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Pilot study on: Modelling of the Groundwater Flow and Contaminant Transport in the Area of the Landfill Mastwijk (Linschoten, the Netherlands)

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SUMMARY

The Mastwijk landfill can be regarded as a potential source of contaminants for the pumping water station, situated about one kilometre northeast of the landfill. With the purpose to get insight into the spreading of contaminants originating from the Mastwijk landfill, a pilot study has been performed. In this study contaminant spreading has been simulated with the METROPOL computer package, where the hydrological boundary conditions were taken from calculations with the LGM-model. The groundwater flow field generated by METROPOL is reasonable for this area, and correlates positively with the few measured hydraulic head data available for the area.

From the calculations of contaminant migration the following trends can be indicated:

- The lateral spread of the relative immobile contaminants is no more than a few hundred metres, within a period of a few centuries.
- The relatively mobile contaminants will reach the location of the pumping station within a period of a century; the concentration in the vicinity of the pumping station will be about 0.01 % of the initial concentration at the position of the landfill.

From the pilot study it can be concluded that METROPOL enables a rough indication of the spread of contaminants originating from a specific landfill (in this case the landfill Mastwijk). For risk assessment on the scale of the Dutch landfills, a less time consuming instrument is needed. To this purpose a simpler model can be used (for example a d.s.s. system as has been described in RIVM-report 715207002), or by comparing the spread of contaminants from specific landfills with the results of (for example with METROPOL) pre-calculated standard situations.

SAMENVATTING

De vuilstort Mastwijk kan worden beschouwd als een potentiële bron van contaminanten voor het op een kilometer, noordoostelijk van de vuilstort gesitueerde pompstation. Met het doel inzicht te verschaffen in de verplaatsing van uit de vuilstort afkomstige contaminanten is een pilot-studie uitgevoerd. In deze studie is de verplaatsing van contaminanten berekend met het computer model METROPOL. De hydrologische randvoorwaarden werden ontleend aan berekeningen met het LandelijkGrondwaterModel (LGM). Het met METROPOL berekende grondwaterstromingspatroon is realistisch voor het gebied en komt overeen met enkele gemeten stijghoogten.

Met behulp van de berekeningen van de verplaatsing van de contaminanten kunnen de volgende trends worden waargenomen:

- De laterale verplaatsing van de relatief immobiele contaminanten in een tijdsbestek van enige eeuwen bedraagt niet meer dan enige honderden meters.
- De relatief mobiele en de conservatieve contaminanten zullen binnen een tijdsbestek van een eeuw het pompstation bereiken; de concentratie ter plaatse van het pompstation zal echter niet meer zijn dan 0.01 % van de oorspronkelijke situatie ter plaatse van de vuilstort.

Uit de pilot-studie is te concluderen dat met behulp van METROPOL een grove schatting te verkrijgen is van de verplaatsing van uit een specifieke vuilstort (in dit geval vuilstort Mastwijk) afkomstige contaminanten. Voor risico-analyse van de vuilstorten op Nederlandse schaal is echter behoefte aan een minder tijdrovend instrument. Hierbij kan gedacht worden aan een eenvoudiger model (bijvoorbeeld een d.s.s. systeem, zoals beschreven in RIVM-rapport 715207002), of door de verplaatsing van contaminanten vanuit specifieke vuilstorten te vergelijken met (bijvoorbeeld met METROPOL) doorgerekende standaardsituaties.

1. INTRODUCTION

1.1 General

Research is being carried out by the National Institute for Public Health and Environmental Protection within the theme of waste disposal to determine the risk to public health and the environment from potential sources of soil contamination. Once the risks have been determined, the urgency of the remediation claims can be evaluated to permit prioritization of the known contaminated sites and the potential contamination sources.
The projects concerning landfills and sludge depots within the framework of the "Verwijdering" theme all concern the transport of contaminants emanating from stored wastes, and the threat to the surface water and groundwater resources in the Netherlands due to the emission of these contaminants. The predictions made on the basis of the results are to be used in the development of a simple risk-assessment model, to classify the urgency of remediation of the landfill or depot (*Richardson-Van der Poel, 1994*).
Three main classes of projects have been initiated:

- Inventory of sources of local contamination (point and line sources)
- Modelling of the risk of spreading
- Prioritization of the sites to be rehabilitated

There are approximately 4000 landfills in the Netherlands that are no longer in use. Most of the old landfills have no liners or protective measures installed. The construction and contents of the landfills, and therefore the extent and concentration of the potential polluting sources, are mostly unknown.

The local soil and groundwater are the first to be threatened by leachates emanating from a landfill. As time progresses, the contamination will be spread vertically and laterally via groundwater percolation and general flow regimes. This can threaten potable water through contamination of the groundwater in abstraction fields, as well as surface waters through

seepage.
This pilot study has been performed with the goal to get insight into the spreading of contaminants originating from the Mastwijk landfill. A computer program is used for modelling different aspects of the contaminant transport in the saturated zone.

1.2 Sample site

The sample location landfill Mastwijk is necessary to gain insight into the required accuracy for the calculations involved in the prediction of environmental threat posed by landfill leachate. The chosen sample location in this study lies in the province of Utrecht, southeast of Woerden. The Mastwijk landfill and the drinking water pumpstation Linschoten are located in this area. The availability of data, and the interest of the NV Water Company Middle-Netherlands as well as the Provincial government have had a great influence on the choice. The presence of the landfill and several interesting hydrological phenomena such as the groundwater abstraction wells (Linschoten), a semi-infiltrating river (Hollandse IJssel) and the fact that this area is a polder area make it a good choice as a first exercise (pilot study) in the modelling of landfill leachate spreading with the METROPOL computer package.

1.3 Landfilling and waste disposal

1.3.1 Definition of waste

What is landfilling, exactly, and what defines waste, hazardous waste, and toxic waste; when is a waste considered hazardous or toxic, and when is it considered an environmental threat? Certainly in the European Community, the definitions differ per country, and per province. The Directive on Toxic and Dangerous Waste of the EEC (Directive 78/319/EEC) has not been fully adopted by all member states (*Yong, et al., 1992*). But, the definitions as written include:

(a) 'Waste' means any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force.

(b) 'Toxic and dangerous waste' means any waste containing or contaminated by the substances or materials listed in the Annex to this Directive of such a nature, in such quantities or in such concentrations as to constitute a risk to health or the environment.

(c) 'Disposal' means
  - the collection, sorting, carriage and treatment of toxic and dangerous waste, as well as its storage and tipping above or under ground;
  - the transformation operations necessary for its recovery, re-use or recycling (Article 1).

Waste mostly contains heavy metals and their complexes, organic-halogen complexes, solvents, PAHs, and others. Wastes not included in this directive are: radioactive waste, explosives, animal carcasses and faecal matter, hospital waste, effluents, household waste, mining waste, emissions to the atmosphere and other wastes covered by specific Community rules.

According to the terms of this directive, the Member States are required to draw up a situation report on their disposal procedures every three years, and circulate it via the Commission to the other Member States. Although such a directive may appear to be vague, the specific planning concerning a particular type of waste is not. For example, the laws concerning landfilling are based on the need to "prevent environmental damage caused by landfills and impede the preferential flow of waste towards lower cost disposal sites due to less strict environmental standards...." (*Commission of the European Communities, 1991*). According to the 1991 Council Directive, waste for landfilling is to be classified by origin into one of three classes; hazardous, non-hazardous and inert. Permitting and acceptance procedures are outlined, liability is regulated and an aftercare fund is mandatory.

In the Netherlands, the first code of practice regarding landfilling was made in 1973, and the first laws appeared in 1980. Under the Guidelines for Controlled Landfilling, technical details of landfill construction such as the distance to the average highest groundwater table, manner of layering waste and capping were standardized. In 1985, the laws were extended to cover the IBC concept of Isolate, Manage and Control. Topics such as liners, caps, drainage systems, and other construction details were covered in order to comply with the criteria (*Beker, 1992*). Present landfilling permits fall under two categories; that of the Waste Composition law (Afvalstoffenwet), which concerns domestic/municipal waste, and the Nuisance Law (Hinderwet) which concerns primarily industrial waste. Permits are usually regulated by the Province (*Beker, 1992*).

In the United States, the definition of hazardous waste under the Resource Conservation and Recovery Act (RCRA) is "a solid waste, or combination of solid wastes, which because of its quantity, concentration, or physical, chemical, or infectious characteristics may: (A) cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or (B) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed". It is classified as any waste which "contains substances which are defined as hazardous, or exhibits characteristics of ignitability, corrosivity, reactivity or toxicity".

In Canada, the responsibility for hazardous waste management is partly under the Federal Department of the Environment, and partly under the respective Province Ministry of Environment; resulting in different definitions and classifications for what is hazardous waste, and what is not.

1.3.2 Landfilling

Landfilling is a method of storage of wastes that has been in use for centuries. Modern-day landfills consist of one or two underliners (atop a clay bed) with a leachate collection system installed and a waste body that can be composed of cells which can be filled in different ways; (the most usual is that the day's waste is covered with soil and compacted). After the landfill has reached capacity, it is covered with a thick clay layer, and a thin layer of topsoil in which grass is planted as an erosion barrier. Landfills often have venting systems for gas release to prevent cracking of the clay layer, due to expansion and contraction of the waste body.

In theory, the waste will decompose and dry out after a certain number of years, thereby compacting further. In practice, this is not always the case. Exhumation of the Fresh Kills Landfill in New York has shown that even organic materials can rest more or less intact for much longer than their natural degradation time. *Rathje (1991)* showed photographs of green lettuce that was still intact, although dehydrated, after 5 years of burial. Meat that still had identifiable fats attached after 15 years of burial was found. Leaves that had been raked up 24 years prior to the exhumation, and guacamole (a mexican avocado sauce) that had been buried 21 years before. This raises the question of the efficiency of landfilling: could it be that landfilling, in certain cases, is actually aggravating the problem of waste disposal by interfering with natural degradation processes? Anaerobic degradation processes such as those which generate methane, are much slower processes than aerobic process such as those which are used in composting.

It is presently not known exactly how great a threat landfill leachate is to the environment. Chemical and biochemical processes such as precipitation, complexing, and decomposition all play a role in neutralization and detoxification of some contaminants. For example, does a contaminant plume that takes 500 years to reach an aquifer have the same final chemical composition as a contaminant plume that takes 25 years to reach the aquifer, assuming that the beginning concentrations of contaminants were equal? That seems hardly likely. Will it be more toxic or less toxic?

Landfills pass through four documentable chemically separable phases (*Beker, 1992*):

- an aerobic phase;
- an anaerobic acidification phase;
- an anaerobic, unstable methanogenesis phase;
- an anaerobic stable methanogenesis phase.

The amount and composition of the leachate and gas produced differ in each of these phases. Different areas within the landfill itself can be in different phases at the same time, producing different leachates and gases locally. Due to the extreme complexity of the chemical/biological reactions occurring within the body of the landfill, it is impossible to predict or model what is taking place internally. One can only begin with the estimated landfill emissions, and try to predict their spreading.

Considering the age of the landfill, it can probably be assumed that most of Mastwijk is in one of the methanogenesis phases. However, no specific contaminants were modeled in this study; attention is focused on hypothetical contaminants, characterised by adsorption coefficients.

2. DESCRIPTION OF THE LANDFILL MASTWIJK

The landfill Mastwijk lies in the province of Utrecht, east of the city of Linschoten, in a polder area (see Figure 1). The surrounding land is primarily grassland and farmland.

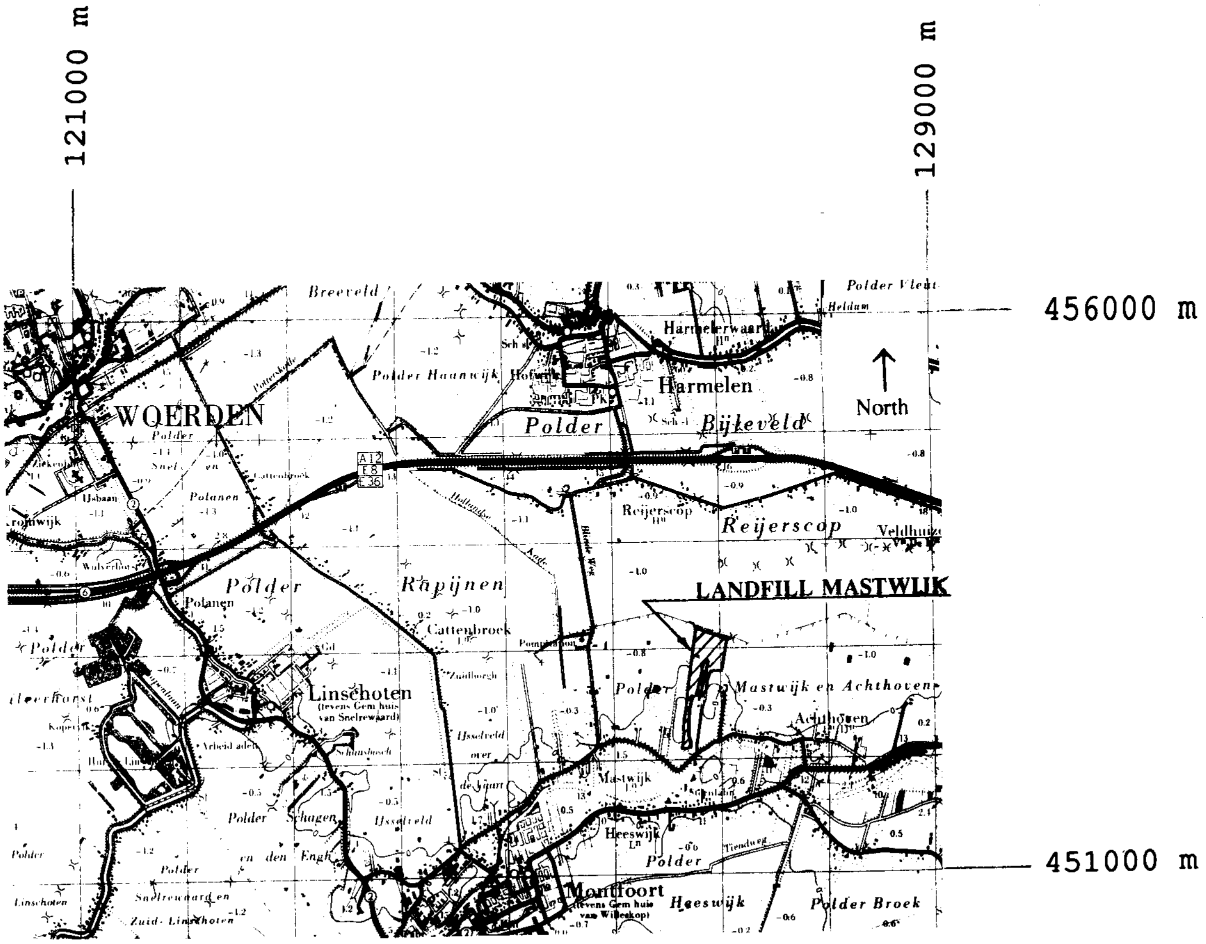

Figure 1: **Situation of the landfill of Mastwijk (scale 1:75.000).**

In Figure 2 the situation is presented in more detail. From this figure it can be seen there is a groundwater pumping station for drinking water located approximately one kilometre northwest of the landfill, which is downstream of the landfill according to the local groundwater flow pattern. The Hollandsche IJssel flows next to the landfill, and has a direct connection to a water body lying atop the landfill.

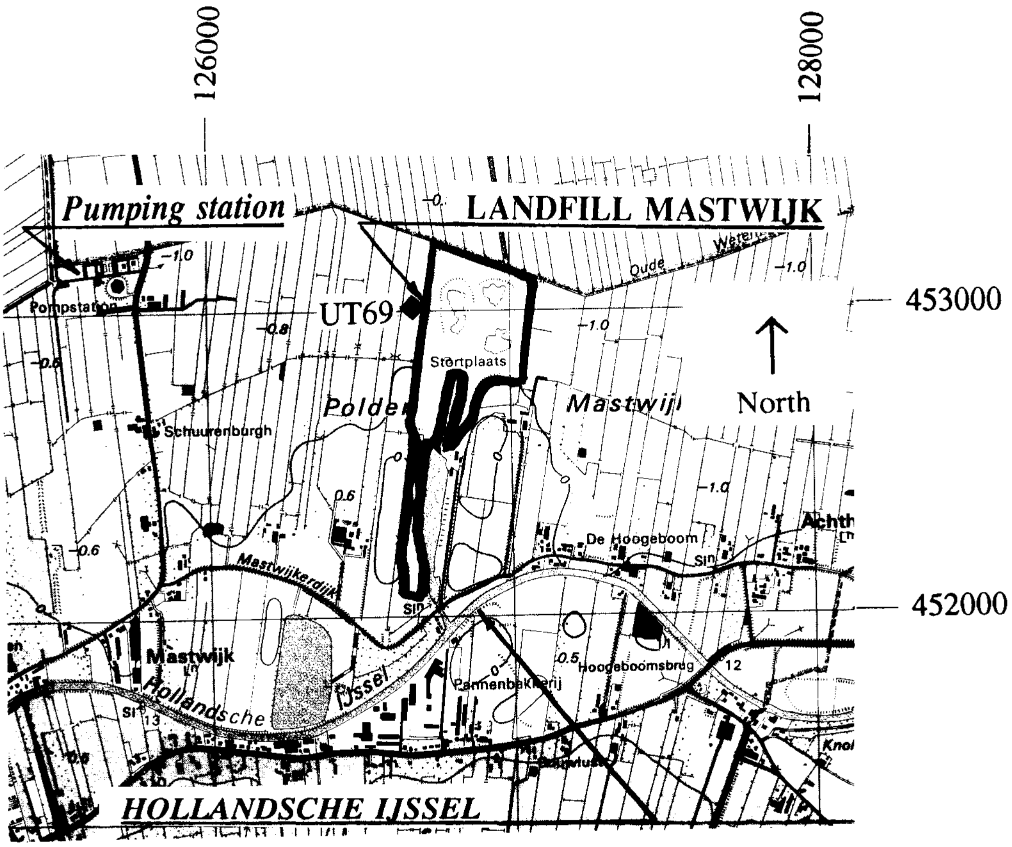

Figure 2: Situation of the landfill of Mastwijk and the pumping station(Scale 1:25.000).

2.1 Site history

Until approximately 1935, the area enclosing the present landfill was a mining area for sand for highway construction by the Amsterdam Ballast Maatschappij. Thereafter it was used for a landfill site for domestic waste for the city of Utrecht. The waste was brought to the site by ship. In 1947, permission was granted under the Hinderwet to the city of Linschoten to deposit household wastes in the landfill. The Province of Utrecht became the owner of the site between 1965 and 1987, when the site was finally closed for waste disposal. It is presently under private ownership.

During the various mining operations, the sand was removed to an end depth of approximately 20 meters below NAP. Materials deposited in the landfill over its history include domestic waste, water purification sludge, market wastes, industrial waste, construction and junkyard wastes and leftover ground from highway construction. The present land surface covered by the landfill is 16 hectares, part of which is under water. The height of the present protruding area is approximately 3 meters above NAP.

A field trip to the site, which was then being covered with dewatered sludge, revealed standing water puddles of yellowish green, viscous water on the elevated section of the former landfill. At the time, a covering layer of sludge was being applied to the northern edge of the landfill.

2.2 Description of the contents

The waste deposited in the landfill Mastwijk over its long history has included quite a variety of different categories. Furthermore, the composition of waste thirty years ago was not the same as the present composition. Market, domestic and industrial wastes have changed; for example, the use of plastics has increased, while other products, such as lead paints on children's toys, have been discontinued or are no longer in widespread use. While it is possible to compile a fairly non-specific list of what was deposited in Mastwijk (market waste, industrial waste, domestic waste, etc.), the physical meaning of this list would be neither quantifiable nor qualifiable.

2.3 Geology

The geological profile of the area is given in Figure 3.

The area is covered by a partially eroded peat layer from the Pleistocene age, with the exception of the area close to the river which is fluvial sands. This lies atop a permeable layer of coarse sand and some gravel (Kreftenhaye formation). Underneath is a semi-permeable clay layer (Kedichem) atop a second permeable layer (Sterksel formation). Underneath is a second semi-impermeable layer (Teugelen) atop a third permeable layer

(Maassluis formation). For more detailed information, consult *Heij (1979)*.

In analogy with the general geology as described above, a site specific geological profile has been constructed based on two deep borings nearby. This profile is presented in Table 1.

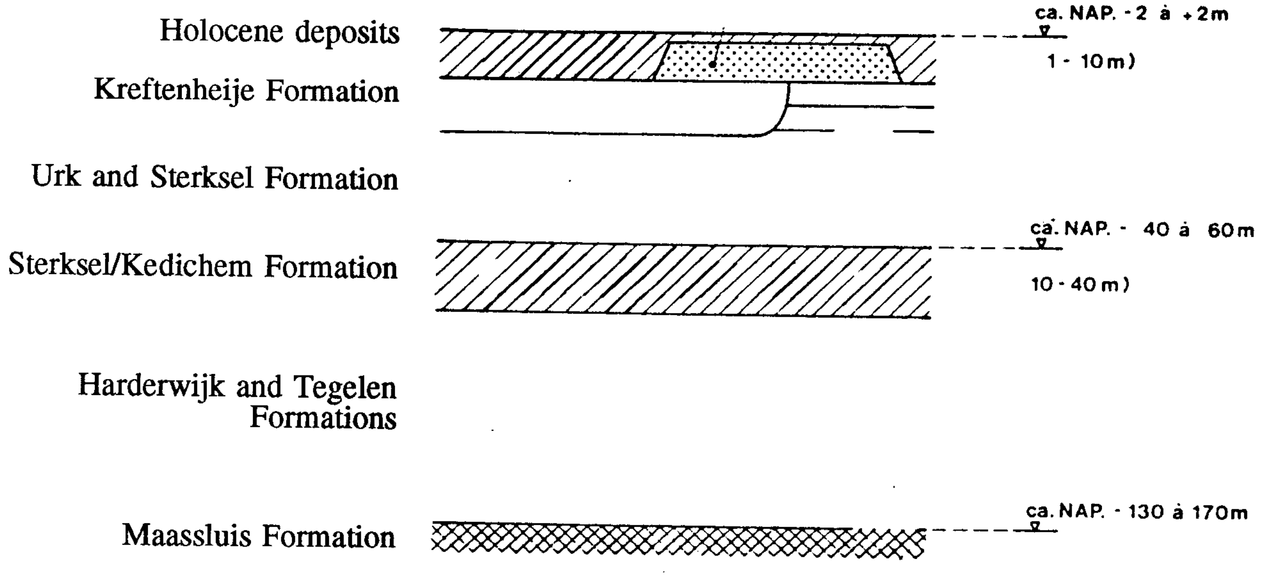

Figure 3: Geological profile of the area where the landfill Mastwijk is situated.

Table 1: Site specific geological profile.

DEPTH (m)	UNDERGROUND MATERIAL
0 - 4	clay
4 - 13	medium sand
13 - 17	coarse sand and gravel
17 - 28	very coarse sand and gravel
28 - 30	very coarse sand
30 - 47	fine sand and clay, with thin coarse sand and clay layers
47 - 55	coarse sand and clay

2.4 Measured Hydraulic Heads

Groundwater heads were measured in three locations in the neighbourhood of the landfill during the period 1988-1989. The heads were measured in several different depths, representing the different aquifers (*Doedens, 1992*). One of the measurement locations was within 400 meters of the landfill, while the other two were within one kilometre distance.

2.5 Measured Contaminant Concentrations

In an attempt to get an idea of how the Mastwijk leachate was moving through the soil, and whether or not an immediate environmental threat was present, chemical analyses from several monitoring wells were obtained from the Water Supply Company Middle-Netherlands (Waterleidingsbedrijf, Midden-Nederland). Detailed chemical analyses were only obtainable for two of the monitoring wells, UT69 and UT70 (see placement on Figure 2). Unfortunately, these detailed analyses were only from one sampling date. The only species that were consistently in excess of the former Dutch B-values (no actual standards, like intervention values, are available for this contaminants yet) in both monitoring wells (i.e., were found in groundwater samples from each filter) were potassium, ammonia, barium, and orthophosphate. Excesses of sodium were found in UT70. Species appearing in only one filter were considered to be artifacts.

Barium has been found in the groundwater in other locations in the Netherlands in concentrations ranging from 5 to 2500 (μg/l), the latter of which is far in excess of the concentrations measured in the monitoring wells at Linschoten. Barium is an element that is often used in well drilling fluids, which could have been deposited in the landfill (the wells in the vicinity have been pulse-drilled).

Benzene and phenol were found in excessive amounts in all of the filters of one of the monitoring wells, but not one that was on the edge nor atop the landfill.

The environmental threat of excessive sodium and/or potassium is hard to quantify. Sodium is often found in high concentrations in the Netherlands, due to the seawater intrusion in some areas. High potassium could be due to the use of animal manure for

fertilizer.
In Figures 4 and 5, relative (scaled) concentrations (i.e., multiplied or divided by a multiple of ten to obtain a value between 0 and 20) of the chemical species were plotted in a depth profile to obtain a general idea of how far the leachate has moved. The distribution of chemical species in the depth depends on a combination of the species characteristics and the type of aquifer material, as well as the time elapsed since the percolation was begun. The aquifer characteristics were obtained from the boring logs for the wells, as schematised in Table 2.

Despite the fact that only detailed analyses from one sampling period and two monitoring wells were available, some general conclusions about the leachate emanating from the Mastwijk landfill can be drawn:

Potassium

There is a relatively high potassium concentration at lower depths; however, the distribution with depth is irregular. Because there is no reason why potassium should be less strongly bound in the deeper, clayey layers, which would explain the higher solute concentrations, one possible explanation is that the leaching process has reached the stage where the front of the plume has already passed through the upper layers of the upper aquifer, and there is no more potassium leaching from the landfill.

Orthophosphate

There is a homogenous, low-concentration profile for orthophosphate. Phosphate ion binding takes place on clay minerals and sesqui-(hydr)oxides. However, there is no significant change in the phosphate solute concentration to indicate stronger sorption in the clay layers. A possible explanation can be, that, although phosphate ions are bound rather strongly by clay minerals, the adsorption capacity is relatively poor due to the small edge surface (*Bolt, 1978*).

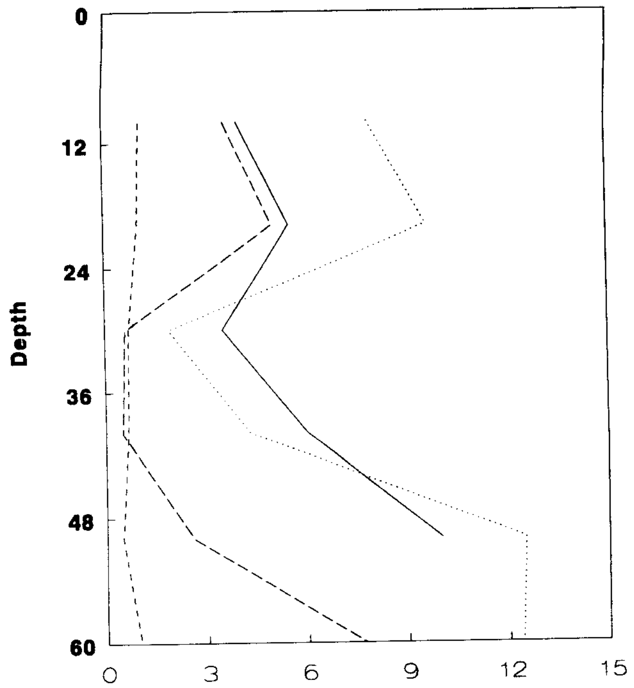

Figure 4: Relative (scaled) concentration of potassium (——), orthophosphate (----), nitrate (— — —) and barium (....), as a function of depth for monitoring well UT 69.

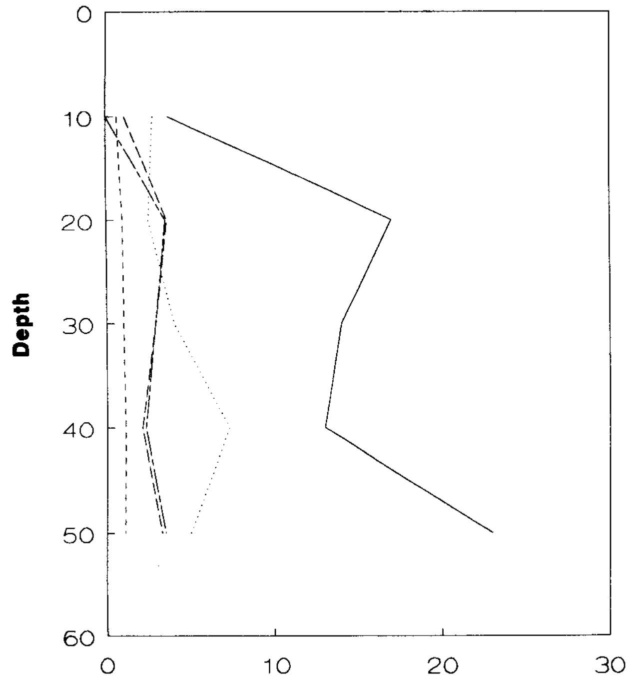

Figure 5: Relative (scaled) concentration of potassium (——), orthophosphate (----), nitrate (— — —) and barium (....), as a function of depth for monitoring well UT 70.

Ammonia

There are slight increases in the ammonia concentrations in the depth ranges 10-20 meters, and again at 40-50 meters. The same theory probably holds for ammonia as for potassium; the ammonia has percolated down through the profile. The slight increase in the depth range 10-20 meters can be attributed to the lack of sorbents in the coarse/gravel layer.

Barium

No specific trends are seen with barium concentrations.

In general, it can be concluded that the leaching process has been underway for a long period, and that the leading edge of the contaminant plume, at least for this rather mobile contaminants, has passed the depth of the monitoring filters in the upper aquifer.

In order to determine if the raised level of these species could have had another source, water quality data for the Hollandsche IJssel was obtained from the Province of Utrecht (*de Bles, 1992*), and the RIVM report concerning the general ground-water quality in the Netherlands was reviewed (*Beugelink et al., 1989*). No indication was found that the source was other than the landfill.

3. CALCULATIONS USING METROPOL

3.1 METROPOL

In order to make predictions about the leaching of components from a landfill, a modelling code was necessary that encompassed three-dimensional flow through porous media (groundwater flow) as well as solute transport and adsorption, both in transient and equilibrium conditions.

METROPOL (**ME**thod for **TR**ansport **O**f **Pol**lutants, *Sauter et al., 1993*) which simulates the three dimensional flow of groundwater is based on the finite element method. The model consists of a package of computer programs for preprocessing, simulation and postprocessing. The preprocessing package includes programs for mesh generation and refinement and data distribution over a given mesh. The simulation package contains programs for steady state and transient groundwater flow with constant density or transient flow with transport of dissolved salt or adsorbing and decaying species at low (tracer) concentrations. The postprocessing package includes programs for particle tracking and the generation of contour plots in two-dimensional cuts. Only the programs used in this study are shortly mentioned below.

Of the preprocessing package the following four programs are used:
METROMESH : a three-dimensional mesh generator;
METROREF : a program for automatic mesh refinement;
METROPRE : a program for the generation of large input data files for distributed data;
METROWELL : a program for the generation of an input data file for injection/extraction wells.

From the postprocessing package, three programs are used:

METROPART : calculates three dimensional particle trajectories in a steady state velocity field;

METROPLOT : plots the results of the calculations as contours, velocity vectors and/or particle trajectories in two-dimensional cuts;

METROREAD : enables inspection of the unformatted output files generated by the different programs and generates plot files of time profile graphs.

Two simulation programs are used which are described below.

3.1.1 METROPOL-1

METROPOL-1 is a program for the simulation of steady state groundwater flow with constant liquid density. METROPOL-1 computes hydraulic heads or pressures depending on the input given by the user. The differential equations to be solved are the mass and momentum balances of the liquid phase. The conductivity (permeability) tensor, the porosity and the viscosity are allowed to vary in space. Sources (sinks) are point sources (sinks) and must be situated in nodal points. All parameters are time independent. It is possible to specify a no flow boundary, to fix the head (pressure) at the boundary or to prescribe the flux, simulating precipitation and/or evaporation.

3.1.2 METROPOL-4

METROPOL-4 is a program for the simulation of the transport of tracers (low concentration solutes) by groundwater. METROPOL-4 computes mass fractions of the solutes, taking into account linear adsorption and first-order decay. In this case, the flow field, which is used as input for METROPOL-4, is a result of computations with METROPOL-1.

Linear equilibrium adsorption is taken into account by the retardation factor R, which is given by the relation:

$$R = 1 + K_d \left(\frac{1-n}{n} \right) \rho_r , \qquad (1)$$

with:

ρ_r : rock density [M/L^3], taken as 2650 kg/m^3,

K_d : linear adsorption partition coefficient [L^3/M],

n : porosity [-], taken as 0.4.

Retardation factors and decay constants can vary in space. Sources (sinks) are point sources (sinks) and must be situated in nodal points. The velocity field is constant in time. It is possible to specify a no flow boundary and to fix the mass fraction at the boundary. A constant mass flux at the boundary can be simulated by introducing point sources at this boundary.

Three-dimensional meshes are generated by METROMESH and refined by METROREF. The allocation of the head values for the top surface to the nodal points in the finite element grid is done by the program METROPRE. METROWELL distributes the discharge of the pumping wells from the Linschoten pump station to the nodal points. Simulation of the flow problem is done by METROPOL-1 which produced head values in the nodal points of the mesh and a velocity field in the domain. METROPOL-4 uses this velocity field to solve the transport problem. Different retardation factors are used in order to simulate the behaviour of different contaminants. Once the simulation has been done, results can be presented in a number of ways: contourplots of heads and/or concentrations and/or velocity fields and/or projections of trajectories in 2-d cuts (METROPART and METROPLOT); time profiles of head and/or concentrations in selected nodes of the finite element mesh (use METROREAD).

Typically, this report does not contain detailed information about the physical and mathematical background of the equations and numerical methods on which the programs are based. For more detailed information on these subjects, the reader is referred to *Sauter* *et al. (1990)*; *Sauter et al. (1993)*; *Hassanizadeh (1986a)*; *Hassanizadeh (1986b)* and *Hassanizadeh and Leijnse (1988).*

3.2 Groundwater modelling

The area coordinates defining the Metropol modelling domain were taken from the Geological Survey of the Netherlands (Rijks Geologische Dienst, or RGD), Topographic Map 31G, Woerden. The north/south coordinates range from 123000 to 129000, and the east-west from 450000 to 455000. This encompasses an area of 30 square kilometres. The depth ranges from the surface to approximately 270 meters deep.

The Landelijk Grondwater Model (LGM) is a national groundwater model for the Netherlands which contains GIS databases of geologic, hydrologic and cadastral data. The LGM calculates groundwater flow with a resolution of 1 square kilometre. Data calculated with the LGM were used for boundary conditions in the more localized METROPOL modelling study. The LGM is thoroughly described in *Kovar et al. (1992).*

In this study, hydraulic head values were taken from the LGM, for the external lateral surfaces of the modelling domain. The geological base was left as a no-flow boundary. The head values for the top surface of the domain were digitized in polygons (see Figure 6) from a 1978 polder head map produced by the RGD, using ARC-INFO. The polygon files were converted to an ASCII file, and entered into the program by the METROPRE pre-processing program. The head for the Hollandsche IJssel was given as NAP, as was the water body atop the landfill that has a direct connection with the IJssel. Internal heads were computed by METROPOL.

Conductivities for the permeable layers were taken from formations on the RGD maps. Conductivities for the semi-impermeable layers were calculated by formulas based on the type of formation. These values were entered into a coarse 3-dimensional mesh, the elements of which were 1 kilometre in length in the X and Y directions, and divided into formations in the Z direction. As the mesh was further refined, the values were interpolated by METROPOL. The final mesh contained 20160 elements. The number of nodal points in X,Y,Z-directions are respectively 41, 37 and 15.

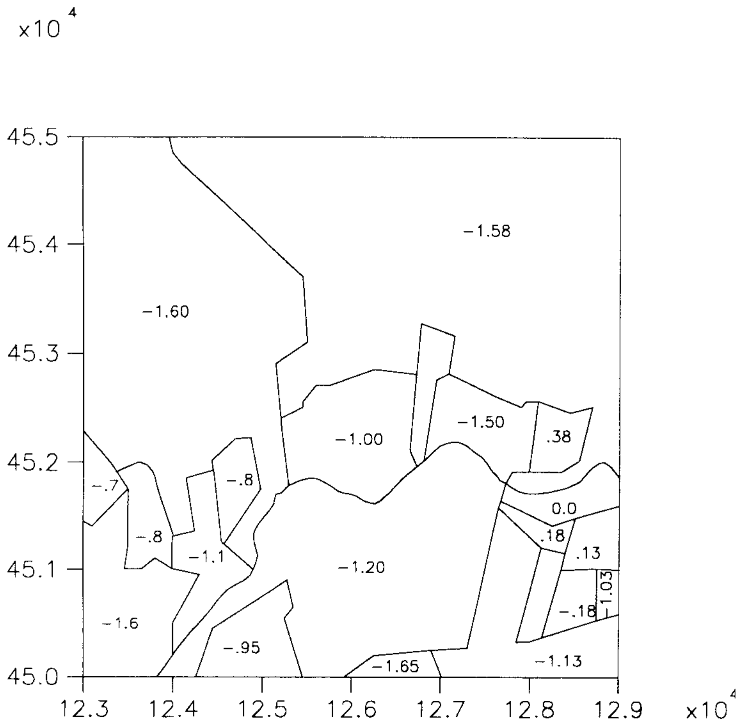

Figure 6: Digitized head values (metres) for the top surface of the calculation domain (RGD coordinates in metres).

Since the surface of the modelling domain is a polder area, precipitation was not taken into account except on the landfill itself. In a polder area, the groundwater levels are strictly maintained to prevent land subsidence, so excess rainfall is drained by pumping. Effective rainfall on the part of the landfill above water was estimated at 1 mm per day. Infiltration from the Hollandsche IJssel was estimated as 0.24 cubic meters per meter length per day.

The groundwater abstraction of the 16 pumping wells from the Linschoten pump station near Montfoort was simulated by the METROWELL package. The estimated discharge was given as 120 m^3/day/well. The total groundwater extraction was divided over the number of filters. These were entered into the mesh by X,Y,Z-coordinates, and some of the filters were vertically adjusted to fit the geologic strata as defined in the mesh. In Figure 7 the refined mesh on the top surface is presented with the placement of the pumps from the pumping station and the location of the landfill.

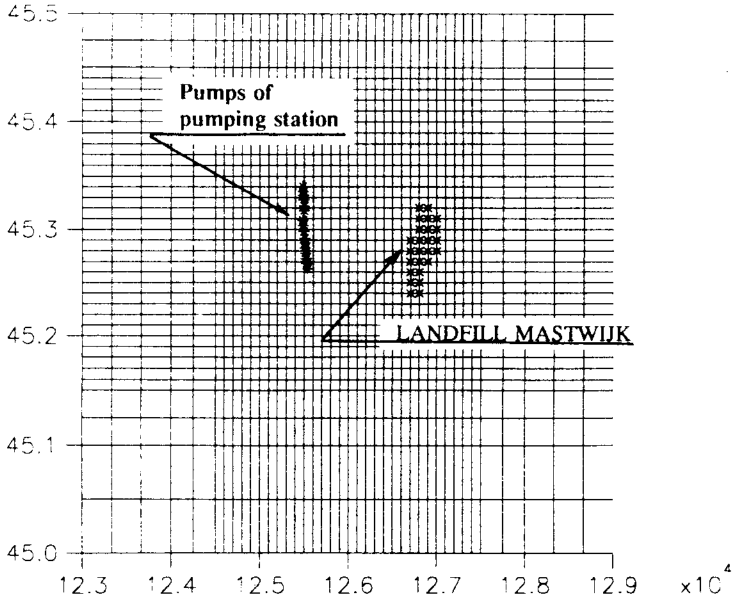

Figure 7: The refined mesh on the top surface with the location of the landfill and placement of the pumps from the pumping station (RGD coordinates in metres).

3.3 Transport modelling

Leaching behaviour was simulated by treating the contaminant as a non-renewable mass fraction at the surface. As rain infiltrated the surface of the landfill (constant flux), the contaminant was mixed in with the water, and entered the groundwater system. Due to the fact that this landfill is situated in a former sand quarry and half-covered by a water body, transport in the unsaturated zone was not considered.

3.3.1 Varied adsorption (hypothetical contaminant)

Transport rates differ with different compounds. In order to obtain an idea of the different rates of leaching, several hypothetical contaminants were modeled using different adsorption coefficients. The linear adsorption coefficients used, as well as the actual leachate components they could be said to represent, are listed in Table 2. A hypothetical contaminant that did not adsorb (such as chloride) was modeled as a "worst case" scenario.

Table 2: Linear adsorption coefficients of the hypothetical contaminants considered in this study, possible contaminants that are represented, and mobility of this contaminants.

Kd value (l/kg)	Representative group	Mobility
0.1 0.5 1.0	Volatile aromatics/ Chlorinated hydrocarbons	Mobile to very mobile
100.0 500.0	Heavy metals/ PAH's	Relatively immobile
1000.0	Dioxins, lead	Very immobile

4. RESULTS AND DISCUSSION

Several depth profiles, cross-sections and surface plan views are presented in this chapter. When describing the results reference will be made to Figure 8 for the position of the depth-profile, cross-sections or surface plan views. Because this study concerns a pilot study discussion is mainly based on a qualitative analysis of the model results.

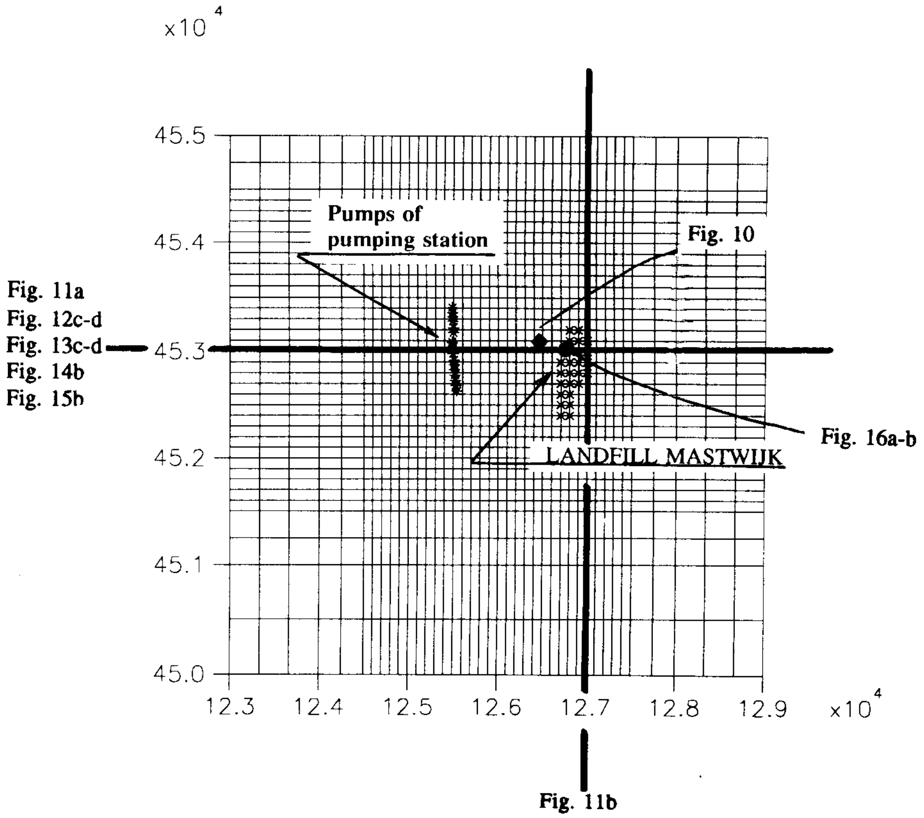

Figure 8: Position of the depth-profile, cross-sections and surface plan views as mentioned in this chapter. The numbers refer to the figures in the following text (RGD coordinates in metres).

4.1 Groundwater modelling results

The subsurface groundwater flow field generated by METROPOL is presented in Figure 9, together with the polder head map for the top surface in the model domain.

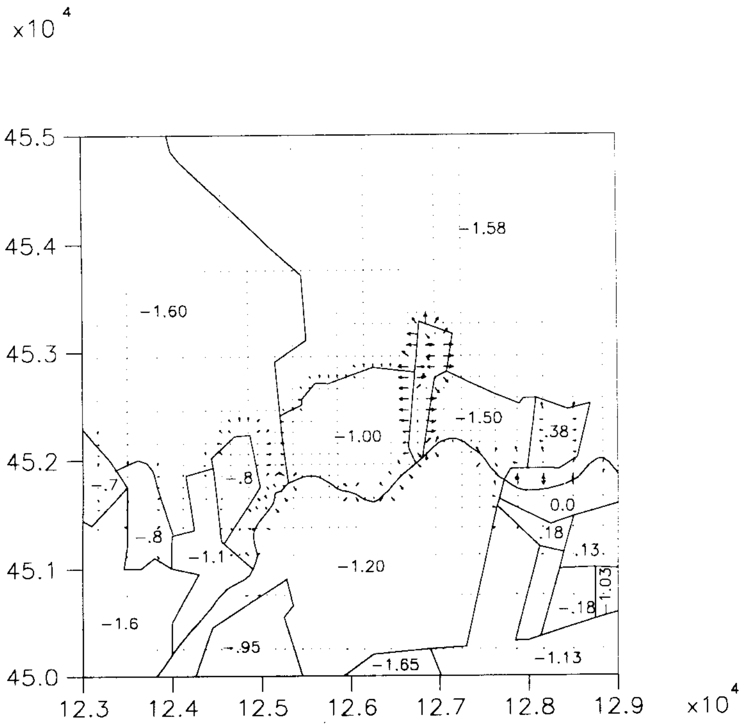

Figure 9: The subsurface groundwater flow field generated by METROPOL, together with the polder head map in metres for the top surface in the model domain (RGD coordinates in metres).

The general trends show infiltration from the river and the landfill. River infiltration is to be expected in a polder area. As stated in Section 3.2, the different polders were digitized in ARC-INFO and entered into the METROPOL program. Due to the schematization of the surface polders, which results in an abrupt change in head over a short distance, a rather large groundwater flow can be seen at these boundaries in Figure 9. Whether or not these abrupt changes in head cause this flow in reality can only be measured in the field. Since these data were not available, it is assumed that for the purpose of these simulations this flow field is sufficiently accurate.

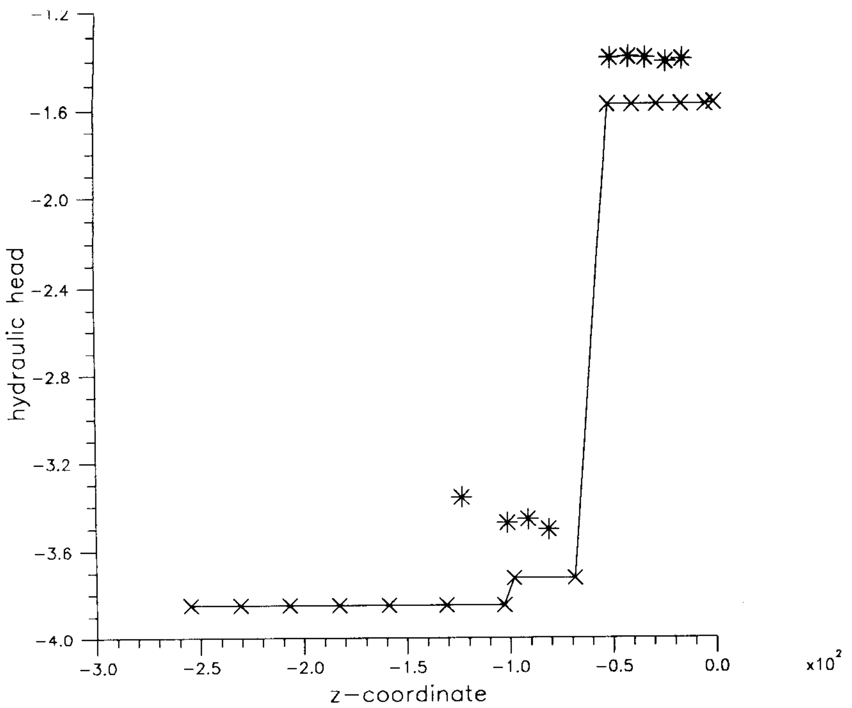

Figure 10: Several hydraulic head measurements (*, in metres) at different depths (Z-coordinate) for a monitoring well with X,Y-coordinates (126458, 453098; for the position see Figure 8) and the calculated heads (X, in metres) by METROPOL (RGD coordinates in metres).

In Figure 10, several hydraulic head measurements measured in the field at different depths are shown in contrast to the heads calculated by the METROPOL programs for a monitoring well with X,Y-coordinates (126458,453098).

The hydraulic heads calculated by METROPOL were reasonably close to those measured in the field. These values were not used for model calibration due to the fact that there were not enough data available to perform an adequate calibration. The boundary groundwater heads were obtained from the validated LGM model for the area, which was performed at a much larger scale.

A part of the resulting flow field from METROPOL, which is used as input for the calculations of the solute transport in METROPOL, is shown in Figure 11a and 11b. The velocities are plotted on log scale (the length of the arrows are scaled according to the log of the velocities magnitudes), so the direction of the velocity field can be better shown. Figure 11a is a XZ-cross-section with constant Y-coordinate 453000 m and Figure 11b is a YZ-cross-section with constant X-coordinate 126700 m.

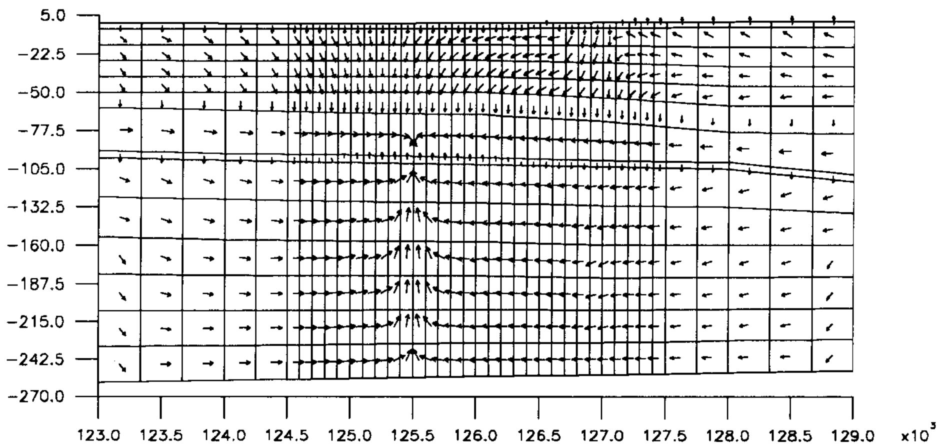

Figure 11a: A part of the resulting flow field from METROPOL (XZ-cross-section with constant RGD Y-coordinate 453000 m); for the position of the cross-section see Figure 8).

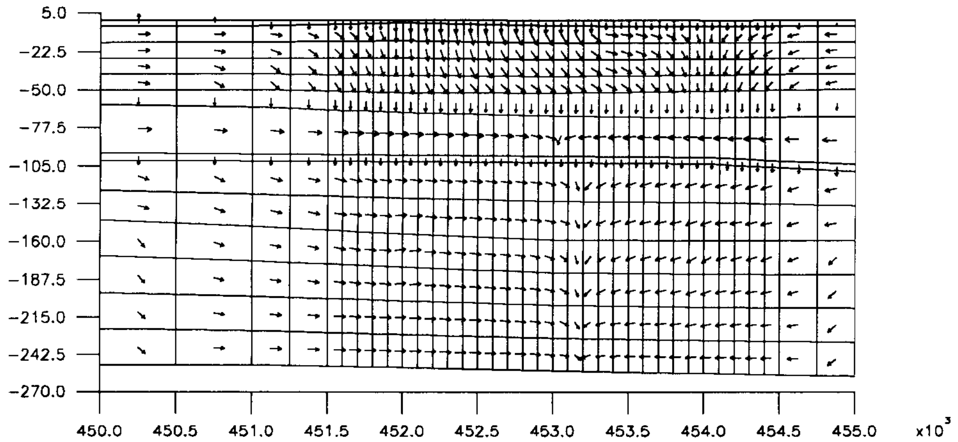

Figure 11b: A part of the resulting flow field from METROPOL (YZ-cross-section with constant RGD X-coordinate 126700 m); for the position of the cross-section see Figure 8).

Examination of the groundwater flow fields shows a generalised groundwater flow toward the pumping station in (Figure 11a), filtration in the area of the landfill (Figure 11b), and seepage in the surrounding polder areas. This is consistent with the physical description of the area. Furthermore, the influence of the thin clay layer at a depth of about 100 m is noticeable. The water flow velocity pattern, as pictured in figures 11a and 11b, is used as an input for the calculation of the solute transport with METROPOL.

4.2 Contaminant transport modelling

All simulations of contaminant migration were performed with the same hypothetical initial concentration of the contaminants of 1.0 (µg/l) in order to compare the spreading of the contaminant. Because linear adsorption is used the results can be scaled to the actual concentration of the contaminant under the landfill. The values of the contours in the contour plots, which are presented here (Figures 12 - 15), are shown in the Table 3. For example contour number 1 shows the isoline of 10^{-4} times the starting concentration of the contaminant under the landfill. The contour plots in the XY-plane have a RGD Z-coordinate between -2.0 and -6.1, the XZ-plane has a constant Y-coordinate of 453000.

To simulate the spreading of several hypothetical contaminants the K_d value has been varied for the different simulations. The K_d value is defined as the relation of the content of a contaminant in/on the solid phase of the underground material to the concentration of the contaminant in the liquid phase (see Equation 1). Hence, the K_d value is a measure for the affinity of a contaminant to migrate through the underground: if the K_d is high, much sorption of the contaminant takes place and transport velocity is low. When, on the other hand, K_d is low, contaminant transport is fast, not hampered by sorption of the solid phase of the underground.

Table 3: Contour lines considered in the calculations.

contour number	values in percent
1	0.01
2	0.10
3	0.25
4	0.50
5	0.75
6	1.00
7	2.50
8	5.00
9	7.50
10	10.0
11	12.5
12	15.0
13	17.5

In Figures 12a to 12d predicted contour lines are shown for a contaminant with a partition coefficient, K_d, of 100 l/kg, after 100 and 500 years. The retardation factor for these contaminants is 400. In Figures 12a and 12b a surface plan view is presented, while a cross-section is given in Figures 12c and 12d. The model has also been run with higher Kd values, but the results does not show any significant spreading. Therefor, the results of these runs have not been presented. The transport over longer modelling periods was also calculated, but due to the uncertainty of the data and the probable changes in land use, the results are considered to be too speculative.

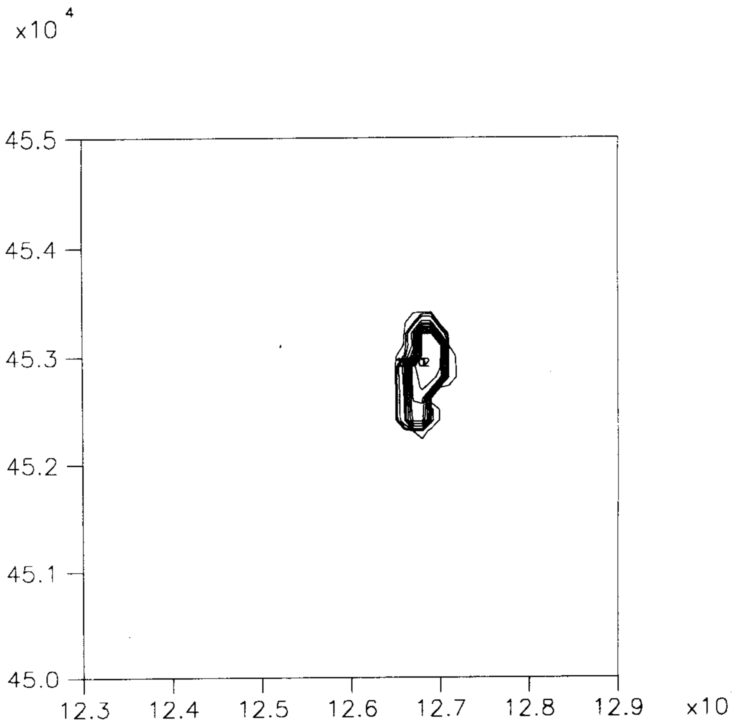

Figure 12a: Contour lines of a hypothetical contaminants with K_d = 100 l/kg after 100 years, in the RGD XY-plane (surface plan view).

From the figures 12 can be concluded that an influence of transport for this relatively immobile contaminants can be found at a distance of at most a few hundred metres from the landfill (an increase with 0.01 % of the initial concentration) and to a depth of at most 100 metre, during a time period of several centuries. This implies that this relative immobile contaminants do not threat the pumping station during a period for at least a few centuries (see also Figure 8). However, these relative immobile contaminants do reach the second (deeper) aquifer within this time period.

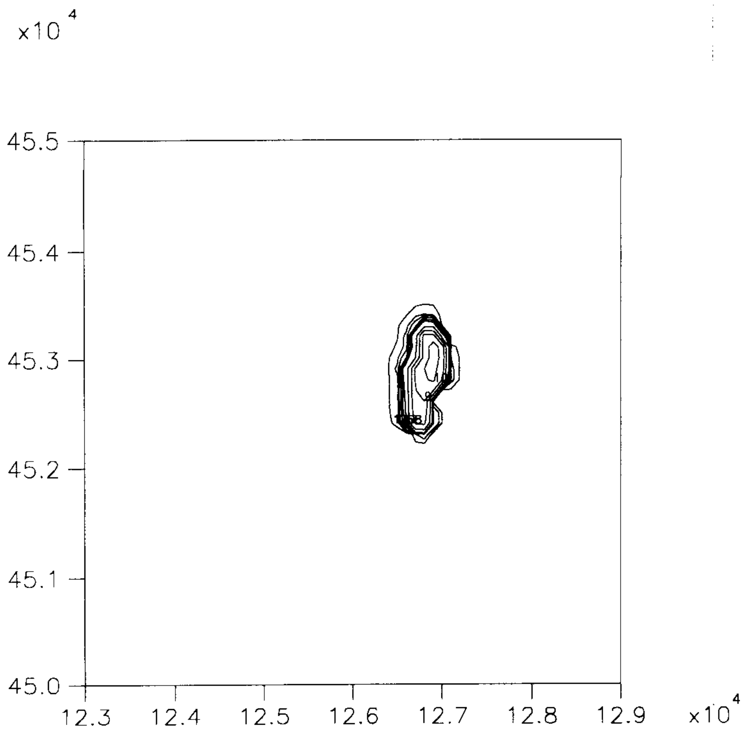

Figure 12b: Contour lines of a hypothetical contaminants with K_d = 100 l/kg after 500 years, in the RGD XY-plane (surface plan view).

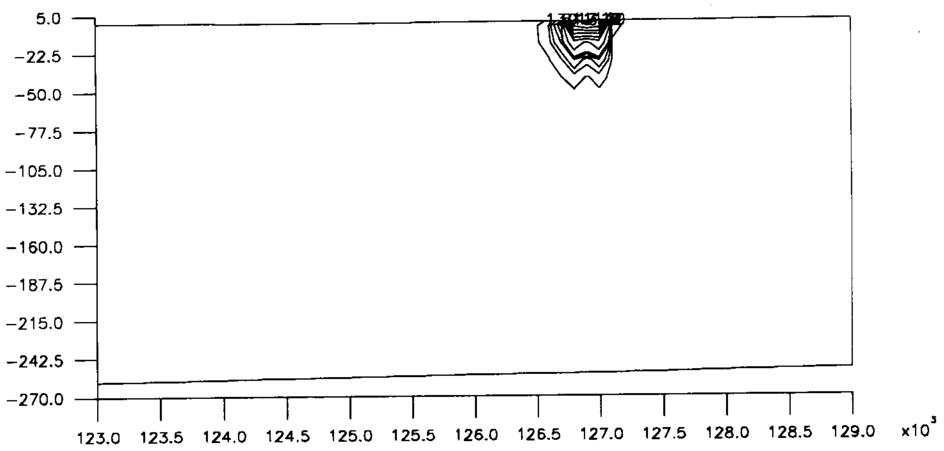

Figure 12c: Contour lines of a hypothetical contaminant with K_d = 100 l/kg after 100 years, in the RGD XZ-plane; RGD Y-coordinate 453000 m; for the position of the cross-section see Figure 8.

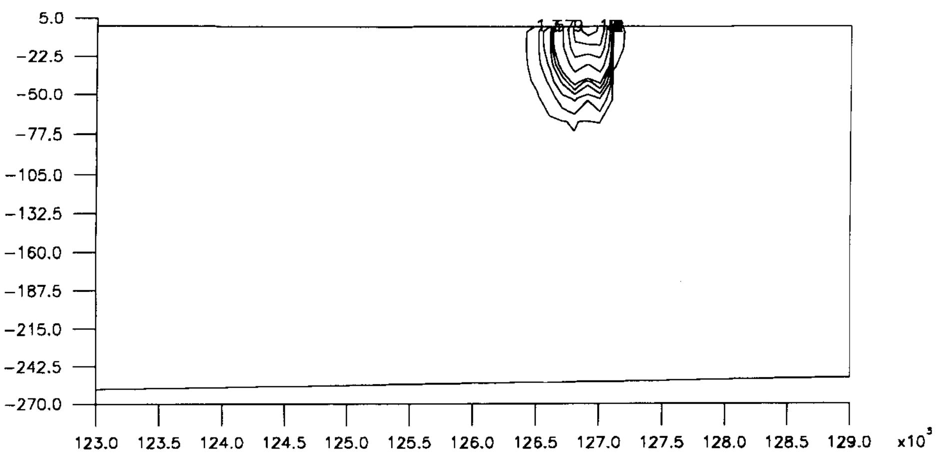

Figure 12d: Contour lines of a hypothetical contaminant with K_d = 100 l/kg after 500 years, in the RGD XZ-plane; RGD Y-coordinate 453000 m; for the position of the cross-section see Figure 8.

In Figures 13a to 13d the contours are plotted for 100 and 500 years for adsorption coefficient 1 l/kg. The retardation factor for these contaminants is 5. Here, in Figures 13a and 13b a surface plan view is presented, while a cross-section is given in Figures 13c and 13d.

For this rather mobile contaminants, some more transport has taken place during a few centuries. Horizontal migration resulted in an increase of contaminant concentrations (0.01 % of the initial concentration, contour line 1) at a distance of more than a kilometre from the landfill, mainly is eastern direction, after a period of one century. This implies that the pumping station comes under the influence of these relatively mobile contaminants. In vertical direction migration took place up to the third aquitard (Formation of Maassluis) within one century. After 5 centuries the highest concentration found in the area, at the position of the landfill, is only 0.25 % of the initial concentration (contour line 3). Furthermore, further spreading in the direction of the pumping station only takes place at very low concentrations (smaller than 0.01 % of the initial concentration). Contaminants has reached the hydrological base, at about 250 metre, after 5 centuries.

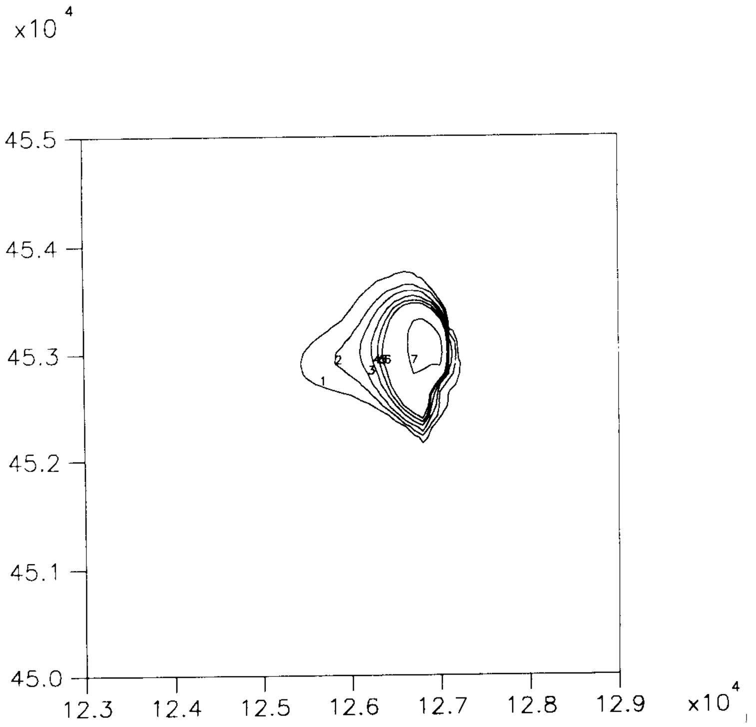

Figure 13a: Contour lines of a hypothetical contaminants with K_d = 1 l/kg after 100 years, in the RGD XY-plane (surface plan view).

In Figures 14a, 14b contours are plotted for a contaminant with Kd value 0.1 l/kg, after 100 years. The retardation factor for these contaminants is 1.4. Here, in Figure 14a a surface plan view is presented, while a cross-section is given in Figure 14b.

Compared to the contaminants with a K_d of 1 l/kg, the contaminants have moved a little further and deeper and have reached the position of the pumping station after a period of a century. At the location of the landfill concentration have dropped after a century to about 0.75 % of the initial concentration (contour line 5), where in the case of a K_d of 1 l/kg concentrations of 2.5 % of the initial concentrations were still found (contour line 7).

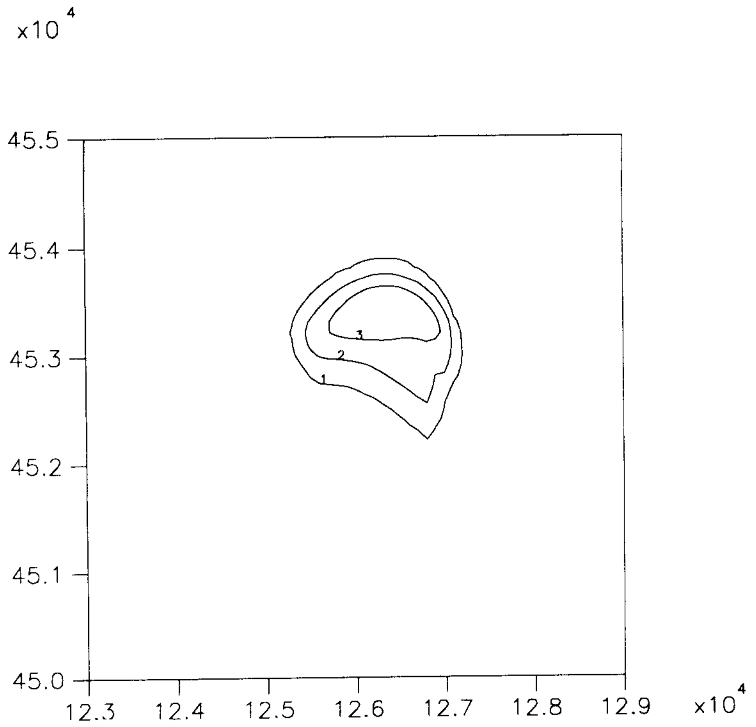

Figure 13b: Contour lines of a hypothetical contaminants with K_d = 1 l/kg after 500 years, in the RGD XY-plane (surface plan view).

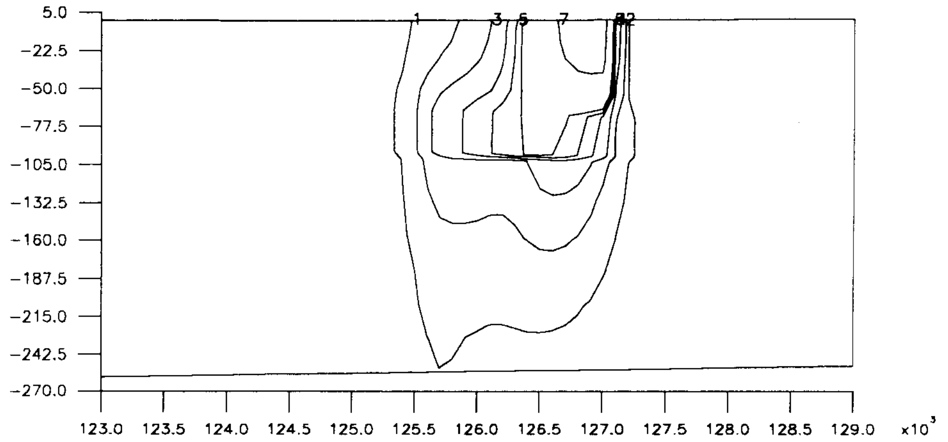

Figure 13c: Contour lines of a hypothetical contaminant with K_d = 1 l/kg after 100 years, in the RGD XZ-plane; RGD Y-coordinate = 453000 m; for the position of the cross-section see Figure 8.

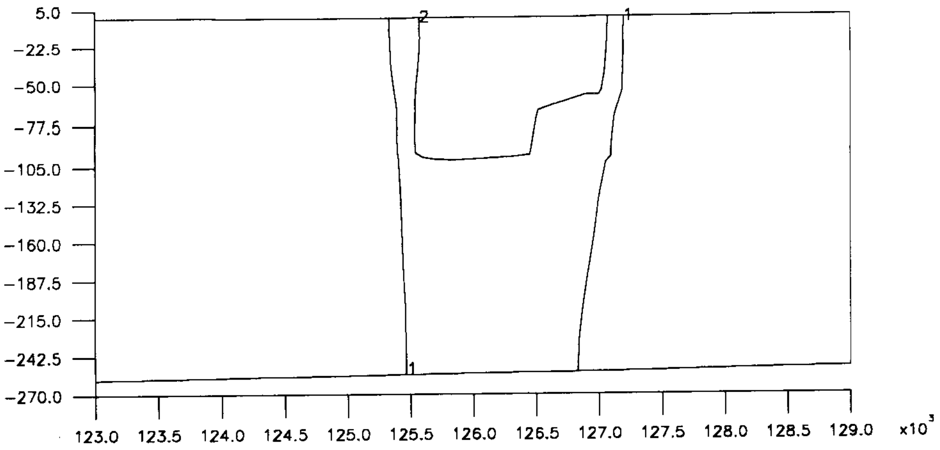

Figure 13d: Contour lines of a hypothetical contaminant with K_d = 1 l/kg after 500 years, in the RGD XZ-plane (cross-section); RGD Y-coordinate = 453000 m; for the position of the cross-section see Figure 8.

In Figures 15a and 15b contours are plotted for Kd value 0.0 (retardation factor = 1) for 100 years. Here, in Figure 15a a surface plan view is presented, while a cross-section is given in Figure 15b.

When comparing with the relatively mobile contaminants, migration of this non-sorbing contaminants has progressed further in time and has reached the position of the pumping station after a period of a century. After a century, only 0.25 % of the initial concentration is left at the position of the landfill.
Note that the contour lines are exactly the same as the contour lines of contaminants with a K_d of 1 l/kg, after a period of 5 centuries. This is due to the fact that the retardation factor for contaminants with a K_d of 1 l/kg equals 5. Because of the assumption of linear sorption the spreading for a contaminant with a retardation factor of 1 (retardation factor = 1) after a time period of a century is equal to the spreading of a contaminant with a retardation factor of 5, after a period of 5 centuries.

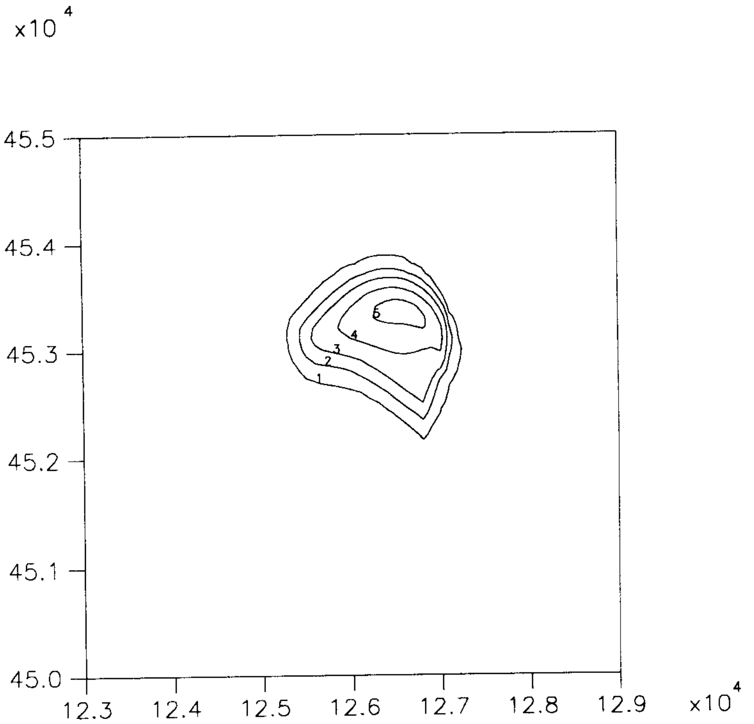

Figure 14a: Contours for a hypothetical contaminant with K_d = 0.1 l/kg after 100 years, in the RGD XY-plane (surface plan view).

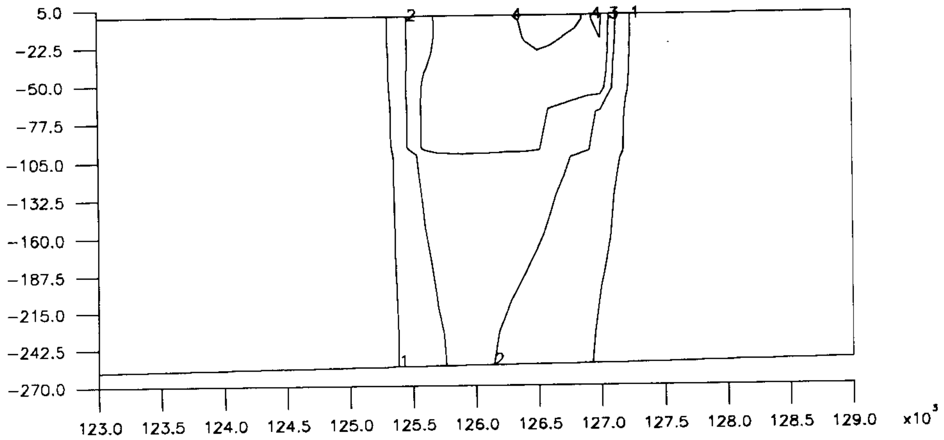

Figure 14b: Contours for a hypothetical contaminant with K_d = 0.1 l/kg after 100 years, in the RGD XZ-plane (cross-section); RGD Y-coordinate = 453000 m; for the position of the cross-section see Figure 8.

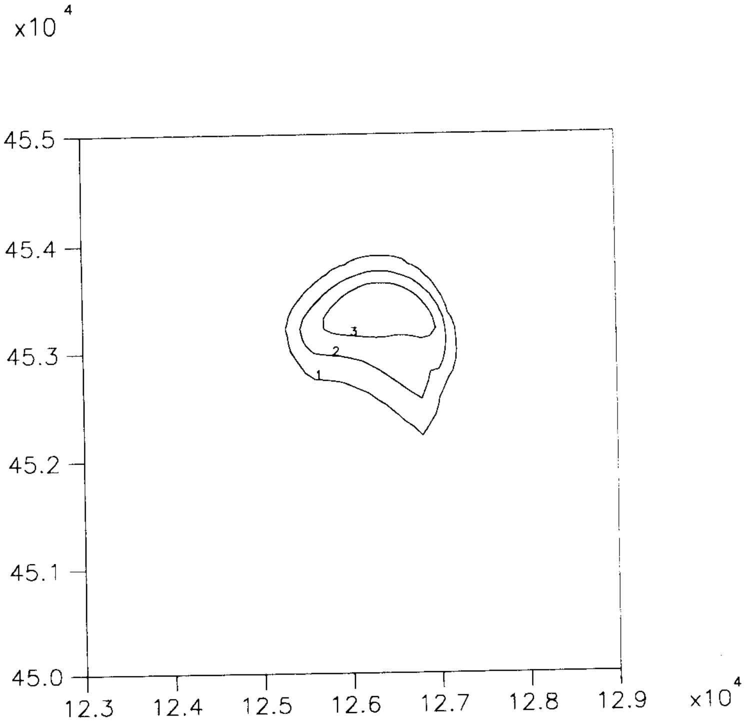

Figure 15a: Contours for a hypothetical contaminant with $K_d = 0$ after 100 years, in the RGD XY-plane (surface plan view).

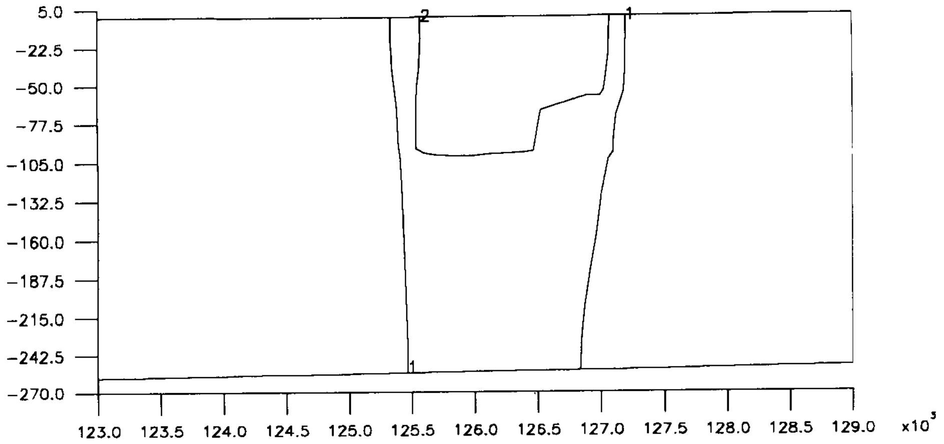

Figure 15b: Contours for a hypothetical contaminant with $K_d = 0$ after 100 years, in the RGD XZ-plane (cross-section); RGD Y-coordinate = 453000 m; for the position of the cross-section see Figure 8.

For Kd values 0.1 and 0.0 the contour plots for 500 years are not shown because the concentration of the contaminant in the plotted plane is below the 0.01% of the starting concentration.

In order to visualize the movement of the contaminants through the nodal points, a time series was plotted for a relatively mobile contaminant (K_d = 1 l/kg) and for a non-sorbing contaminant. The nodal points lying atop each other in both the first upper and the middle aquifers at depth of 100, 105, 130, and 160 metres (break-through curves; see Figures 16a and 16b). The X,Y-coordinates of the position are (126800, 45300).

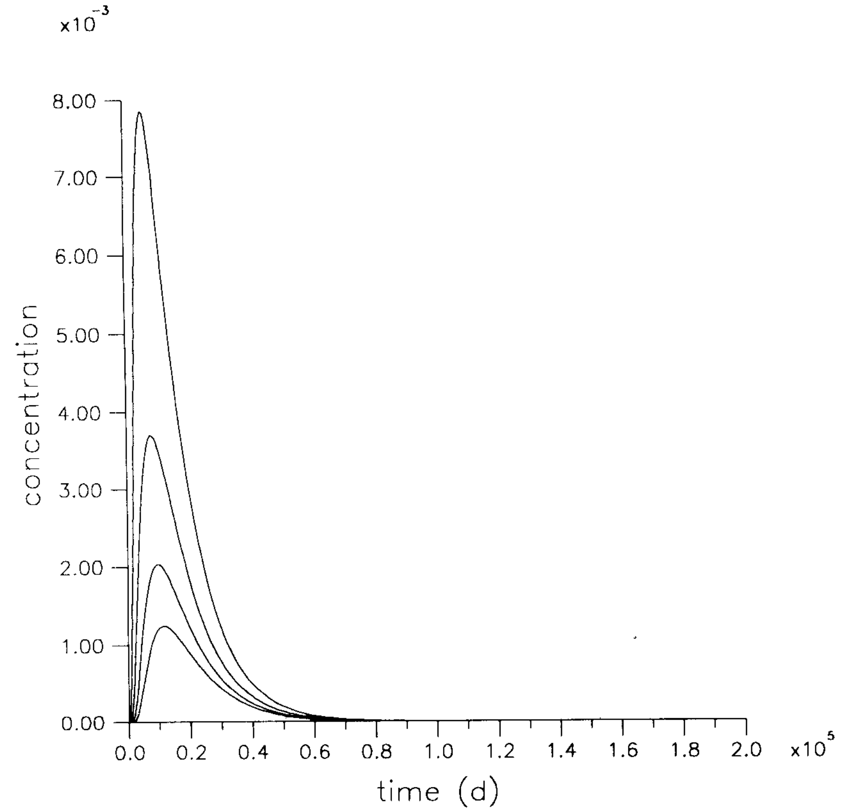

Figure 16a: Time series of concentrations for four nodal points lying atop each other in both the first upper and the middle aquifers for K_d = 1 l/kg; RGD X,Y-coordinates: (126800, 45300); for the position see Figure 8.

These graphs show a smooth downward movement of the leachate plume as the concentration first builds up, then slowly leaches out of each nodal point. Due to diffusion and dispersion peak concentrations are much lower deeper in the profile. Also the effect of the adsorption coefficient on the time the curve reaches it maximum concentration can clearly been seen: for the contaminants with a K_d of 1 l/kg after a period of about 20.000-60.000 days; for the non-sorbing contaminants after a time period of about 10.000 - 15.000 days.

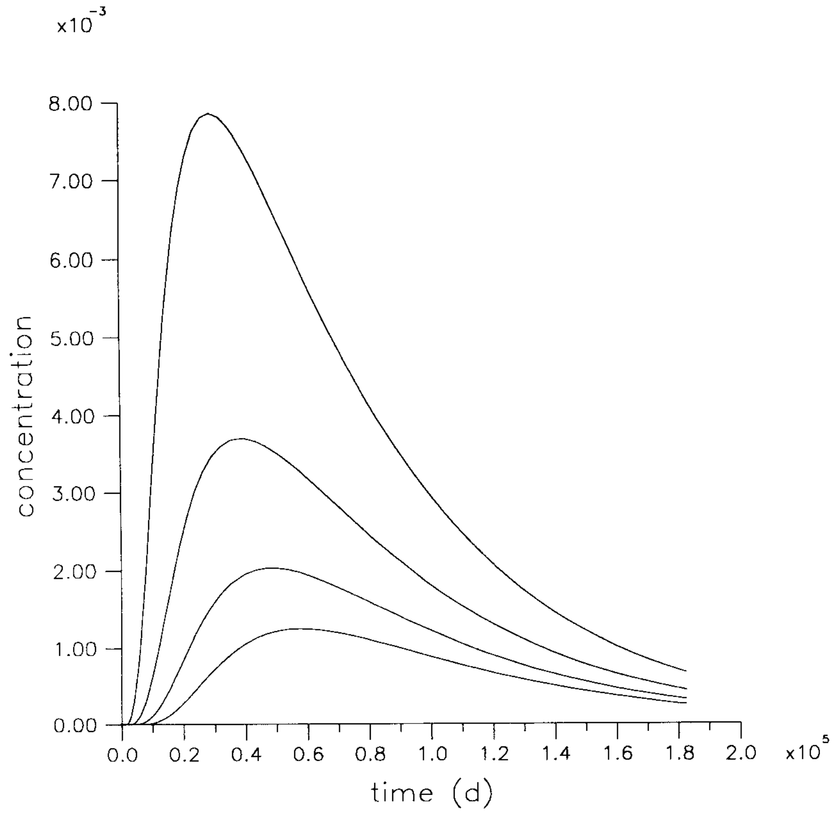

Figure 16b: Time series of concentrations for four nodal points lying atop each other in both the first upper and the middle aquifers for non-sorbing contaminants; RGD X,Y-coordinates: (126800, 45300); for the position see Figure 8.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

With the purpose to get insight into the spreading of contaminants originating from the Mastwijk landfill, a pilot study has been performed, using the computer code METROPOL. Data calculated with the LGM model were used for hydrological boundary conditions.

The groundwater flow field generated by the model simulations is reasonable for this area, and correlates positively with the few measured hydraulic head data available for the area. An attempt to correlate contaminant concentrations sampled from monitoring wells aside and in the vicinity of the landfill was unsuccessful due to the scarcity of significant chemical data. From the calculations of contaminant migration the following main conclusions can be drawn:

- The lateral spread of immobile contaminants is no more than a few hundred metres, within a period of a few centuries.
- The relatively mobile contaminants will reach the location of the pumping station within a period of a century; however, the concentration in the vicinity of the pumping station will be less than 0.01 % of the initial concentration at the position of the landfill.

As a first exercise in the modelling of landfill leachate spreading, the METROPOL model appears to be an useful computer code. However, it should strongly be stated that this pilot study only indicate a possible trend. The composition of the leachate, the precise amount of each contaminant, the exact composition of the aquifer material and the exact groundwater flow cannot be given. This is further aggravated by the lack of available data to calibrate the model.

5.2 Recommendations

For more detailed calculations a more specific description of the underlying layers is found needed, perhaps by scale enlargement or a by modelling a smaller part of the domain (especially in the area around the landfill and wells), using this pilot study results as boundary conditions. This study was performed with a large (30 square kilometre) domain. However, if no better data concerning local head values and chemical analyses of the groundwater are available, further refinement would not yield any significant results.

The effect of adsorption has been simulated, for different hypothetical contaminants. Supplementary studies could include the combined effect of chemical behaviour and transport with that of adsorption. Further simulations could include the effect of density changes modeled by METROPOL-3, as "fingering" can occur under landfills.

At a further stage, it is anticipated that the same model domain will be calculated with the LGM and the results compared with those presented in this study.

6. REFERENCES

Article 1, Official Journal of the European Communities 31.3.78, No. L 84/43, Council Directive of 20 March 1978 on toxic and dangerous waste (78/319/EEC)

Beker, D., 1992. "Het Storten van Afvalstoffen", HMB Bodembescherming, E1200-1 to E1200-42.

Beugelink, G.P., et al., 1989. "De kwaliteit van het grondwater in Nederland", National Institute of Public Health and Environmental Protection, Bilthoven, Report Number 728820001.

Bles, F. de, Water Quality Data for the Hollandsche IJssel (D12), 1980-1991, Province of Utrecht, Department of Surface Water Quality, private communication, 1992.

Bolt, G.H., M.G.M. Bruggenwert, and A. Kamphorst, 1978. "Adsorption of cations by soil", Soil Chemistry. A. Basic Elements, Chapter 4., Elsevier, Amsterdam.

Commission of the European Communities, 1991. "Proposal for a Council Directive on the Landfill of Waste; COM(91)102 final", Office for Official Publications of the European Communities, Catalogue number CB-CO-91-174-EN-C.

Doedens, Gert-Jan, 1992. IGG-TNO data "Overzicht afgeleide grondwatergegevens t.o.v. N.A.P." Catalogus over de periode 01/01/89 tm 01/01/90, private communication.

Hassanizadeh S.M., 1986a. Derivation of basic equations of mass transport in porous media, 1, Macroscopic balance laws, Adv. Water Resour. 9: 196-206.

Hassanizadeh S.M., 1986b. Derivation of basic equations of mass transport in porous media, 2, Generalized Darcy's and Fick's laws, Adv. Water Resour. 9: 207-222.

Hassanizadeh S.M., T. Leijnse, 1988. On the Modelling of Brine Transport in Porous Media, Water Resources Research, vol. 24, no. 3, pages 321-330.

Heij, G.J., 1979. Beschrijving van het geohydrologische systeem in West Utrecht, Rijksinstituut voor Drinkwatervoorziening, Report Hy.H. 79-11.

Kovar, K., A. Leijnse and J.B.S. Gan, 1992. "Groundwater Model for the Netherlands. Mathematical Model Development and User's Guide", National Institute for Public Health and Environmental Protection, Report Number 714305002, November 1992.

Ministerie van Volksgezondheid en Milieuhygiene, "Richtlijn voor provinciale plannen inzake de verwijdering van ziekenhuisafval", DGMH/AST/171093, Liedschendam, March 1982 (in Dutch).

Richardson - Van der Poel, 1994. Towards a Methodology for a Risk Assessment System for Contaminated Sites. RIVM-report 715207002.

Rathje, W.L., 1991. "Once and Future Landfills", National Geographic, Volume 179, No. 5, May 1991 pp. 116-134.

Sauter F.J., S.M. Hassanizadeh, A. Leijnse, P. Glasbergen, A.F.M. Slot, 1990. METROPOL: a computer code for the simulation of transport of contaminants with groundwater, Report of the European Communities, EUR 13073 EN, Luxembourg.

Sauter F.J., A. Leijnse, A.H.W. Beusen, 1993. METROPOL, user's guide. National Institute of Public Health and Environmental Protection, Bilthoven. Report 725205-003.

Yong, R.N., A.M.O. Mohamed and B.P. Warkentin, 1992. Principles of Contaminant Transport in Soils, Elsevier, Amsterdam.