, with attention to not only the technical aspects but also to the policy aspects of this technology;
- the development of a number of principles of scale and boundary conditions for implementing these technologies at polluted locations.

Passive concept
'Funnel and Gate' is an in situ remediation technique in which contaminated groundwater is channelled under the influence of the prevailing natural groundwater flow and isolation walls (funnel) through a controlled reactive zone in the soil (gate). In this reactive zone the groundwater contaminants are remediated with biological, chemical, physical and/or electro-kinetical techniques.

'Funnel and Gate' has several important advantages with respect to conventional 'Pump and Treat' systems:

- pumping of groundwater is not needed;
- most provisions can be installed below the soil surface;
- the remediation processes are better controllable as well as more flexible with respect to bio-screens.

The emphasis of the Canadian experiments with 'Funnel and Gate' presented, lies on cutting off the contamination plume in a passive way when source clean-up is technically difficult or needs to be postponed. A so-called passive system is subjected to changes in directions of groundwater flow. Also, in some countries like the Netherlands, remediation goals have to be achieved within a certain period.

Development of the active concept
The possibilities are studied for adjustment of the original 'passive' concept in such way that remediation times can be reduced. This resulted in an 'active' system, whereby upstream of the water-inlet of the gate, a low capacity pumping well is installed. The 'captured' area is more intensely flushed and the mobile components are more quickly leached from the polluted area leading to a decrease of the total remediation duration. Cleaned groundwater can be re-infiltrated upstream in the captured zone to intensify the leaching or downstream in the saturated zone to increase the degradation of the contaminants in the plume zone.

In fact, one could say that the 'Pump and Treat' is uniquely combined with the original 'Funnel and Gate'-concept.

Except for the smaller duration of remediation, an active system still has other advantages:

- it is not subjected to changes in directions of groundwater flow;
- it makes the use of infiltration possible;
- flushing can be accelerated and so remediation goals can be achieved;
- both retention and retardation zone can be treated;
- it is flexible to operate.

Design of '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) and remediated. This makes 'Funnel and Gate' suitable for:

- Source clean-up and source control: The system cuts-off the source from the plume zone so all contaminants released from the source are directed towards the reactive zone of the system. To decrease remediation duration, the system can be activated.
- Plume control: A system which is installed downstream groundwater pollutions prevents a further increase of the plume size. If the source is not removed, the groundwater pollution will be continuously 'feeded' by dissolution from the pure product in the source. To decrease remediation time the source can be removed. Activation of the system is in this situation less effective.

For the selection of the potential applicability of 'Funnel and Gate' it is important to establish the data in table I.

Table I. Requirements for use of 'Funnel and Gate' systems.

criterion	passive system	active system
remediation objective		
remediation period	long term	medium term
remediation options	source and plume control	source clean-up or plume control
contamination		
solubility (in water)	no demands	$K_{ow} < 1000$ [1]
degradability	biological [2]	preferably biological [2]
location	unsaturated as well as saturated zone	preferably for the most part in saturated zone
geohydrology		
permeability	moderate	good
depth to groundwater table	< 4 m below ground level	< 8 m below ground level
depth of the pollution	< 25 m below ground level	more than 25 m, depending on the specific geohydrology
rate of groundwater flow	> 0.05 m/day	no demands
direction groundwater flow	stable	may fluctuate
dispersion		
medium	water	water
direction of dispersion	horizontal	mainly horizontal
location specific criteria		
presence of obstacles	as less as possible non-removable obstacles should be present	some flexibility exists regarding non-removable obstacles
presence of vulnerable buildings	special attention (during the installation phase)	special attention during the installation/exploitation phase

[1] If the remediation objective is source clean-up. In other cases no demands.
[2] Preferably aerobic.

Test site 'Lijnbaan/Westeinde' in The Haque

Part of the project consists of testing the 'Funnel and Gate' concept on a test site at 'Lijnbaan/Westeinde' in The Hague. A system has been devised for this site that not only provides sufficient information to optimize the concept, but is also suitable for remediating the soil contamination present on the site.

'Funnel and Gate' offers 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.

Consideration has been given to the way the test phase is to be carried out as far as the consortium is concerned 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:

1. research into the effect of biological treatment at different influent concentrations and variable abstraction rates;
2. research into the impact of a 'Funnel and Gate' system on the geohydrological situation;
3. research into the occurrence of precipitations in the abstraction and infiltration segments and in the treatment process and the risk of clogging;
4. inventory of policy-related and legal boundary conditions that could constitute an obstacle to the application of the 'Funnel and Gate' concept;
5. development of guidelines for designing 'Funnel and Gate' systems.

CHAPTER 1

INTRODUCTION

In the early 1990s the University of Waterloo, Ontario Canada, 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 the 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 a project entitled 'In situ bioremediation of contaminated groundwater by Funnel and Gate' was started in the Netherlands. The project is being carried out by 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. The project is financed by the research and remediation budgets of the consortium members and a subsidy from the Dutch Research Programme In-Situ Bioremediation (*Nederlands Onderzoeksprogramma Biotechnologische In-situ Sanering* = NOBIS).

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- the optimization of a 'Funnel and Gate' system, with attention to not only the technical aspects but also to the policy aspects of this technology;
- the development of a number of principles of scale and boundary conditions for implementing these technologies at polluted locations.

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.

Referring to the current Policy Review on Soil Remediation (*Beleidsvernieuwing bodemsanering*), an active version of the 'Funnel and Gate' concept has been developed as part of the above-mentioned project. Its great flexibility and controllability should provide the updated concept wider applications. For this reason the consortium decided to test the active concept at the site 'Lijnbaan/Westeinde', The Hague. A system was devised which not only provides sufficient information to optimize the concept, but which also provides for the remediation of the soil contamination present at the site.

The installation phase is completed and the starting signal is given for a one-year test period, in which the operation of the active system will be studied in detail.

Chapter 2 describes the origin and application of 'Funnel and Gate'. In chapter 3 the design process of a 'Funnel and Gate' system is discussed. Chapter 4 contains information about the (case) project entitled 'In situ bioremediation of contaminated groundwater by Funnel and Gate' at the 'Lijnbaan/Westeinde' test site in The Hague and the system used there. The testing and monitoring programme for this pilot is elaborated in chapter 5. This chapter provides a list of parameters to be investigated, the location of measurement and sampling points and the frequency of measurement and sampling. In chapter 6 the conclusion is given.

CHAPTER 2

POTENTIALS OF 'FUNNEL AND GATE'

2.1 Origin of 'Funnel and Gate'

A variety of (petroleum) hydrocarbons from fuel leaks, refining, chemical manufacturing, wood preserving and oil/natural gas production can create significant dissolved pollution plumes in the groundwater. In some cases in North America and Great Britain, these plumes are merely monitored to study the extent of natural attenuation and its potential to stop (or slow down) spreading.

Some plumes require more than monitored natural attenuation to meet site clean-up goals. For petroleum hydrocarbons, this usually involves the manipulation of physical, chemical and/or biological properties within the subsurface to eliminate rate-limiting factors limiting biodegradation. Typically, electron acceptors - usually oxygen - and macronutrients - such as nitrogen - are added to the subsurface. Even then, success is often limited by low oxygen solubility and limited dispersion leading to incomplete in situ 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 reactive barrier technology.

'Funnel and Gate' is an in situ remediation technique conceived at the beginning of the 1990s in Canada. In this technique contaminated groundwater is channelled under the influence of the prevailing natural groundwater flow and isolation walls (funnel) through a controlled reactive zone in the soil (gate). In this reactive zone the groundwater contaminants are remediated (see Fig. 1).

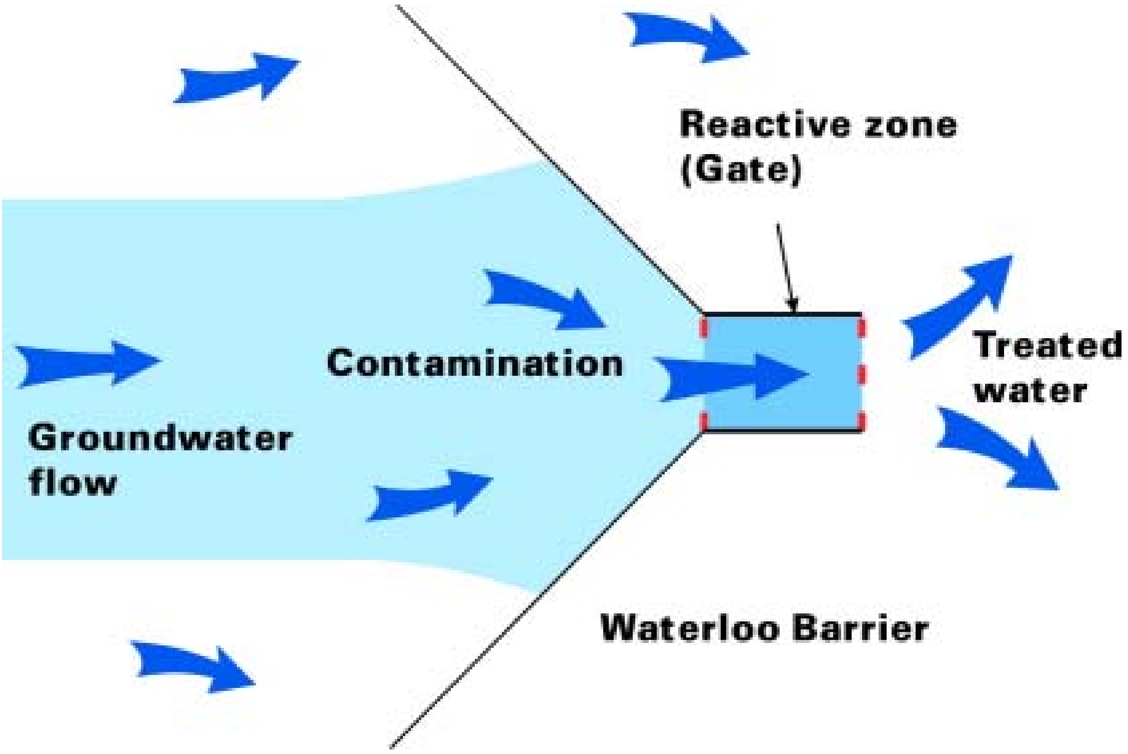

Fig. 1. Schematic representation of the operating 'Funnel and Gate' (on-top view).

The reactive zone can be regarded as a compact, permeable in situ 'reactor', in which the collected groundwater is remediated in various ways. Besides the use of a biological remediation method for the groundwater treatment in the gate, one can also consider chemical, physical or electro-kinetical remediation techniques (e.g. by using activated carbon, air sparging or electrical tension fields).

'Funnel and Gate' has several important advantages with respect to conventional 'Pump and Treat' systems. If the natural groundwater flow can be put to use, pumping of groundwater with all necessary side-provisions and supplies (monitoring, abstraction units, water remediation units, infiltration, drainage of cleaned water, etc.) is not needed. This renders the technique also suitable in areas with deeper, soil-mechanically unstable soil layers. Moreover, most provisions can be installed below the soil surface. With respect to bioscreens, the remediation processes in 'Funnel and Gate' are better controllable (owing to the relatively compact reactive zone) as well as more flexible (a range of remediation techniques can be used).

2.2 **Experiences with 'Funnel and Gate' systems**

In this paragraph three pilot-scale in situ groundwater treatment cases are presented which use a 'Funnel and Gate' [Starr and Cherry, 1994] or a 'Trench and Gate' system. It should be stressed that the original 'Funnel and Gate' concept is extensive and makes as much use as possible of the natural groundwater flow and the self-cleaning capacity of the soil. The intention is to 'guide' the groundwater contaminants via the funnel through the gate without the need of a pump.

The three 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. 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 source zones or plumes.

Pilot-scale 'Funnel and Gate' system at operating industrial plant in Alberta, Canada
At a refinery/chemical plant, a small system uses a sheet piling funnel and a gravel-filled, oxygen sparge gate to cut-off a plume of BTEXS (BTEX and styrene) in a sand fill emanating from a small, recurring source area. At this site the groundwater contamination is located in the upper 5 m of an unconfined aquifer with a shallow water table (0.5 to 1.5 m) below the soil surface. The unconfined aquifer locally consists of silty sand backfill, overlying a layer of clayey silt (0.2 to > 3 m thick). The direction of the groundwater flow is quite variable, the average local groundwater velocity being about 1 m/yr. During the test phase, a pumping well was operated downstream the gate, to enhance groundwater and BTEXS fluxes through the gate.

The funnel consists of steel sheet piling sections, driven just to or into the confining layer. The gate zone itself measures 1 m in diameter and is 5.3 m deep. It consists of back-filled pea gravel (average grain diameter: 13 mm; porosity: 0.38) installed with the aid of a removable caisson. A series of five 'u'-shaped, 2.5 cm OD diameter, steel pipes are embedded within the gravel zone. Each one extends above the soil surface, and has two injection ports. The horizontal sections of the pipe have 3.2 mm diameter holes, spaced every 25 mm, to release the carrier fluids along the complete width of the gate, in a plane perpendicular to the groundwater flow. The injection system can make use of air, O_2 or NH_3 gas cylinders.

BTEXS aerobic biodegradation was found to be nitrogen-limited in a microcosm study using site materials. Hence providing nitrogen into the system was desired. Since an oxygen gas delivery system was needed at this site anyhow, it was convenient to deliver the nitrogen as well by sparging a gas (ammonia, NH_3). Nitrogen becomes bioavailable as soon as the NH_3 hydrolyses to NH_4^+.

The system was not able to treat the unexpectedly high BTEXS flux at the site (groundwater concentrations higher than 150 mg/L BTEXS). This points out the need for good site assessment and for a conservative 'Funnel and Gate' design, especially near recurring sources where NAPL-saturated groundwater may 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 problem that great care would be required to ensure a 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 volatilization, and better distribution of residual O_2 in the pea gravel gate.

Full-scale 'Trench and Gate' system at operating gas plant in Alberta, Canada
A second system, called 'Trench and Gate', at a natural gas processing plant in Alberta, uses permeable trenches to draw groundwater migrating in a till into a remedial gate, where biosparging was sufficient to clean-up the BTEX-contaminated groundwater (final concentrations meeting drinking water objectives).

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 gray clay-rich sandy till. A less than 1 m thick, relatively permeable weathered bedrock regolith lies between the tills and the bedrock. Hydraulic conductivity of these layers is heterogeneous, ranging from 10^{-10} m/s for shale bedrock to 2×10^{-5} m/s in fractured or sand-strigger tills.

Construction called for two, 30 m long collection trenches to about 5 m depth just into bedrock to be installed at right angle approximately corresponding to the down gradient property boundary corner. The cobbly till could not be penetrated by continuous trenching. Therefore, conventional trenching with considerable excavation was employed. Trenches were equipped with slotted PVC pipe to act as drains to the gate and back-filled with screened gravel.

The gate, at the junction of the collection trenches, consisted of 3, 1.8 m in diameter and 6 m high, cylindrical galvanised culverts, set vertically into a concrete base (see Fig. 2). These are connected 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 that no mounding occurs 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 subdivided into two parallel compartments and the third culvert could also be equipped with a biosparge system.

The right side of the second culvert was used as a control and the left side as the active treatment zone to demonstrate treatment efficacy. The first experiment compared the addition of N and P to no addition. Identical 'containers' (well screens, 5.5 m long and 10 cm in diameter, wrapped with micropore 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 dicalcium phosphate) and phosphate rock (carbonate-substituted fluoro apatite). The control side container was filled with silica sand. In a second experiment, NH_3 was added to both sides of the second culvert via the emitter tubing. Phosphate was added to the 'amended' side only, in the same way as in the first experiment.

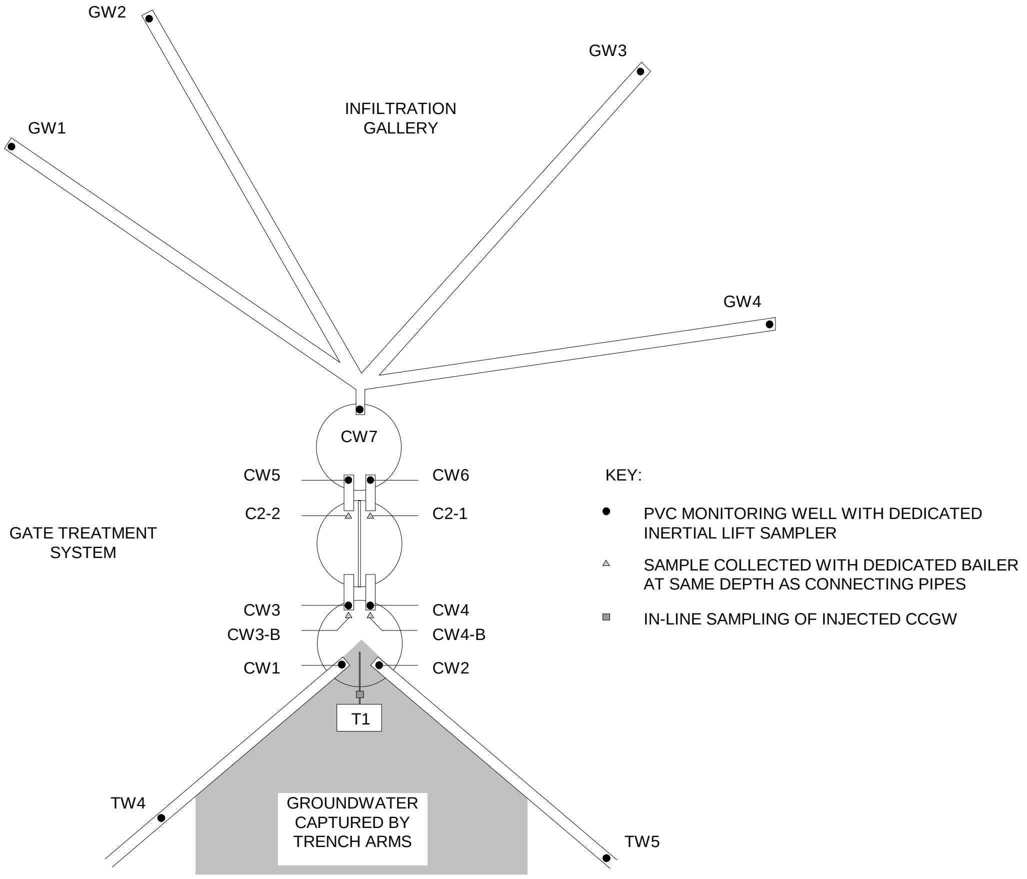

Fig. 2. Schematic representation of the 'Trench and Gate' in Alberta, Canada.

The benefits of using open gates are threefold: a more flexible, easily modified treatment zone; the residence time of the groundwater within the gate is longer, allowing more time for the treatment method to be effective; and 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.

Hydraulically, the 'Trench and Gate' worked as designed, even when fluxes into the system increased substantially after rain events. Even when the flux of BTEX entering the gate was enhanced to > 2 mg/L, the treatment system maintained its performance. 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. As in the first case in this case sparging has an added advantage for gate treatment, in that it promotes homogenization of often heterogeneous groundwater concentrations. 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 3-culvert treatment system continues to operate successfully with only air sparging into the first culvert.

Pilot-scale 'Funnel and Gate' naphtalene plume at CFB, Borden

At the CFB Borden aquifer research site, a persistent groundwater plume dominated by naphthalene was intercepted by a 'Funnel and Gate'. Treatment involved the addition of nitrate from concrete briquettes to promote naphthalene biodegradation by denitrifying bacteria (see Fig. 3).

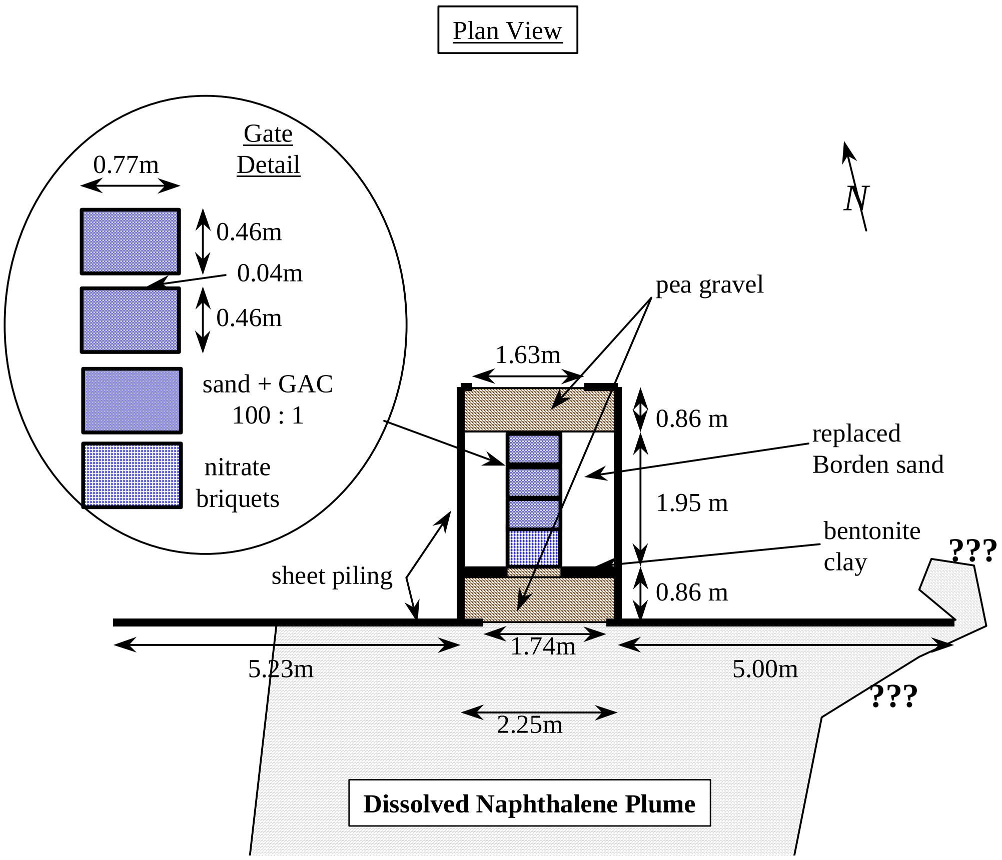

Fig. 3. Schematic representation of the 'Funnel and Gate' at Borden, Canada (on-top view).

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. An 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 Visual MODFLOW, version 2.00. The 'Funnel and Gate' was 'hanging'; that is, it was not keyed into an underlying aquitard. In many cases this can produce considerable cost saving, but does allow a plume to flow underneath the system.

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, 1998], as anticipated from laboratory studies. 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 upstream 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. While successful in reducing the 1 - 5 mg/L influent naphthalene concentrations to below detection limits (< 10 µg/L), it was not clear what the relative contribution of denitrifiers and aerobes was. The hydraulic performance appears to be as predicted in design modelling, but plume capture is currently being monitored. Research is ongoing.

2.3 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 clean-up is technically difficult or needs to be postponed. A so-called passive system is subjected to changes in directions of groundwater flow (for instance induced by nearby abstractions). Also, in some countries like the Netherlands, remediation goals have to be achieved within a certain period.

A consortium consisting of Shell Global Solutions, University of Waterloo, Technical University of Delft, Ingenieursbureau 'Oranjewoud' B.V. and the Municipality of The Hague studied the possibilities for adjustment of the original 'passive' concept in such way that - without removal of the pollution source - remediation times can be reduced. This resulted in an 'active' system, whereby upstream of the water-inlet of the gate, a low capacity pumping well is installed. Using this well the 'captured' area is more intensely flushed. The mobile components are more quickly leached from the polluted area leading to a decrease of the total remediation duration. Cleaned groundwater can be re-infiltrated in the captured zone (upstream the gate) or in the saturated zone (downstream the gate). An upstream infiltration will result in a more intensive leaching of the captured zone (and a subsequent further decrease of remediation times). The active system thus is capable of remediations of the source zone (increased leaching of the pure product from the soil), as well as of the plume zone (degradation of the contaminants in the groundwater).

In fact, one could say that the 'Pump and Treat' is uniquely combined with the original 'Funnel and Gate'-concept. Except for the smaller duration of remediation, an active system still has other advantages. 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 infrastructural limitations (cables and conduits, buildings, roads etc.).

Also, more flexibility is achieved when changes or adjustments are required (uncertain local geohydrological situations). The system is furthermore well-suited for telemetric control. As for the passive variant of 'Funnel and Gate' (without active pumping), the active variant is fully installed below the soil surface. Only the groundwater flow is actively influenced; cleaned groundwater is re-infiltrated into the soil. The remediation therefore remains - from a geohydrological point of view - only detectable on local scales. Owing to the latter, licence-technical convenience is achieved as well.

Also for complex pollution situations (former gasworks locations, oil depots etc.) an active 'Funnel and Gate' system can provide solutions. In such situations parallels exist between conventional isolation variants, combining 'Pump and Treat' with e.g. vertical isolation screens. The innovating aspects of the active 'Funnel and Gate' concept, however, is that isolation screens are only installed downstream of the pollution instead of fully around. Furthermore, groundwater is abstracted at the border of the pollution, not in its core. Indeed, the natural groundwater flow is put to use as much as possible. 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.

Concluding, an active system has the following advantages:

- it is not subjected to changes in directions of groundwater flow;
- it makes the use of infiltration possible;
- flushing can be accelerated and so remediation goals can be achieved;

- both retention and retardation zone can be treated;
- it is flexible to operate.

Naturally, the cost-effectiveness of an active system will vary from site to site. Determining factors are, amongst others, subsurface and suprasurface obstacles (buildings, roads, cables, etc.). The choice between an active of passive variant therefore should be site-specific.

2.4 **Guidelines for application**

2.4.1 *Remedial options with 'Funnel and Gate'*

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) and remediated. This makes 'Funnel and Gate' suitable for:

- the cut-off of source zone from plume zone, thus preventing further 'loading' of the plume zone and trapping all contaminants coming from the source (source clean-up and source control);
- controlling the plume zone and - in this way - preventing a further increase of the groundwater pollution (plume control).

Source clean-up and source control

With 'Funnel and Gate' it is possible to cut-off the source from the plume zone. This aims at the removal of the mobile contaminants which are released into the groundwater by the pollution source. To meet this objective, the system should contain the retention zone. In that case all contaminants released from the source 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 source 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 aftercare - 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 source 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 geohydrological situation and (telemetric) controllability can also form important aspects. Subparagraph 2.4.2 will further discuss such and other criteria.

Plume control

As follows from paragraph 2.2, former pilot tests usually involved passive 'Funnel and Gate' variants, which were installed downstream groundwater pollutions. In this way a further increase of the plume size was prevented. If the source is not removed, the groundwater pollution will be continuously 'feeded' by dissolution from the pure product in the source. The remediation will finally end once all mobile components are dissolved from the source, and the groundwater pollution as a whole has disappeared by natural groundwater flow through the gate.

To decrease remediation time the source 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 source (to prevent further dissolution into the plume). An active system can however be effective in the following situations:

- an unstable geohydrological 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 source, rendering the system more sensitive to small changes in the direction of the groundwater flow.

2.4.2 *Criteria for application*

For the selection of the potential applicability of 'Funnel and Gate' it is important to establish the following data (see also table 1):

- remediation objective;
- contamination situation;
- geohydrological situation;
- dispersion situation;
- location specific criteria.

Remediation objective

The objective for remediation can vary strongly depending on the choice between passive and active 'Funnel and Gate' systems. See subparagraph 2.4.1. for detailed explanation.

Contamination

The contamination must be soluble in water. Obviously, if the site has a retardation zone, the contamination must be soluble. The rate of solubility however is also important. This is especially the case for remediation variants aimed at (complete) removal of contaminants, in which the funnel and the gate are placed directly downstream the source zone. The presence of one or more poorly water soluble contaminants indeed directly influences the feasible end concentrations and thus the remediation efficiency. The solubility of contaminants is also important when calculating abstraction and infiltration quantities (related to the remediation period required).

Furthermore, the contamination must be (biologically) degradable, as such this is a critical parameter. The background to this assumption is that no residues should arise that have to be processed separately, as 'Funnel and Gate' is an 'on-site' remediation method. Strictly speaking, a 'Funnel and Gate' system can of course also function well where this criterion is not satisfied, for example through the use of an active carbon filter or iron fillings. The contaminant could also be volatile and a sparge gate could transfer the contaminant to the air for treatment or sorption onto carbon.

The presence of contamination in the saturated zone is of vital importance in applying the concept. No use can be found in flushing the water-unsaturated soil layer and consecutively applying 'Funnel and Gate' to solve the resulting groundwater contamination. In most cases, however, the contamination will be present in both zones.

Geohydrology

An essential requirement for the design of a 'Funnel and Gate' system is that the geohydrology should be suitable. The soil must have a reasonable permeability, at least a few meters per day (fine sand). The fluctuation of the direction of groundwater flow is also important. The contamination must be present within one aquifer. The maximum depth for application of a passive system is 25 m, this is determined by constructional demands. For application of an active system this depth can increase, dependable on the geohydrological conditions (like the vertical permeability of the soil and the distance to an aquitard).

Dispersion

'Funnel and Gate' systems are especially well-suited to remediate complex LNAPL-pollutions that to a large extent disperse horizontally. It is far from evident to treat DNAPL-pollutions with 'Funnel and Gate', since they disperse vertically as well as horizontally.

Table 1. Requirements for use of 'Funnel and Gate' systems.

criterion	passive system	active system
remediation objective		
remediation period	long term	medium term
remediation options	source and plume control	source clean-up (depending on K_{ow}) or plume control
contamination		
solubility (in water)	no demands	K_{ow} < 1000 [1]
degradability	biological [2]	preferably biological [2]
location	unsaturated as well as saturated zone	preferably for the most part in saturated zone
geohydrology		
permeability	moderate	good
depth to groundwater table	< 4 m below ground level	< 8 m below ground level
depth of the pollution	< 25 m below ground level	more than 25 m, depending on the specific geohydrology
rate of groundwater flow	> 0.05 m/day	no demands
direction groundwater flow	stable	may fluctuate
dispersion		
medium	water	water
direction of dispersion	horizontal	mainly horizontal
location specific criteria		
presence of obstacles	as less as possible non-removable obstacles should be present (subsurface as well as at the surface)	some flexibility exists regarding non-removable obstacles (location of the system is adjustable)
presence of vulnerable buildings	special attention (during the installation phase)	special attention, both during the installation phase (i.e. vibrations) and exploitation phase (grondwater subsidences [3])

[1] If the remediation objective is source clean-up. In other cases no demands.

[2] Preferably aerobic.

[3] If necessary possibilities for upstream infiltration need to be investigated.

Location specific criteria

When an increasing number of subsurface obstacles are present, preventing the installation of the system at its most optimal geohydrological location, chances for a successful passive 'Funnel and Gate' system decrease. Since the location of the system should be in agreement with all infrastructural plans on the site, active systems are less sensitive in this aspect. Displacement of the system probably leads to higher pumping quantities required, however. If installation of the system downstream a source or plume zone is found to be infeasible, use of the 'Funnel and Gate' concept is not evident.

CHAPTER 3

SYSTEM DESIGN

3.1 **Introduction**

From the foregoing chapter it can be derived in which situations a 'Funnel and Gate' system is an attractive remediation option and what kind of system could be applicable (passive and/or active). In this chapter the design process is dealt with. The design of a system starts with modelling the geohydrological situation. This is described in paragraph 3.2.

As stated in paragraph 2.4 the objective for a remediation project can be the following:

- source clean-up;
- source control;
- plume control.

Source and plume control can be achieved with passive 'Funnel and Gate' systems. This is dealt with in paragraph 3.3. Source clean-up within a reasonable period is only possible with an active 'Funnel and Gate' system. Some guidelines for the design are described in paragraph 3.4. In paragraph 3.5 some remarks about the design of an active system for plume control are made. Design principles for the capacity of the gate are stated in paragraph 3.6.

3.2 **Groundwater modelling**

3.2.1 *Objectives*

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.

3.2.2 *Modelling*

Type of model

At the start of the design process it is not clear which remediations options are involved, so it is important to use a model which is flexible and easy adaptable. For instance funnels must be easy to model and quickly 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 hydrologically spoken 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.

Geohydrological data
Next is to establish the geohydrological situation in the project area. Among others this includes the determination of the following aspects:

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

It is important to have an insight into the temporal variety of the direction of the 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.

3.3 **Passive system for source and plume control**

3.3.1 *Introduction*

As far as the passive 'Funnel and Gate' system is concerned, the remediation period is not relevant to the determination of the dimensions of the system, as the configuration of the design depends solely on the prevailing geohydrological situation (direction and velocity of groundwater flow, etc.). In order to prevent a further dispersion via the groundwater all contaminants must be captured by the funnel. Moreover, it is important that the direction of the groundwater flow will not alter by the installation of the funnel walls and that dispersion of contaminants by passing around the funnel walls is prevented. The shape of the funnel therefore should be choosing taken into account the occurring geohydrological conditions (soil structure and groundwater flow).

3.3.2 *Location of system*

The system can be situated downstream of the source (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.).

3.3.3 *Funnel length*

In a passive 'Funnel and Gate' system use is made of the natural groundwater flow. The assumption for the determination of the funnel length is that all groundwater contaminants originating from the retention zone (source control) or retardation zone (plume control) 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 is determined by means of iterative calculations.

3.3.4 *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 a aquitard, a complete funnel;
- a funnel not reaching into a aquitard a so-called 'hanging' funnel.

Obviously, for shallow aquifers (< 10 m) 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. When the contamination does not reach the aquitard, the groundwater model can be used for determining the optimum depth.

3.3.5 *Depth of gate structure*

One of the criteria to determine whether it is possible to apply 'Funnel and Gate' is the maximum depth of the gate. In subparagraph 2.4.2 a maximum depth of the gate of 8 m is stated. In most cases this depth will not coincide with the depth at which the aquitard is 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 more shallow 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.

3.4 **Active system for source clean-up**

3.4.1 *Introduction*

The design process for an active 'Funnel and Gate' system is more complicated than for the passive systems. The main reason for this is that the system has more variables because the abstraction (and possibly infiltration) rate is variable, whereas in the passive variant the driving force behind the system (the natural groundwater flow) is fixed.

3.4.2 *Design variables*

The dimensions of an active 'Funnel and Gate' system are determined by a number of variables. The essential variables are shown in figure 4.

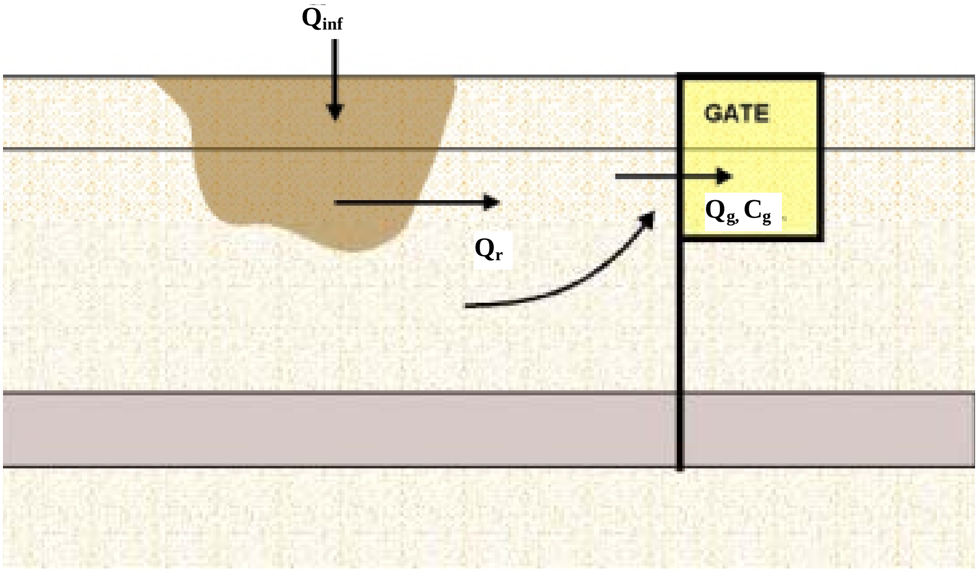

Fig. 4. Design variables.

The essential variables comprise:

- the flow rate through the retention zone (Q_r), which together with the solubility of the contamination determines the duration of the remediation;
- the infiltration rate (Q_{inf}), at which additional flushing of the retention zone can be achieved;

- the quantity of water that flows in through the gate per unit of time (Q_g), which together with the influent concentration in the gate (C_g) and the degradability of the contamination determines the capacity of the remediation system.

3.4.3 *Required remediation period*

Source clean-up within a reasonable period is only possible with an active 'Funnel and Gate'. This aim will have been achieved when the concentration of contamination in the influent from the gate is below a certain value. The maximum (allowed) remediation period is determined by government policy.

To asses the remediation period the following data are required:

- total contamination load (site assessment);
- mobility (oil characterization, soil core leaching test, literature).

With these data the relationship between the number of flushes and the remediation period can be determined for different contamination loads. An example is given in figure 5. With a given remediation period the minimal number of flushes can be derived and so the minimal required flow rate through the retention zone.

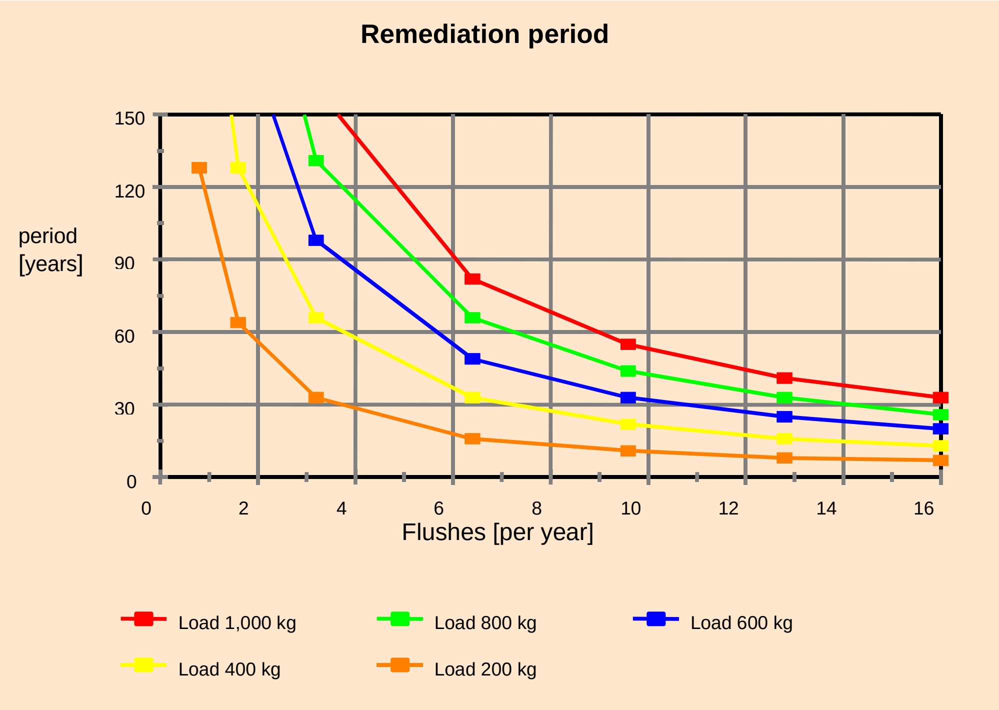

Fig. 5. Relationship between flow rate through retention zone and remediation period at different loads.

3.4.4 *System dimensions*

Preliminary design

In subparagraph 3.4.3 the minimal required flow rate through the retention zone (Q_r) is derived. The rate of the abstraction near the gate (Q_{gate}) will be higher than Q_r. The ratio between Q_{gate} and Q_r depends on the thickness of the retention zone, the water-bearing height of the gate (the distance from the water table to the threshold of the gate) and the stratification of the soil.

The length and depth of the funnel depend on the abstraction rate. 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 cost 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.

The effect of the funnel depth on short circuit currents under the funnel can be determined at varying funnel depths. The use of an abstraction will lead to more shallow funnels than with passive systems.

Use of infiltration
During the design process it could appear that the required flow rate through the retention zone cannot be achieved. In that case, the use of infiltration becomes necessary.

Furthermore, abstracting groundwater in the gate lowers the groundwater level (this becomes clear when the preliminary design is completed). This may cause the retention zone to run dry (in places), which means that the contamination cannot be flushed and therefore can only be inadequately remediated. This is unacceptable if it extends the remediation period. Corrective measures may be taken by infiltration.

Also, any subsidence that occurs as a result of abstracting groundwater in the gate must be kept to a minimum in order to prevent any damage resulting to surrounding buildings (and other sensitive properties). Where practicable, infiltration may be used to overcome this problem.

Adjustment design
When the use of infiltration is necessary, the preliminary design must be adjusted. Depending on the objective, an infiltration system is designed (dimensions and location). Next, the groundwater model must be adjusted with the infiltration components.

After that some iterative calculations must be made to further optimize the design. This can lead to an adjustment of the funnel length and the rate of abstraction. Of course, using infiltration can shorten the duration of the remediation below the allowed period. However, this must be seen as an additional benefit.

3.4.5 *Plume control*

Effects active 'Funnel and Gate' system
The foregoing design has not taken the presence of contamination downstream of the system into account (in the so-called retardation zone). Furthermore, because on the downstream side of the gate remediated water is infiltrated into the soil, the contaminants in the retardation zone may disperse to an unacceptable level. This is most likely to happen where the full quantity of water abstracted is infiltrated downstream of the 'Funnel and Gate' system, as the flow velocity surges dramatically at that point and changes the direction of flow. A substantial discharge rate actually causes a radial flow from the gate, which makes the retardation zone fan out (mainly perpendicular to the natural direction of flow). This will alter the shape of the retardation zone, which may cause legal problems (such as crossing property boundaries). Corrective measures may be taken.

Plume control measures
Monitoring

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:

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

Infiltration

By infiltrating (some of) the effluent from the gate back into the retention zone it is possible to counteract any inadmissible spreading of the groundwater contaminants into the retardation zone, as this restricts the discharge rate of the gate.

Abstraction

If the groundwater contamination grows to an inadmissible extent, active intervention is a must. This can be done by increasing the oxygen content to the desired level (for example, by aeration or the addition of oxygen release compounds) or by temporary abstraction until the groundwater contamination has returned to its original extent. If the extent of the retardation zone remains the same or decreases, only the attenuation process will be monitored. Active intervention is then unnecessary.

3.5 **Active system for plume control**

In some specific cases, the design of an active system for plume control will be necessary. These reasons are stated in paragraph 2.2. For the design process the reader is referred to the foregoing paragraphs.

3.6 **Design of the gate**

3.6.1 *Treatment system*

The design of the treatment system depends on the characteristics of the contamination and the presence of natural substances like iron and manganese.

The main principle of the treatment is determined by the characteristics of the contamination. As 'Funnel and Gate' is an 'on-site' remediation method, the contamination must be (biologically) degradable (see subparagraph 2.4.2). Strictly speaking, a 'Funnel and Gate' system can of course also function well where this criterion is not satisfied, for example through the use of an active carbon filter or iron fillings. The contaminant could also be volatile and a sparge gate could transfer the contaminant to the air for treatment or sorption onto carbon.

The design of the treatment system is also 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 which 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.).

3.6.2 *Capacity*

The design of a 'Funnel and Gate' system results into a rate of the flow into the gate (Q_g). The biological degradability of the contamination, and therefore the minimum residence time in the gate, is determined with laboratory tests. Subsequently, the flow rate and residence time lead to the required capacity of the treatment system.

In the foregoing it is assumed that the contamination determines the treatment capacity. However, with short residence times, it is possible that the time for removal of natural components (like iron) becomes decisive. Therefore it is recommended to elaborate aeration tests.

CHAPTER 4

CASE: LIJNBAAN/WESTEINDE THE HAGUE

Part of the project consists of testing the 'Funnel and Gate' concept on a test site at 'Lijnbaan/Westeinde' in The Hague. A system has been devised for this site that not only provides sufficient information to optimize the concept, but is also suitable for remediating the soil contamination present on the site.

4.1 Approach to optimization

The project consists of 6 phases:

Phase A	Preparation work and establishment of consortium (1997).
Phase B	Marking out land and contaminated groundwater on the Lijnbaan/Westeinde test site (1998).
Phase C	Design of a 'Funnel and Gate' system for the remediation of Lijnbaan/Westeinde (1998 - 1999); see Appendix A.
Phase D	Installation of the active 'Funnel and Gate' system on the test site (1999).
Phase E	Test phase (1999 - 2000).
Phase F	Remediation by 'Funnel and Gate' (from 2000).

Phases A to C have now been completed. Phase D (the installation of the system on the site) was started in June 1999 and was completed in October 1999. Following this, a test phase is started, in which the operation of the installed system will be studied and optimized.

4.2 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 (see Fig. 6). Public streets border the site in all directions. The total area of the site is approximately 1,000 m^2.

Fig. 6. Test site: public park (view direction: southwest).

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 polluted 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 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.

Soil profile

The soil profile, on a regional scale, is summarized in table 2.

Table 2. Soil structure and geohydrology of remediation location.

formation	sedimentary deposit	position (m bgl)	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: sand;
- 16.5 - 17.8 m: clay with sandy layers;
- 17.8 - 19 m: sand.

The results of soil samples demonstrate that the source area of the pollution, 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 (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. The retention zone is defined as the polluted 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 Pollutants in Soil and Groundwater' (part of the Dutch legislation, the so-called 'Wet Bodembescherming'). The basis of this framework is the definition of so-called Target and Intervention values, which have the following meaning:

- *Target value (= S-value)*
  The target value is defined as the natural background concentration, which is found for the different soil types in The Netherlands, or is related to the limits of detection of current methods of analysis. The target value is comparable to the formerly used A-value. Once exceeded, the soil is classified as 'polluted'.
- *Intervention value (= I-value)*
  The Dutch Governmental policy establishes that a soil pollution at a certain site should be classified as 'a case of severe soil pollution' if the intervention value is exceeded in 25 m^3 of soil or 100 m^3 of groundwater (soil volume). If this is the case, a necessity to remediate is present. The urgency of the remediation depends on the results of a risk evaluation, covering both human-toxicological as well as eco-toxicological and spreading/dispersing risks of the specific pollutants.
- *Reference value (= T-value)*
  Within the governmental policy, the criterion for the execution - either or not - of a further soil investigation, depends on the fact if or not the so-called reference value T is exceeded. The reference value is defined as the average of the target and intervention value (T = (S+I)/2).

In the text the term 'slightly elevated' will be used if the S-value is exceeded, but the intervention value is not. The term 'strongly elevated' is used if concentrations exceed intervention values.

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

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

Most elevated oil and BTEX concentrations in the groundwater were measured in the source area at depths of 5.0 m below the soil surface. In the source area the pollution has moved downwards to the depth of the separating soil layer at approximately 17 m below the soil surface. The groundwater pollution in the plume has not descended as deeply as the pollution 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 pollution in the soil and the groundwater can be related to specific (local) soil structural details.

In horizontal direction, the pollution is equally far directed upstream as the soil pollution itself does. Downstream the pollution is extended in the direction of the Trambaan (south-southwest) up to about 30 meters starting from the gate.

4.3 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 risks to humans and the environment. The chance of dispersion, however, has 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 source control were calculated respectively on Dfl 3,700,000 and Dfl 2,600,000 (Dfl = Dutch florin).

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 Dfl 2,900,000. Later on, for policy reasons the system was activated. The costs for an active 'Funnel and Gate' system were calculated on Dfl 3,200,000.

'Funnel and Gate' offers 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 (see Fig. 7). 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.

4.4 'Funnel and Gate' construction used

Principle
An active system has been developed for the Lijnbaan/Westeinde site (see also Appendix A), 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.

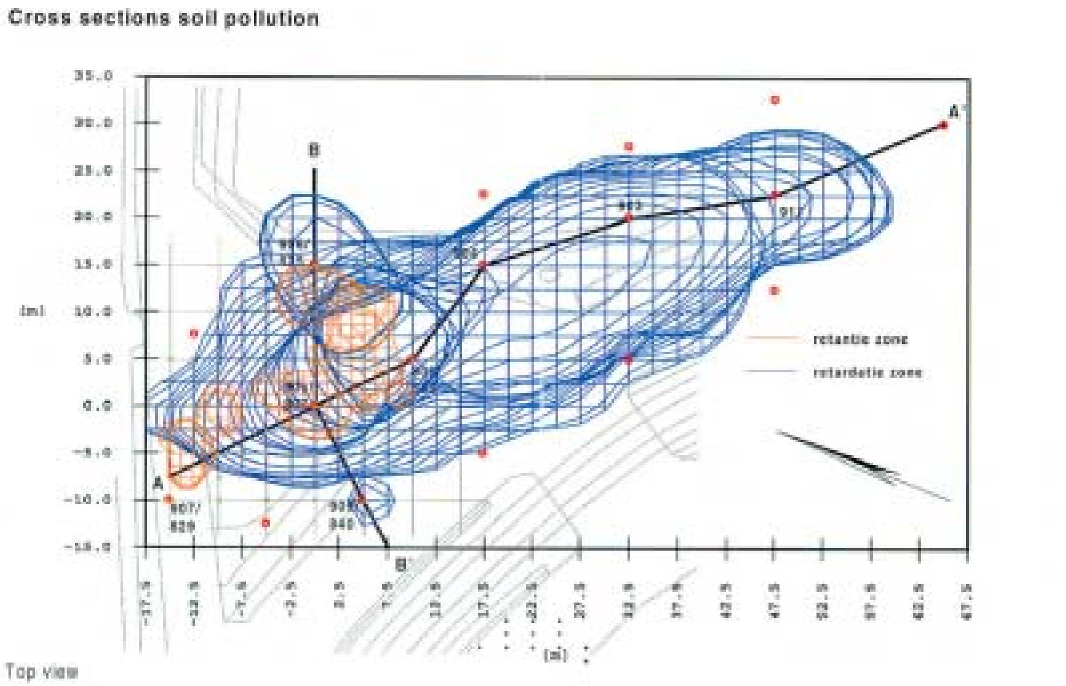

Fig. 7. Location of the funnel and the gate related to the retention zone and the retardation zone.

The system has two infiltration options:

- infiltration via six gravel drains (1 m below ground level) and six vertical infiltration wells (diameter 125 mm and filters from 2 to 5 m below soil surface) in the unsaturated zone (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 infiltratation drains and pits are chosen according to the boundary conditions, imposed by the nature and dimensions of the pollution, 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.

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.

Gate construction
The gate consists of two circular walls, forming double rings (see Fig. 8). 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. 8. Gate construction at the test site.

The walls consists 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 (see Fig. 9).

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.

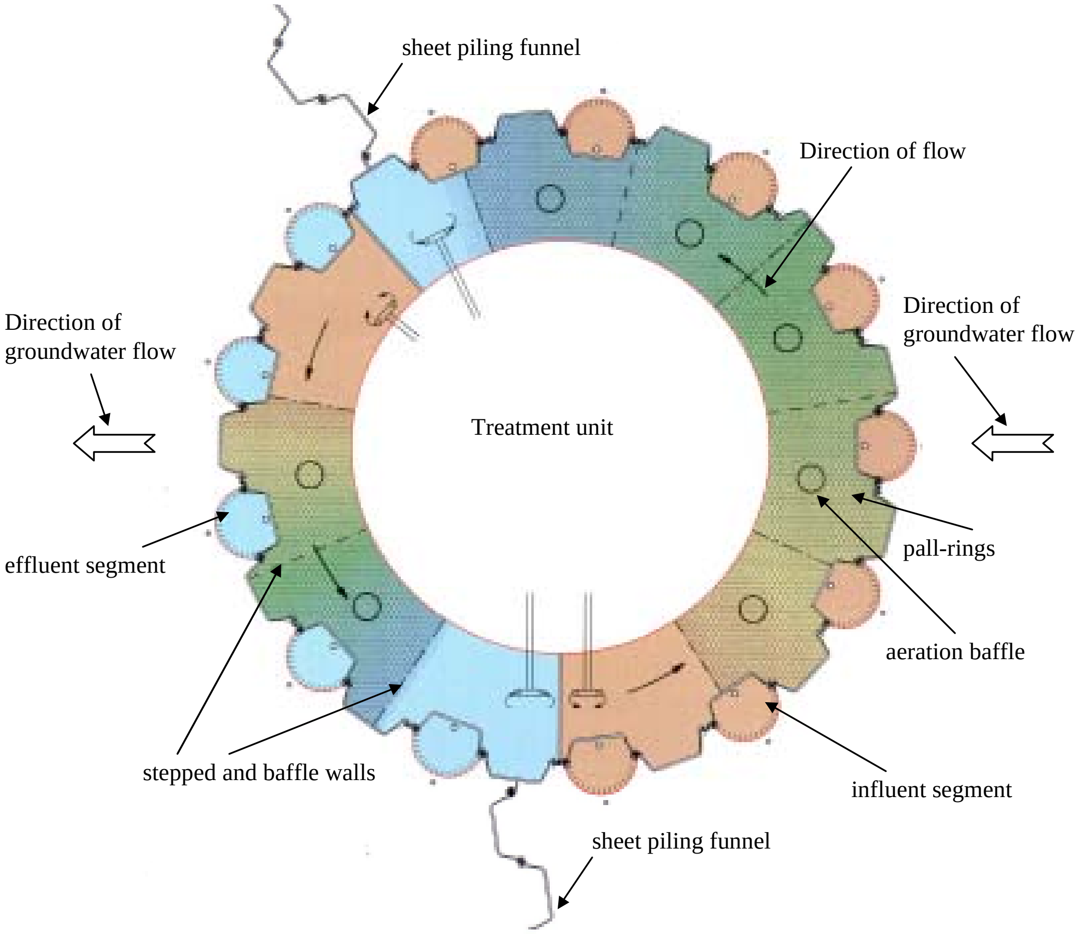

Fig. 9. Gate construction.

Treatment unit
The treatment unit is circular (see Fig. 9) with a diameter of almost 5.5 m and 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 being 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 six water buffers.

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.

Operation

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 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 water in these zones is aerated to stimulate the biological degradation of the groundwater contaminants. Wherever possible, the residence time in de zones is attuned to the influent quality and the abstraction rate.

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 six vertical infiltration wells (upstream of the system) and/or the five vertical infiltration segments (downstream).

Control system

Groundwater flows are controlled by analogue level measurements. Water can be abstracted and infiltrated selectively (by time and/or flow rate). The entire abstraction and treatment process is controlled and monitored by a telemetry system (CARS: Central Alarm and Recording System). The required cables and pipes are placed below ground in pipe sleeves. In figure 10 to 12 examples are presented of CARS screens.

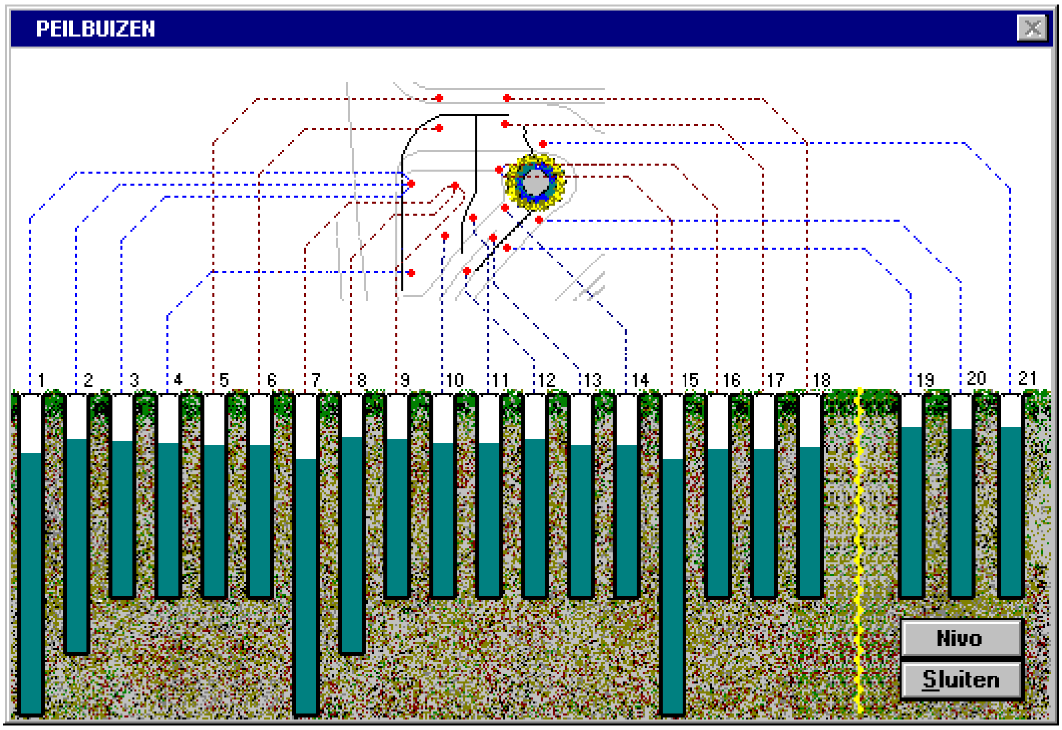

Fig. 10. Example of CARS screen with indication of groundwater levels in the monitoring wells.

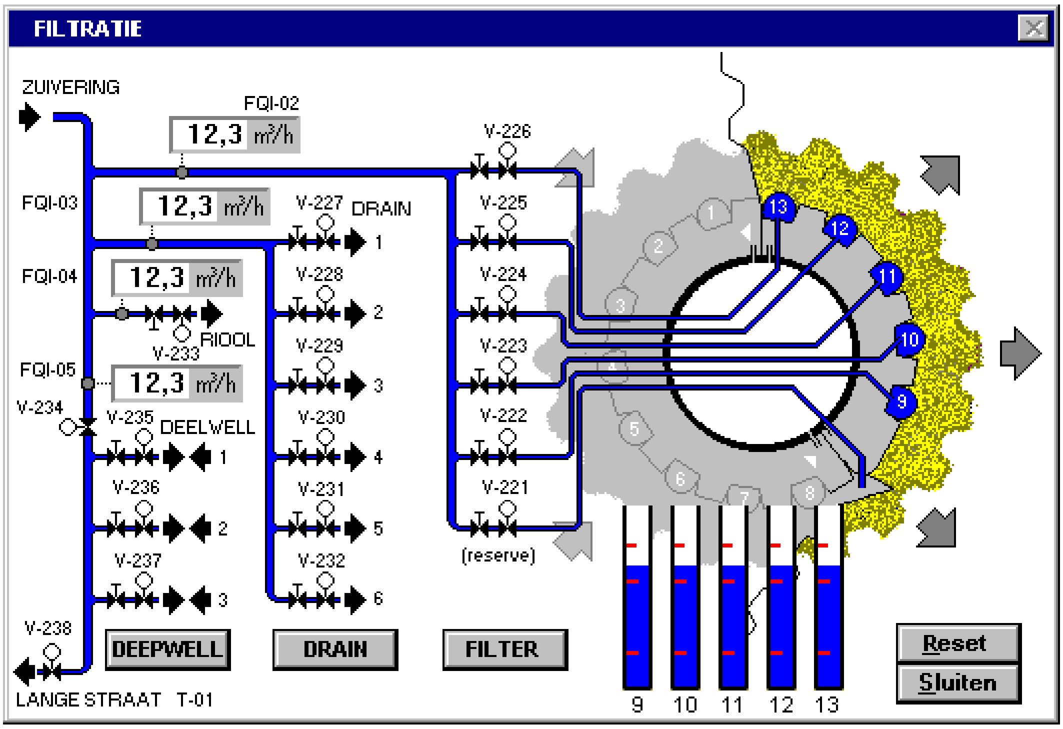

Fig. 11. Example of CARS screen with indication of connections to effluent segments.

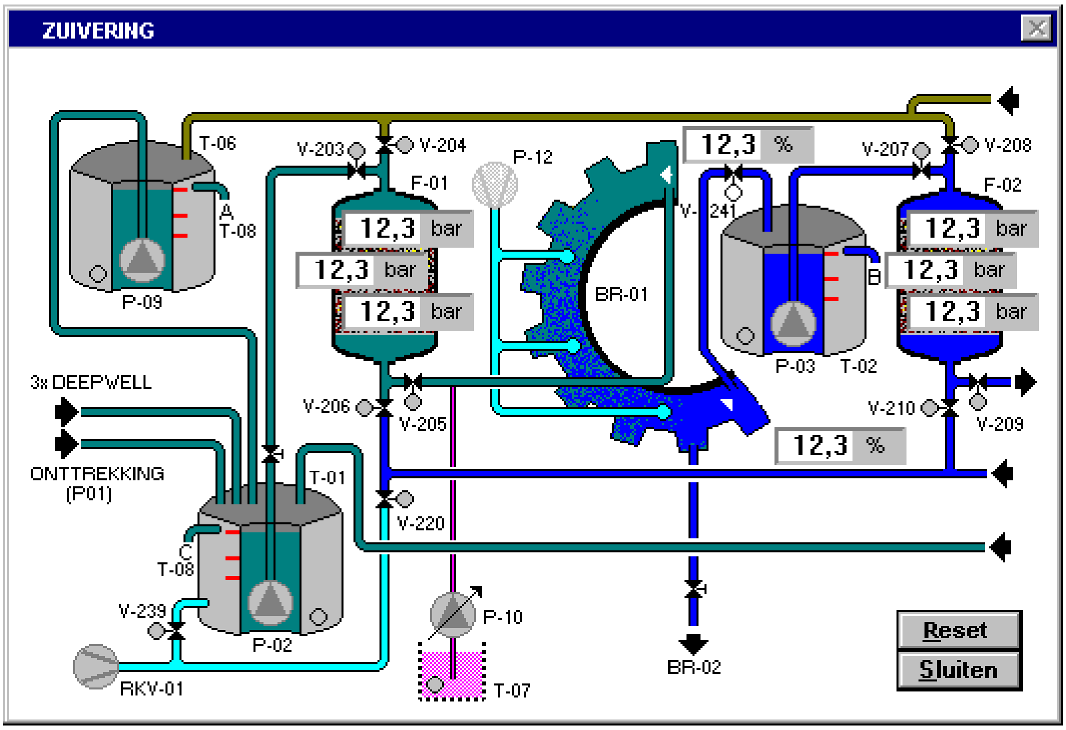

Fig. 12. Example of CARS screen with indication of the remediation unit.

CHAPTER 5

TESTING AND MONITORING PROGRAMME AT THE TEST SITE

5.1 Introduction

Consideration has been given to the way the test phase is to be carried out as far as the consortium is concerned and a number of research questions have been used as the basis for a joint testing and monitoring programme. In this chapter the purpose of this programme is underpinned and elaborated in detail.

The following parts of research were chosen:

1. research into the effect of biological treatment at different influent concentrations and variable abstraction rates;
2. research into the impact of a 'Funnel and Gate' system on the geohydrological situation;
3. research into the occurrence of precipitations in the abstraction and infiltration segments and in the treatment process and the risk of clogging;
4. inventory of policy-related and legal boundary conditions that could constitute an obstacle to the application of the 'Funnel and Gate' concept;
5. development of guidelines for designing 'Funnel and Gate' systems.

The duration of the test phase has been set at 1 year. The research into 'Bioremediation' and 'Geohydrological situation' 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 it will be sufficient to present the interim results and a (cautious) conclusion 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 (for these subjects the reader is referred to the foregoing chapters) , the (interim) results of the other parts of research from the test phase and the experience of consortium members with other 'Funnel and Gate' projects. The results of this research will also be presented at the conclusion of the test phase.

5.2 Preparation

Installing standpipes
To carry out the testing programme circa 35 standpipes are used. All standpipes are used for monitoring the groundwater level. About 12 standpipes are also used for monitoring the quality of the groundwater in the retention zone.

Reference situation
Before the test phase begins the reference situation is established by sampling mineral oil and aromatics from all the standpipes. Samples are also taken from 4 filters (2 shallow and 2 deep) to check for cyanide. The groundwater levels in all the standpipes are recorded as well.

Groundwater contamination retardation zone (plume)
In this phase the downstream groundwater contamination is marked out. The standpipes are used during the test phase to monitor the extent of the contamination.

5.3 Test periods

The test phase is divided into three periods:

- period 1: November 1999 - February 2000;
- period 2: March 2000 - June 2000;
- period 3: July 2000 - October 2000.

A number of variables are kept constant for each period, whereas other variables are varied. Remediation rates, concentrations of contaminants and rises in level are monitored in this way. The testing and monitoring programme is elaborated for each period in the section below.

5.4 Elaboration

5.4.1 *Period 1: November 1999 - February 2000*

The objective of the test phase during period 1 is:

- to check on any leakage from behind and underneath the system;
- to grow bacteria and start biodegradation;
- to test the infiltration system (downstream).

Abstraction and infiltration

In the first two weeks the mechanical aspects of the system (pumps, valves) are tested. After this period the abstraction will start and gradually increase (within a few weeks) to a constant rate of 15 m^3/day (design rate).

By recording the groundwater levels it is possible to deduce whether the abstraction is yielding the desired geohydrological result. Calibration of the groundwater model will be effected once treatment has begun and the control system has been adjusted. A steady state is expected to be approached after about one month.

During this period infiltration will only be carried out downstream and treated groundwater will be brought in via one or more infiltration segments downstream. The consequences for the geo-hydrological situation will be monitored. A subject of interest is to establish the impact of the infiltration flow on the downstream groundwater contamination (plume).

Treatment

The residence time in the treatment system will remain constant. One third of the abstracted flow passes over the short treatment zone and two-thirds over the long treatment zone.

In the first week no oxygen is added in the short treatment zone. The effluent concentrations of the short and long treatment zone are compared. In this manner it can be demonstrated whether mass removal occurs in the short treatment zone, for example caused by physical and chemical processes.

After this period oxygen will be added to activate the bacteria. The bacteria already present will slowly adapt and multiply. The bacteria will be robust within a week to one month. For monitoring the process samples are not only collected from the in- and effluent but also part way through the system.

During this period it will be established whether it is a good idea:

- to divide influent flows into categories;
- to add nutrients;
- to extend the residence time;

- to increase the oxygen concentration;
- to graft bacteria.

In case the biological degradation is too slow, laboratory experiments will be executed to stimulate the process.

5.4.2 *Period 2: March 2000 - June 2000*

Period 1 ends when the biomass has grown to the optimum level. The objective of period 2 of the test phase is:

- to determine the maximum load of the system;
- to test the upstream infiltration system.

Abstraction and infiltration

During this period the abstraction rate is stepped up from 15 to 30 m^3/day.The entire flow will be infiltrated through the gravel drains which are lying nearest to the gate. On the basis of the results the groundwater model will be adjusted with the infiltration elements. The new flow system will be complex so a new calibration will not entirely be possible.

Treatment

As a result of the infiltration the influent concentrations will increase: of course it will take some time to measure this effect in the influent (about three weeks). So, the maximum load of the system will increase during this period.

Measurements of concentrations in the compartments and effluent are used as a basis for checking whether the residence time in the treatment zones is sufficient, even at higher abstraction rates. Efforts will be made to find a relationship between load, residence time and aeration rate. For this purpose it can be necessary to direct the entire flow through the short treatment zone, thus creating the shortest residence time and thereby maximal conversion.

The sand filters are inspected for traces of biomass, calcium deposits and/or iron preciptations. It is expected some bacteria will be adsorbed in the sand filter.

5.4.3 *Period 3: July 2000 - October 2000*

This period is only completed once the results of the preceding periods are known. The provisional objectives of this period are:

- to determine the optimum distribution across treatment compartments;
- to simplify the treatment unit.

Abstraction and infiltration

During this phase the infiltration and abstraction rates are kept constant. These (optimal) rates are, hopefully, established in period 2.

Treatment

When the optimum conversion rate is established, the facilities of the treatment unit are tested. The benefits of differentiated treatment (dividing it into very contaminated and less contaminated flows) are investigated.

A test will be executed in which both treatment zones are connected and the water will flow under free fall. In this manner some economic aspects of the treatment unit can be investigated: i.e. maybe a smaller flow leads to lesser treatment costs (because lesser pumps are used).

5.5 **Monitoring scheme**

5.5.1 *On-line measurements*

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

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.

Groundwater levels in the vicinity of the system are recorded by divers.

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.

5.5.2 *Soil and (ground)water sampling*

Retention zone

Monitoring the standpipes in the retention zone provides a picture of the progress of the concentration of contaminants being flushed out. Even the contaminant load entering the treatment unit gives an impression of the quantity of contaminants flushed out, although account must be taken of any increased concentrations of contamination in the infiltration water.

Retardation zone

Standpipes have been installed to mark out the contamination downstream. Monitoring these standpipes provides information on the spread of the contamination downstream. If the concentrations rise above the intermediate value, water has to be abstracted from the deep wells. At the earliest the abstraction starts after the test period has been finished.

Treatment unit

In the following parts of the treatment unit samples will be taken on a regular base:

- compartments of abstraction (influent at gate, 8 compartments I1-I8);
- influent buffer (collected influent V1, V2);
- effluent aeration tank (B1, B2);
- influent at treatment unit (BL1, BL2);

- compartments of treatment unit (C1 - C6, C8 - C10);
- effluent treatment unit (C7, C11);
- effluent sand filter (Z1, Z2).

Oil characterization

Initially, the intention had been for the consortium also to calibrate the oil model developed previously (at NOBIS). A range of oil characterizations 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 programme. Calibration of the oil model will still be considered during the remediation phase, but not as part of this project.

5.5.3 *Soil and (ground)water analysis*

Appendix B provides a list of the analyses, and the frequency with which these are carried out for the different sampling points. Of course this list is preliminary, the actual number of analyses is partially depending on the problems occurring in the 'field' like clogging, precipitations etc.

5.5.4 *Air sampling and analysis*

The concentrations of BTEX and mineral volatile components in the gas phase are important for:

1. determining the stripping effect of the treatment;
2. determining the breakthrough time of the carbon filter.

The concentrations in the air originating from the treatment system must be measured regularly. It is important that only the air from the treatment compartments is measured. Its flow rate must also be ascertained so that a mass balance can be prepared. The frequency with which the effluent from the carbon filter is measured is determined by the licensing authority.

To indicate the concentration in the gas phase measurements can be performed using carbon tubes. After flushing, the carbon tubes are sent to the laboratory for analysis. However, the measurement obtained is highly inaccurate. There is also the option of measuring at the system. In this case, flow measurements are taken and the concentrations to the carbon filter are measured. From this, the saturation time of the carbon filter is calculated. These measurements have a higher degree of accuracy and can be combined with emission measurements under the terms of the permit issued under the Environmental Management Act (*Wet Milieubeheer*).

CHAPTER 6

CONCLUSION

With '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) and remediated. This makes 'Funnel and Gate' suitable for:

- source clean-up and source control;
- plume control.

The possibilities for adjustment of the original 'passive' concept are studied in such way that - without removal of the pollution source - remediation times can be reduced. This resulted in an 'active' system, whereby upstream of the gate a low capacity pumping well is installed to decrease the total remediation duration. Cleaned groundwater can be re-infiltrated in the upstream or downstream of the gate. The active system thus is capable of remediations of the source zone (the source is more intensively flushed), as well as of the plume zone (degradation of the contaminants in the groundwater).

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 geohydrological situation and (telemetric) controllability can also form important aspects.

For the selection of the potential applicability of 'Funnel and Gate' it is important to establish the following data:

- remediation objective;
- contamination situation;
- geohydrological situation;
- dispersion situation;
- location specific criteria.

For the design of a 'Funnel and Gate' system the objective for the remediation project determines the type of 'Funnel and Gate' system to chose. Source clean-up within a reasonable period is only possible with an active system. Source or plume control can also be achieved with a passive system.

In this report guide lines for the application of 'Funnel and Gate' and an overview of the design variables are given. At the test site Lijnbaan/Westeinde in The Hague the concept of 'Funnel and Gate' will be tested. A system has been devised for this site that not only provides sufficient information to optimize the concept, but is also suitable for remediating the soil contamination present on the site.

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 to reduce the duration of the remediation. It is constructed entirely underground. Only the groundwater flows are controlled; treated groundwater is infiltrated back into the soil. The abstracted water is pumped to a biological treatment zone where it is aerated to stimulate the biological degradation of the groundwater contaminants. After a sufficiently long residence time the treated water is finally infiltrated through gravel drains and vertical infiltration wells (upstream of the system) and/or the vertical infiltration segments (downstream).

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APPENDIX A

SYSTEM DESIGN 'FUNNEL AND GATE' AT TEST SITE LIJNBAAN/WESTEINDE

Appendix A describes the system design of the 'Funnel and Gate' at the test site Lijnbaan/Westeinde in The Haque. The original text can be found in the chapters 4 'System design' and 5 'Results' of the interim report 'System design' [Consortium 'Funnel and Gate', System design, 1998].

Design variables

The final dimensions of a 'Funnel and Gate' system are determined by a number of variables. The essential variables are shown in figure 4 (see subparagraph 3.4.2) of the main report and comprise:

- the flow rate through the retention zone (Q_r), which together with the solubility of the contamination determines the duration of the remediation;
- the infiltration rate (Q_{inf}), at which additional flushing of the retention zone can be achieved;
- the quantity of water that flows in through the gate per unit of time (Q_g), which together with the influent concentration in the gate (C_g) and the degradability of the contamination determines the capacity of the remediation system.

The dimensions of the resulting design can be expressed as the total funnel length, the funnel depth and the capacity of the gate. The horizontal track of the funnel always follows the contours of the retention zone, in view of the stipulation that the funnel be installed directly around the retention zone.

Design diagram

On the basis of the experience gained in creating the 'Funnel and Gate' design for the test site a number of critical parameters can be defined for such a system. This is discussed in greater detail in this section with the aid of the diagram in figure A1 which illustrates the design process followed for the test site.

The codes used in the decision point correspond to the numbers of the explanatory notes. The diagram can also serve as a handle for the design of a 'Funnel and Gate' system subject to the same overall remediation objective and limiting conditions.

Presence of retention and retardation zones

In view of the design objective for the 'Funnel and Gate' system at the test site it is of vital importance to establish the location and size of the retention and retardation zones. The retention zone is actually to be cut off from the retardation zone by installing the funnel directly around the retention zone. What is more, it is equally clear where the targeted remediation measures for both the retention and the retardation zone must be implemented.

Using the 'Funnel and Gate' approach prevents any further spreading of contaminants as a result of a subsequent discharge from the retention zone. Consequently, there will be no further increase in the overall load of contaminants in the retardation zone. Remediation will be carried out until a situation is reached where no active aftercare is required for the contaminants in the retention zone.

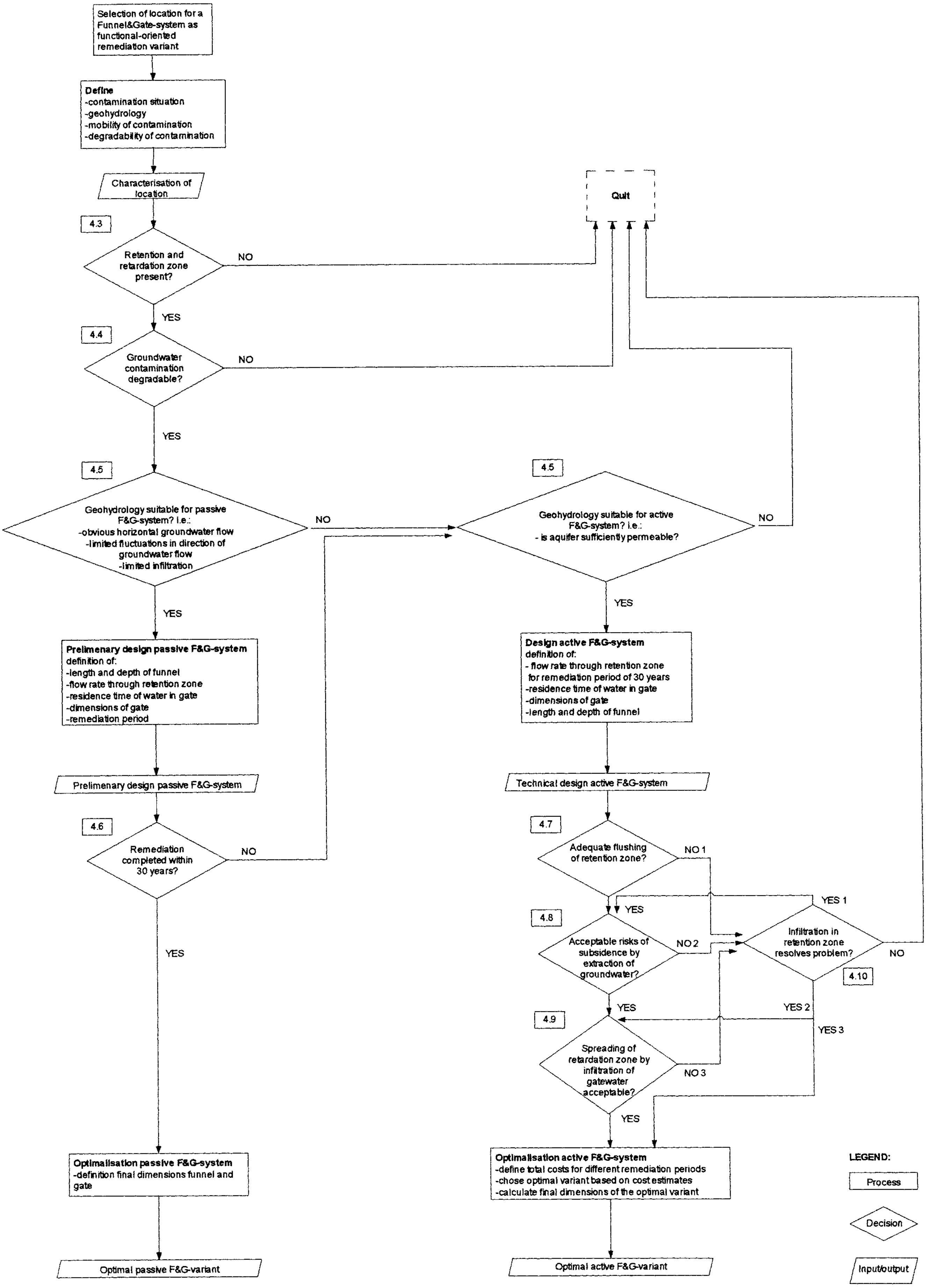


Fig. A1. Design system for 'Funnel and Gate' at Lijnbaan/Westeinde in The Hague.

Degradability of contamination

The assumption behind this project is that the contamination must be (biologically) degradable and as such this is a critical parameter. The background to this assumption is that no residues should arise that have to be processed separately, as 'Funnel and Gate' is an 'on-site' remediation method. Strictly speaking, a 'Funnel and Gate' system can of course also function well where this criterion is not satisfied, for example through the use of an active carbon filter or iron filings.

Geohydrology

An essential requirement for the design of a 'Funnel and Gate' variant is that the geohydrology should be suitable. Table A1 contains a selection matrix for a passive 'Funnel and Gate' system with an overview of the main parameters. This selection matrix is broadly still up to date, with the proviso that the assumption for this matrix was that there would be a complete funnel and an active 'Funnel and Gate' variant had not yet been envisaged at the time. Information on additions and/or amendments to this matrix is given below for both a passive and an active variant.

Table A1. Selection matrix for 'optimum location' for 'Funnel and Gate'.

criteria	excellent	acceptable	undesirable	unacceptable
BTEX or chlorinated solvents	5 - 20 mg/l	1 - 5 mg/l	0.2 - 1 mg/l	< 0.2 mg/l
depth to watertable	< 2 m	2 - 4 m	4 - 8 m	> 8 m
groundwater flow rate	10 - 50 cm/day	5 - 10 cm/day	1 - 5 cm/day	< 1 cm/day
distance to aquitard	< 6 m	6 - 8 m	8 - 10 m	> 10 m
favourable hydrogeology	medium/coarse sand	gravel fine sand	coarse gravel silty sand	silt clay peat
size of area	20 x 80 m	15 x 20 m	10 x 15 m	< 5 x 10 m
ease of construction	sands	gravels	cobbles	hard pan
access (above and below ground)	clear	minimal services	few services	lots of services

Scoring system:		
	excellent:	10
	acceptable:	7
	undesirable:	4
	unacceptable:	0

Passive 'Funnel and Gate' variant

The selection matrix will be retained, with the proviso that the following is also important for the test site.

Fluctuation in direction of groundwater flow

The direction of groundwater flow at the test site has been found to fluctuate. In order to be able to determine the horizontal size of the funnel a design criterion must be set in which it is indicated whether temporary leakage is likely to occur along the sheet piling and if so, how frequently. The design criterion is dependent on any design requirements that may be imposed (for example, the reliability of the system) and the frequency and magnitude of the fluctuations. The horizontal size of the funnel depends on the duration and magnitude of the fluctuations.

Vertical gradient of groundwater

The depth of the funnel is chiefly determined by the depth of the contamination, the location of the funnel and the vertical gradient of the groundwater (the quotient of the magnitude of the horizontal and vertical flow velocity). As part of the research project, the funnel has been installed directly round the retention zone. Any leak of contaminants under the funnel has therefore become a function of the vertical gradient (the vertical reach of the contamination is fixed). A limiting condition is that no leakage of contaminants should be allowed under the funnel. In view of the fact that at the test site there is always a situation of infiltration to the underlying aquifer, this means that the underside of the suspended funnel must always be deeper than the underside of the contamination (depth of funnel = depth of contamination + vertical gradient · distance).

Active 'Funnel and Gate' variant
Only one (geo)hydrological criterion is important for an active 'Funnel and Gate' variant, and that is that the soil should be sufficiently permeable. Poor permeability of the soil can mean that undesired diffusion of groundwater contaminants cannot be eliminated by the active creation of a gradient towards the gate. Poor permeability will also nullify any advantage in remediation time. It is not possible to give an absolute lower limit for permeability, as it also depends on the extent and the material properties of the contamination.

Permitted remediation period
In this research project it is assumed that a functional remediation using 'Funnel and Gate' must be completed within 30 years. If the remediation takes longer, the remediation will assume the characteristics of an isolation variant in the form of a passive 'Funnel and Gate' system.

Flushing the retention zone
Extracting groundwater in the gate lowers the groundwater level. This may cause the retention zone to run dry (in places), which means that the contamination cannot be flushed and therefore can only be inadequately remediated. This is unacceptable if it extends the remediation period beyond 30 years. Corrective measures may be.

Risk of subsidence
Any subsidence that occurs as a result of extracting groundwater in the gate must be kept to a minimum in order to prevent any damage resulting to surrounding buildings (and other sensitive properties). Where practicable, return drainage may be used to overcome the problem.

Spreading of retardation zone
Because on the downstream side of the gate remediated water is infiltrated into the soil, the contaminants in the retardation zone may disperse to an unacceptable level. This is most likely to happen where the full quantity of water extracted is infiltrated downstream of the 'Funnel and Gate' system, as the flow velocity surges dramatically at that point and changes the direction of flow. This will alter the shape of the retardation zone, which may cause legal problems (such as crossing property boundaries). Corrective measures may be taken.

Return drainage
The use of return drainage can achieve the following: the prevention of an inadequate flow through the retention zone, excessive lowering of groundwater levels (risk of subsidence) and an unacceptable spreading of the retardation zone.

Inadequate flow through retention zone
Remediated water from the gate is returned to the soil at the retention zone, thereby ensuring that the soil contamination is adequately flushed in order to achieve a remediation period of 30 years.

Risk of subsidence
Using a return drainage system at the retention zone can limit the lowering of groundwater levels so as to eliminate any risk of subsidence for sensitive properties.

Spreading of retardation zone

By infiltrating (some of) the effluent from the gate back into the retention zone it is possible to counteract any inadmissible spreading of the groundwater contaminants into the retardation zone, as this restricts the discharge rate of the gate. A substantial discharge rate actually causes a radial flow from the gate, which makes the retardation zone fan out (mainly perpendicular to the natural direction of flow).

It should be noted that the spreading of the retardation zone can also be limited by actively drawing groundwater out of this zone. The drainage water is then discharged back into the gate and thereafter treated and infiltrated in the normal way. Strictly speaking, from a spatial point of view, this is not return drainage within the 'Funnel and Gate' system, but the extraction of groundwater does not breach the principle of a closed water system (no discharge into the sewer).

Results

The characterization of the geohydrology and soil contamination at the test site is reproduced in the survey report for the location [Consortium 'Funnel and Gate', Actualisatie verontreinigingssituatie, December 1998]. The design results are described in the amended remediation plan [Consortium 'Funnel and Gate', Aangepast saneringsplan bodemverontreiniging Lijnbaan/Westeinde te Den Haag, December 1998]. The design process itself is discussed in greater detail in this section.

Passive system

The main aspects of the design process for the passive system are described in the amended remediation plan for the location and in the flow chart in figure A1 of this report. A brief explanation follows below.

Remediation period and flushing frequency

As far as the passive 'Funnel and Gate' system is concerned, the remediation period is not relevant to the determination of the dimensions of the system, as the configuration of the design depends solely on the prevailing geohydrological situation (direction and velocity of groundwater flow, etc.). In an active 'Funnel and Gate' system the remediation period does play a part in determining the dimensions of the structure. This is discussed in subsection 'Remediation period and flushing frequency'.

System dimensions

Funnel length

In a passive 'Funnel and Gate' system use is made of the natural groundwater flow. In the contaminated zone, measurements of groundwater levels have shown that this In a passive 'Funnel and Gate' system use is made of the natural groundwater flow. In the flow is in a south-easterly direction, which is confirmed by the direction of spread of the groundwater contamination. The assumption for the determination of the funnel length is that all groundwater contaminants originating from the retention zone are 'caught' in a south-easterly direction of flow by the 'Funnel and Gate'. In the event of a possible temporary south-westerly direction of flow, minimal leakage is accepted. Using the groundwater model created the length of the funnel wall is determined by means of iterative calculations. The dimensions of the system are shown in figure A2.

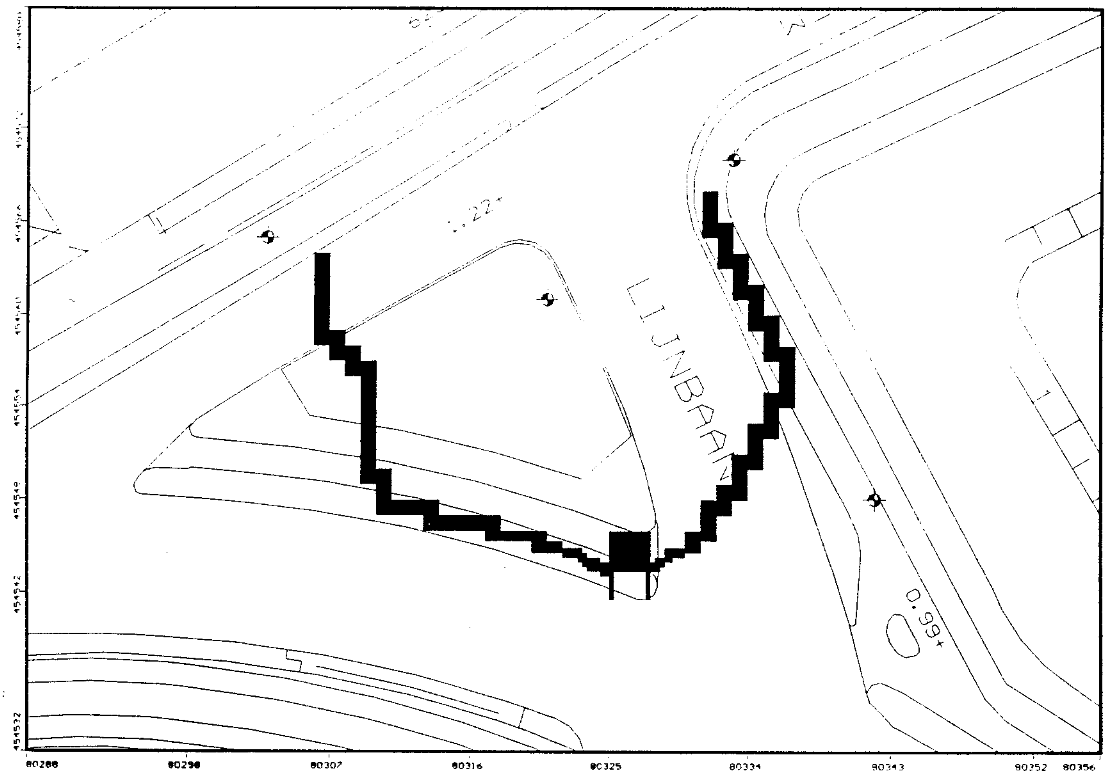


Fig. A2. Dimensions of passive 'Funnel and Gate' system.

Funnel depth

In accordance with the basic project plan [Consortium 'Funnel and Gate', Basic project plan In situ bioremediation of contaminated groundwater by 'Funnel and Gate', November 1997] two variants were computed at the initial phase:

- variant 1: the sheet pile wall of the funnel is sunk down to the basic peat (complete funnel);
- variant 2: a 'hanging' funnel, where the sheet pile wall of the funnel is not sunk to a confining layer (the basic peat).

Both variants have a 'hanging gate', which means a gate that is not sunk to the separating layer but is finished at a shallower level.

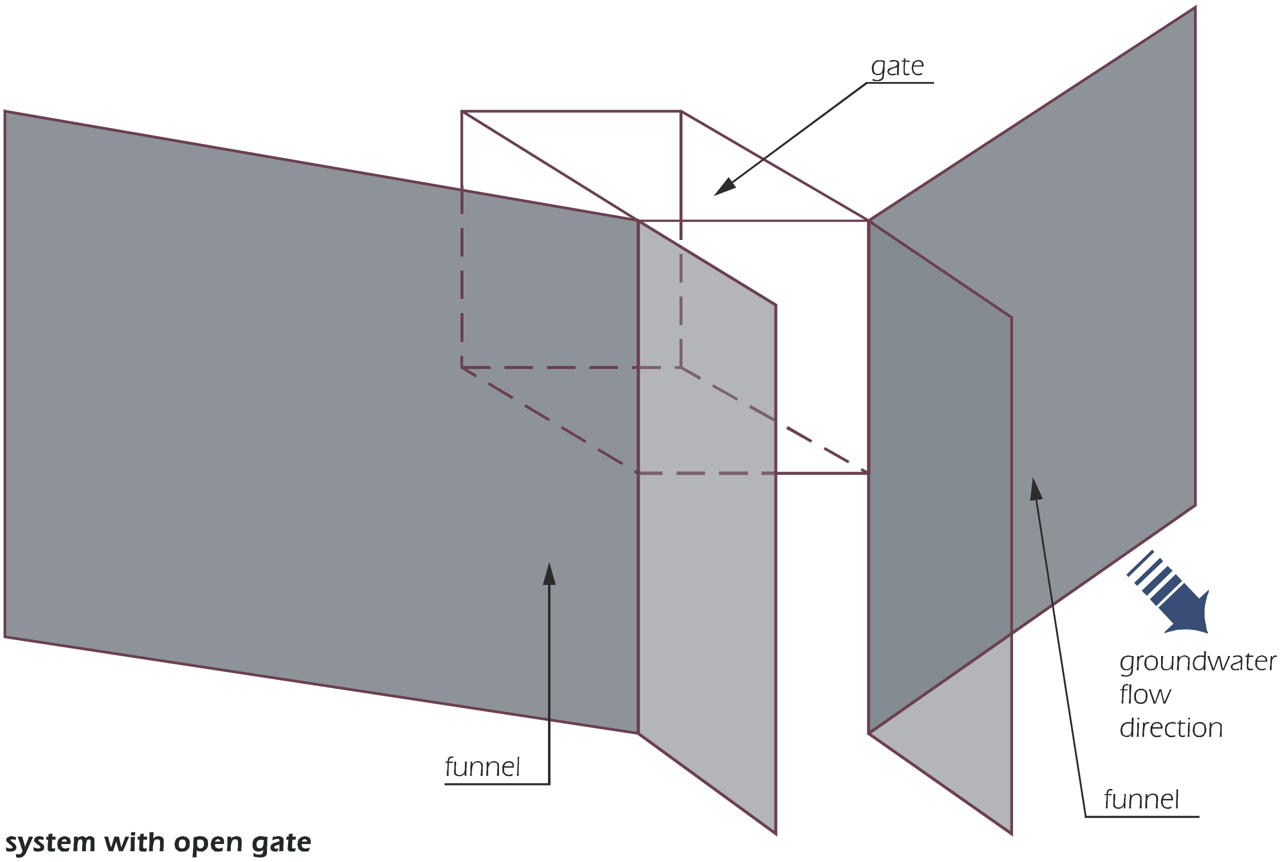
The calculations with the groundwater model showed that using a complete funnel was the only way to prevent contaminants from leaking out under the structure. With a hanging funnel groundwater from the retention zone is flow underneath the funnel.

Depth of gate structure

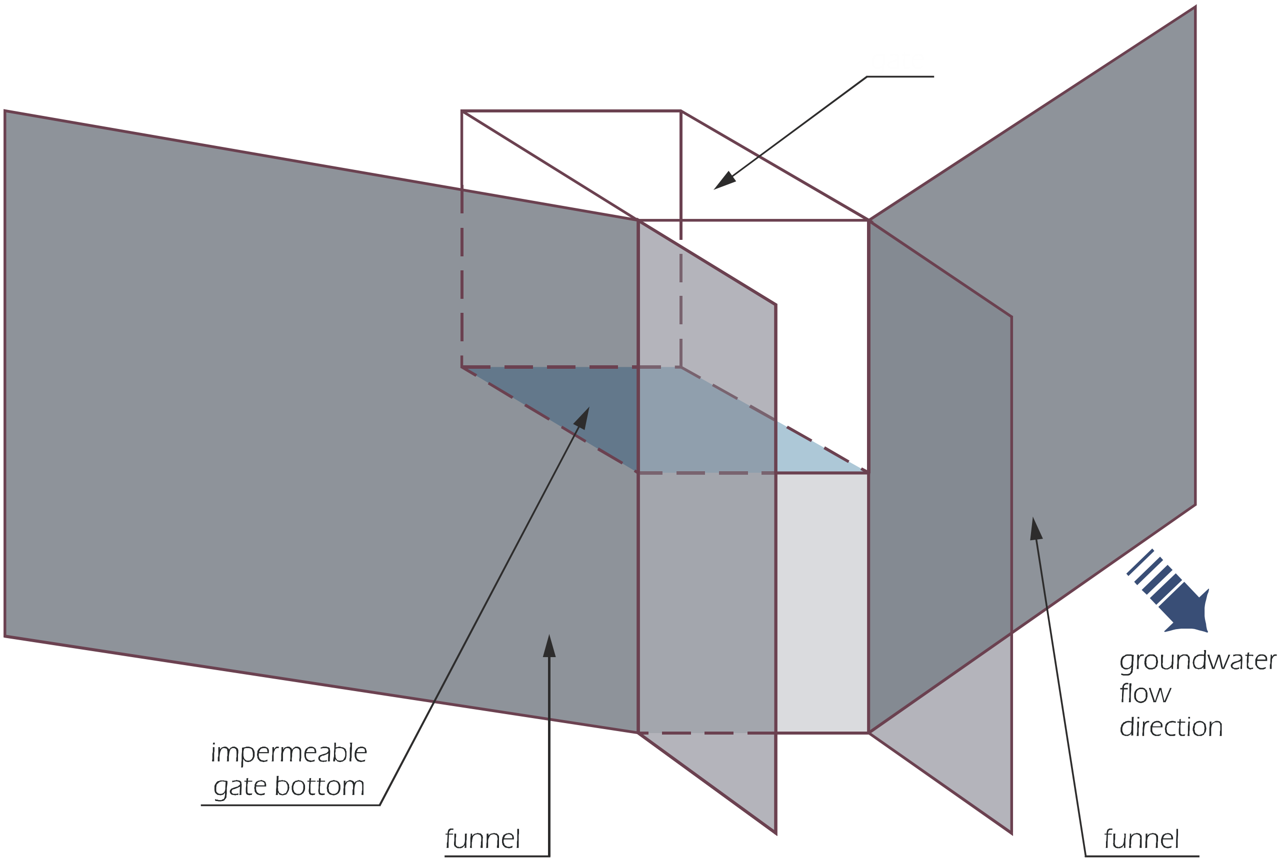
Two options for creating a hanging gate were then investigated (see Fig. A3), namely:

- variant 1a: the space under the gate is open, which means that clean groundwater can flow out under the gate;
- variant 1b: the space between the bottom edge of the gate and the basic peat is confined.

Model calculations show that variant 1a will only function if the gate is installed to a minimum depth of 11.5 m below normal Amsterdam level. With a gate depth of 7.5 m below normal Amsterdam level variant 1b appears to meet the design requirements. Variant 1b was the preferred option for constructional and financial reasons. This variant was therefore worked out into a final design.



system with open gate



system with confined space under gate

Fig. A3. Schematically assessed gate structures.

Active system

A number of aspects of the design process for the active 'Funnel and Gate' variant are also described in the remediation plan. However, as also shown in Figure A1, this process is more complicated than for the passive variant. The main reason for this is that 'the knobs on the system can be turned' at will because the extraction rate is variable, whereas in the passive variant the driving force behind the system (the natural groundwater flow) is fixed. Three aspects of the design process for the active 'Funnel and Gate' variant are discussed below.

Remediation period and flushing frequency

The aim of the active 'Funnel and Gate' system is the functional remediation of the retention zone within a period of 30 years. This aim will have been achieved when the concentration of components of mineral oil or individual BTEX components, for example xylene, in the influent from the gate is below the intervention value.

Mathematical model

The mass balance for a component (i) in the retention zone is calculated using the formula:

$$M_{i(t)} = M_{i(t-dt)} - V_w \cdot F \cdot M_{fi(t-dt)} \cdot e \cdot S/1000$$

with:

$M_{i(t)}$	is the concentration in soil at time t (mg/kg d.s.);
$M_{i(t-dt)}$	is the concentration in soil at time t-dt (mg/kg d.s.);
V_w	is the volume of water in 1 kg saturated soil (l/kg);
F	is the number of times one kg of soil is flushed during time interval dt (-);
$M_{fi(t-dt)}$	is the mass fraction of component (i) in the pure product (-);
e	is the efficiency factor, defined as the quotient of the measured concentration in the groundwater and the balanced concentration (-);
S	is the solubility of a component in (µg/l).

Parameters

- *Mass fraction:*
  The mass fractions of the individual components of the contamination were determined using the oil characterization system described in the soil survey [Consortium 'Funnel and Gate', Actualisatie verontreinigingssituatie, December 1998]. The mass fractions of the various components change constantly during the remediation. The background to this is described in the NOBIS report on oil characterization [CUR/NOBIS,1998].

- *Solubility:*
  The calculation of the remediation period was based on the most critical substance. In the calculation use was made of the knowledge gained from the I&D (Imbibitie & Drainage) project CUR/NOBIS, 1997]. The solubility levels calculated in the oil characterization (soil samples 811 and 819 in the soil survey) are considered representative of the contamination. The content of xylenes in soil sample 811 differs greatly from the content in soil sample 819. On the basis of other soil samples it was decided that soil samples 811 and 819 were representative of 42 % and 58 % respectively of the total load.

- *Efficiency factor:*
  The efficiency factor was determined on the basis of the results of the oil characterization of samples 811 and 819 and the contents measured in the groundwater at the site of cone sipper location 908. Here it was assumed that from a spatial point of view the contamination was of a homogenous composition. The magnitude of the efficiency factor derived from this is 0.23.

Results

The relationship between the flow rate through the retention zone and the remediation period was determined for different contaminant loads. The results are given in figure 5 of the main report (see subparagraph 3.4.3) which shows that a remediation period of 30 years requires a minimum flow rate of 4 m^3/day through the retention zone.

System dimensions

Funnel length

The dimensions of the 'Funnel and Gate' system are based on a remediation period of 30 years in order to make the system as extensive as possible. The cost 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 extraction rate. The capacity of the gate is determined by the extraction rate and it is also found that the length of the funnel depends on both the extraction and the infiltration rate (upstream of the gate).

With regard to the calculations required for the active variant, the groundwater model used has the following limitation: the infiltration is brought into the first aquifer as a complete source. Because the infiltration is carried out at the top of this aquifer, the calculated groundwater flow rate in the retention zone has to be adjusted. To make this adjustment, a simple multi-layer model was created, in which the retention zone is treated as a single layer. The result is that the groundwater flow rate calculated in the MODFLOW model has to be increased by between 25 % and 40 % in the top layer, depending on the extraction and infiltration rate. In figure A4 the calculated groundwater levels are shown at a extraction and infiltration rate of 15.0 and 11.25 m^3/day respectively (75 % of the volume extracted is infiltrated).

The following working methodology was adopted to determine the contours of the selected funnel length. The following calculations were made for a remediation period of 30 years:

1. the appropriate flow rate through the retention zone (Q_r);
2. the extraction rate in the gate (Q_{opt}) needed to achieve Q_r;
3. the length of the funnel.

The length of the funnel was determined for the following extraction/infiltration regimes under the stated hydrological limiting conditions:

1a. $Q_{gate} = 0{,}5 \cdot Q_{opt}$, $Q_{inf} = 0$, Q_{opt} is calculated at item 2 above;
1b. $Q_{gate} = 0{,}5 \cdot Q_{opt}$, $Q_{inf} = Q_{gate}$.

2a. $Q_{gate} = 2 \cdot Q_{opt}$, $Q_{inf} = 0$;
2b. $Q_{gate} = 2 \cdot Q_{opt}$, $Q_{inf} = Q_{gate}$.

The funnel length was determined for each regime. The assumption was that the longest funnel would be the determining factor for the design. It was found that situation 1b with a total funnel length of 22 m was representative.

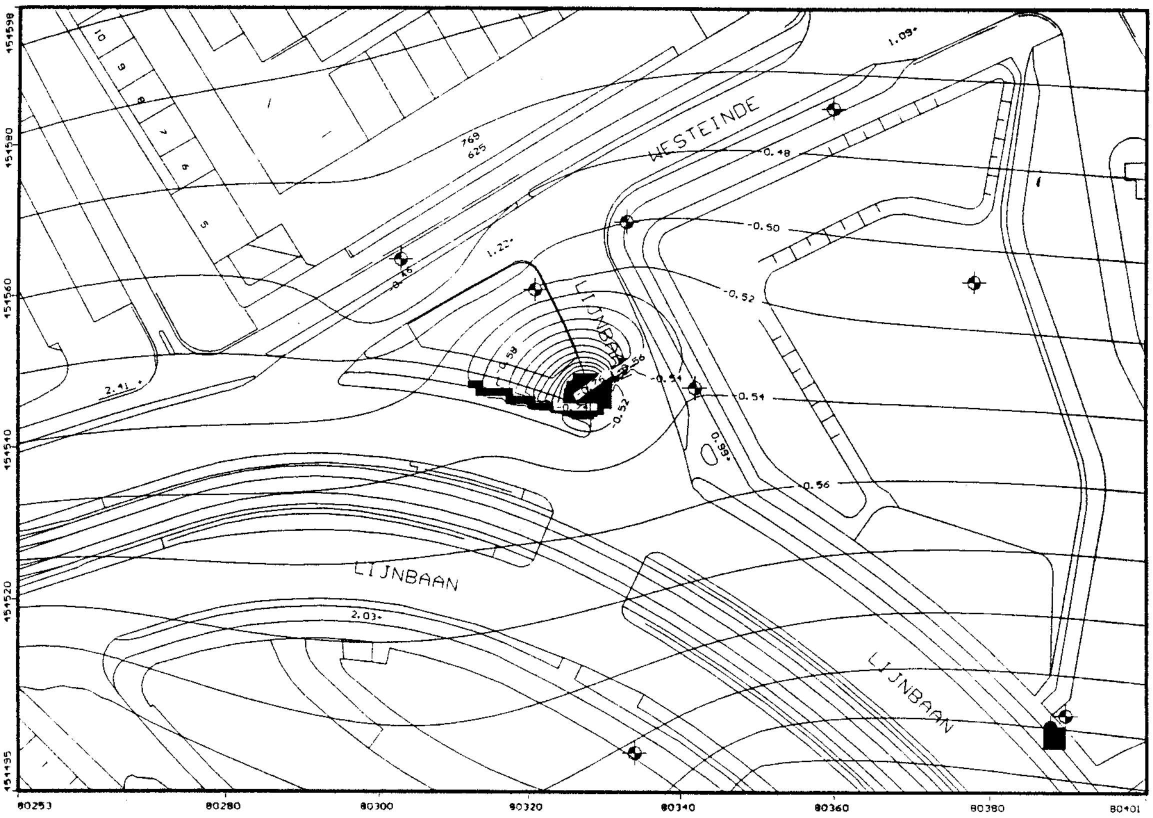


Fig. A4. Calculated groundwater levels in active 'Funnel and Gate' variant.

Funnel depth

By activating the system the funnel depth can decrease. However, a more shallow funnel requires a greater abstraction rate for preventing flow from the retention zone under the system. The effect of the funnel depth was determined at varying funnel depths (about 7 to 16 m below normal Amsterdam level). An optimum is found at about 7 m below normal Amsterdam level. At this depth a thin, resistant aquifer was encountered, which forms a satisfactory base for the bottom of the funnel.

Gate dimensions

The time taken by groundwater contaminants (mineral oil and BTEX) to break down in de gate is 4 days. For the results of laboratory experiments on biological degradation see report 'Afbraakexperimenten grondwater Lijnbaan/Westeinde te Den Haag' [Consortium 'Funnel and Gate', August, 1998]. Assuming a design flow rate of 15 m^3/day the required net gate capacity is 60 m^3. Together with the programme of requirements that was drawn up this has resulted in an innovative and flexible gate. The structure is shown in figure 8 of the main report (see paragraph 4.4).

Gate structure

General

To take account of the limiting conditions and assumptions a circular gate was designed as this shape has the following advantages:

- the direction of flow of the water entering and leaving the gate is always radial, thereby creating a favourable hydraulic situation. This prevents stagnant zones, etc. from occurring in the immediate vicinity of the gate. It also limits the pressure loss thereby minimising the lowering of groundwater levels near the gate;

- the structure does not need to be 'heavy-duty'. For example, no struts are required as the division of forces exerted by the circular shape of the gate is very favourable.

The internal section of the structure has been constructed so that:

- the water to be treated can be divided as required into one or two (component) flows so that it can be treated efficiently;
- water can flow across the full breadth of the gate (or part of it) in and out of the gate.

Construction

The basis of the gate structure consists of an internal sheet piling ring (diameter approximately 6 m) installed inside an external sheet piling ring (diameter approximately 7 m). The two rings are constructed of steel sheet piling and are driven to a depth of approximately 16 m below normal Amsterdam level (into the basic peat). Inside the steel sheet piling rings three plastic rings are set into a concrete floor. The outermost plastic ring is placed hard up against the internal steel sheet piling ring. The concrete floor, depth approximately 6 m below normal Amsterdam level, forms the underside of the gate. Accordingly, the smallest, medium-sized and largest plastic ring are named ring 1, 2 and 3 respectively.

The gate consists of the following functional components:

- *Inflow and outflow compartment:*
  Perforated steel plates covered with soil-retaining fabric are installed between the two steel sheet piling rings. These steel plates are placed at right angles between the two steel rings to produce segments. Alternate segments will be filled with gravel and the remaining segments will be used as influent and effluent buffers. Once the complete gate structure is in place the sheet piling of the external ring will be withdrawn at the gravel segments. This enables the groundwater to flow either into or out of the gate structure.

- *Pre-treatment unit:*
  The bottom section of the space inside ring 1 will be arranged to accommodate a number of water buffers: two aeration buffers, two intermediate buffers, two clean water buffers and two dirty water buffers. Four sand filters will also be installed to remove iron from the influent after aeration and remove any sludge from the effluent.

- *Remediation compartment:*
  The remediation compartment is formed by the space between the internal steel sheet piling ring (with ring 3 attached to it) and ring 2. Baffles are installed inside (at right angles between the rings) to prevent short-circuit currents. Because the groundwater contamination is being biologically degraded the addition of a small amount of oxygen is required. To this end, some aeration baffles and a number of pall-rings will be provided (as carrier material for bacteria). The aeration rate must be limited to minimise stripping of the contamination. It will also be possible to dose nutrients or other substances during the remediation process. The air in the gate structure will be extracted by a ventilation unit and channelled through an active carbon filter before being released into the atmosphere. In the interests of safety the gate is equipped with an emergency system so that in the event of calamities remediated water can be discharged into the sewage system.

- *Switch compartment:*
  Control equipment will be installed inside ring 1. Some equiment may also be set up outside the gate structure. Besides the switching system a number of pumps/ventilation units will also be provided to manipulate water flows. The entire extraction and remediation operation will be controlled and monitored by a telemetry system (CARS: Central Alarm and Recording System).

Flexible work area

In an active 'Funnel and Gate' system an infinite number of combinations of extraction and infiltration rates can be achieved. Only some of these combinations will produce a remediation period of 30 years or less, as shown by the 'scope' of figure A5. This diagram shows the relationship between the flow rate into the gate (Q_{gate}) and the flow rate through the retention zone (Q_r), at different infiltration rates (infiltration shown as a percentage of the influent rate from the gate).

The ratio between Q_{gate} and Q_r depends on the thickness of the retention zone, the water-bearing height of the gate (the distance from the water table to the threshold of the gate) and the stratification of the soil. At the beginning of the design process a gate depth of up to 7.5 m below normal Amsterdam level was assumed, which resulted in a factor of about 5. In the final design the threshold depth of the gate was fixed at a depth of 4.5 m below normal Amsterdam level to take account of constructional requirements. On this basis, a factor of about 3 was established.

The 'scope' in figure A5 is limited by:

- a flow rate through the retention zone that produces a remediation period of exactly 30 years, i.e. 4 m^3/day (lower limit of scope);
- the 100 % infiltration line, which constitutes the upper limit of the scope.

During the operational phase of the 'Funnel and Gate' system the scope can be used as the basis for the extraction and infiltration regime.

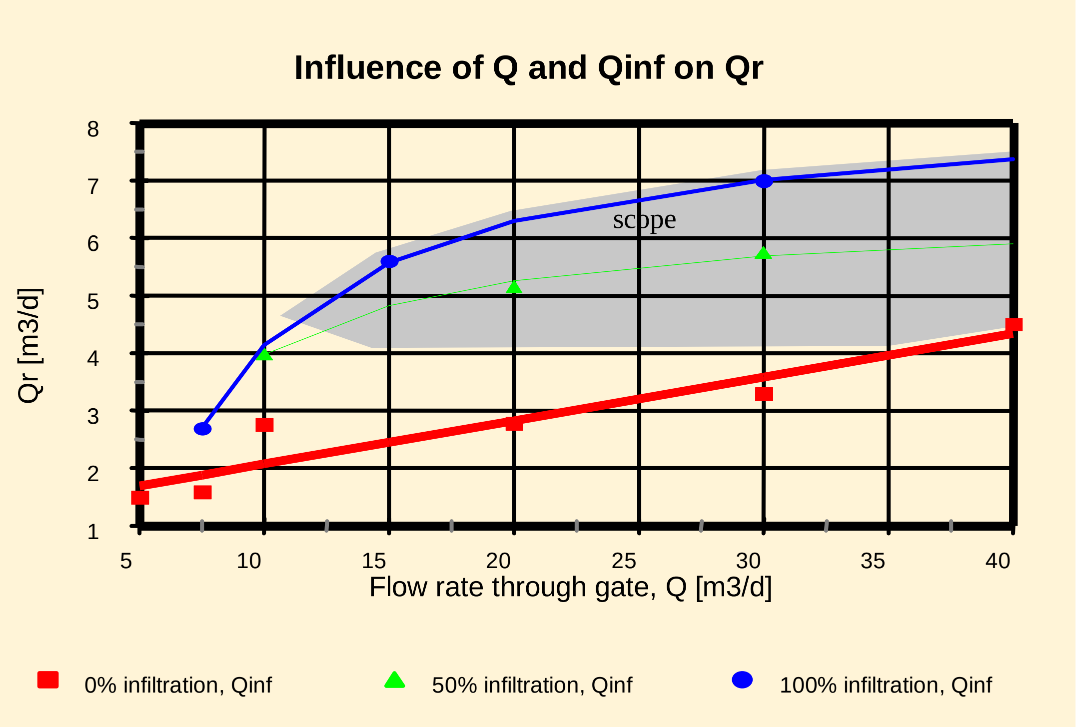


Fig. A5. Scope of 'Funnel and Gate' system, remediation period a maximum of 30 years, gate threshold 4.5 m below normal Amsterdam level.

Management of retardation zone

There is a possibility that the retardation zone will start to spread once the 'Funnel and Gate' system is in operation. Once the system has been installed, standpipes will be sunk to monitor the behaviour of the groundwater contamination. Depending on the results of the series of measurements:

- the retardation zone will be managed by means of stimulated natural degradation or by extracting groundwater (where inadmissible spreading has been found);
- the size of the retardation zone will be ascertained periodically (if no spreading or permissible spreading has been found).

For a comprehensive description of the action plan for the retardation zone, please refer to the amended remediation plan.

APPENDIX B

MONITORING SCHEME

Appendix B provides a list of the analyses, and the frequency with which these are carried out for the different sampling points. Of course this list is preliminary, the actual number of analyses is partially depending on the problems occurring in the 'field' like clogging, precipitations etc.

An overview of the locations for monitoring and the location of the infiltration drains is given in figure B1 below.

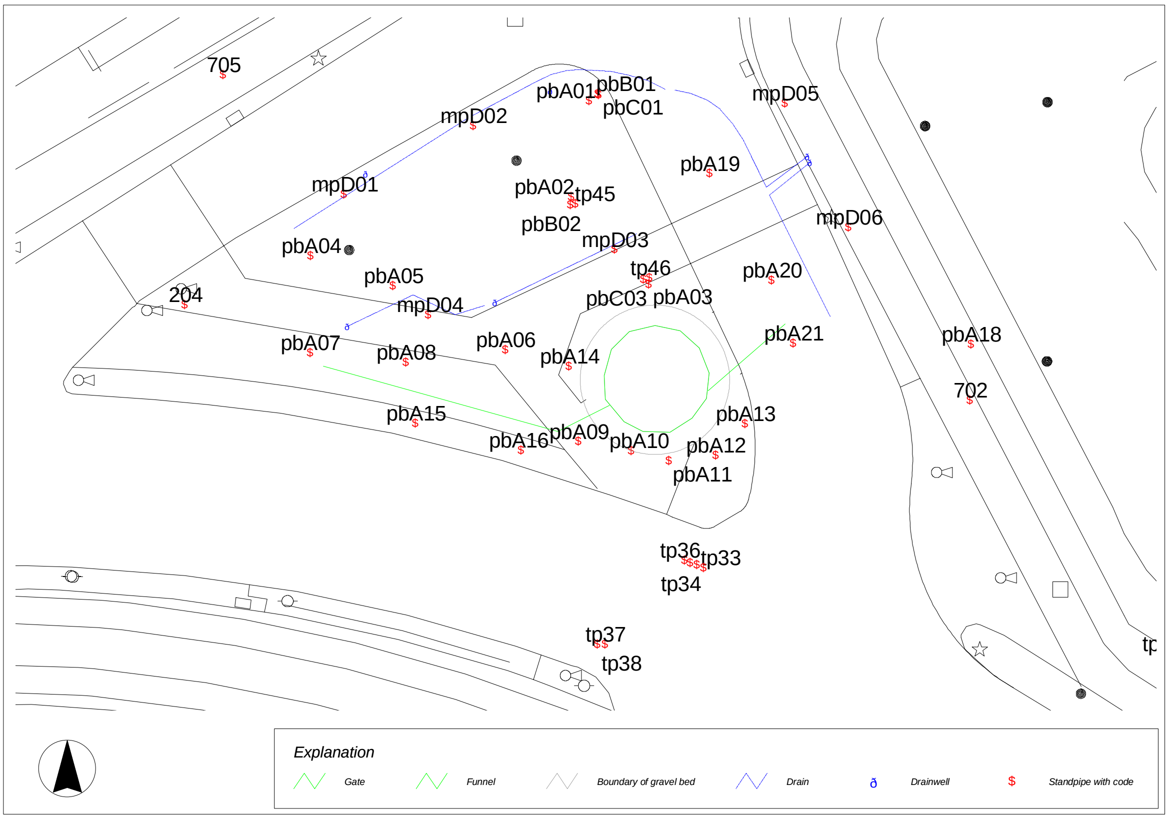


Fig. B1. Location of infiltration drains and monitoring tubes.

Monitoring scheme.

route	standpipes upstream			standpipes upstream			influent at gate			collected influent			effluent at buffer/aeration tank			influent at treatment unit			treatment compartments			effluent at treatment unit			effluent at sand filter			standpipes downstream			standpipes downstream		
sample point	retention zone			retension zone			I1 - I8			V1 and V2			B1 and B2			BL1 and BL2			C1 - C6 C8 - C10			C7 and C11			Z1 and Z2			border retardation			retardation		
no. of sample points	6			12			8			2			2			2			9			2			2			3			2		
period	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
number of samplings																																	
mineral oil				4	8	8	8	8	8	8	8	8	4	4	4	16	16	16	8	8	8	16	16	16	8	8	8	2	2	2	2	2	2
aromatics				4	8	8	8	8	8	8	8	8	4	4	4	16	16	16	8	8	8	16	16	16	8	8	8	2	2	2	2	2	2
N-Kjeldahl	1						1			4	4	4				8	8	8				8	8	8									
cyanide	1						1																										
iron	1						1																		4	4	4						
manganese	1						1																		4	4	4						
carbonate/bicar-	1						1																		4	4	4						
bonate	1						1																		4	4	4						
calcium	1						1																		4	4	4						
sulphate	1						1			4	4	4				1	1	1				1	1	1	4	4	4						
phosphate	1						1			4	4	4				1	1	1				1	1	1	4	4	4						
ammonium	1						1			4	4	4				1	1	1				1	1	1	4	4	4						
nitrate	1						1			8	8	8	4	4	4	4	4	4	8	8	8	4	4	4	8	8	8						
COD	1						1			8	8	8	4	4	4	4	4	4	8	8	8	4	4	4	8	8	8						
BOD	1						1									8	8	8							8	8	8						
undisolved materials																									2	2	2						
AOC																									2	2	2						
MFI																																	
	1						1			4	4	4	16	16	16	16	16	16	4	4	4	16	16	16	4	4	4						
pH	1						1			4	4	4				16	16	16	4	4	4	16	16	16	4	4	4						
temperature	1						1			4	4	4	16	16	16	16	16	16	8	8	8	16	16	16	4	4	4				1	1	1
oxygen	1						1			4	4	4				16	16	16	4	4	4	16	16	16	4	4	4						
conductivity																																	