Technical University of Denmark

DTU

Investigation of emissions from the AV Miljø Landfill
2. Leachate quantity and quality

Søndergaard, Gitte Lemming; Kjeldsen, Peter

DTU Library
Technical Information Center of Denmark

Investigation of emissions from the AV Miljø Landfill - 2. Leachate quantity and quality

Gitte Lemming & Peter Kjeldsen

Investigation of emissions from the AV Miljø Landfill – 2.
Leachate quantity and quality.

Investigation of emissions from the AV Miljø Landfill – 2. Leachate quantity and quality

Gitte Lemming & Peter Kjeldsen
Institute of Environment & Resources
Technical University of Denmark
March 2007

Foreword

This is the second report for the collaboration project between AV Miljø and Institute of Environment & Resources. The aim of the project was to evaluate the present and future emissions from the AV Miljø Landfill both with respect to gas and leachate. This report has been carried out in the period March to December 2006. We like to thank Jonas Nedenskov, AV Miljø for his support in the project and Klaus Berger from the University of Hamburg for his help on the HELP 3.80D model.

List of Content

Dansk sammendrag

Dannelse af perkolat er formentlig den længst varende emission fra lossepladser. Derfor er der et væsentligt behov for at kunne forudsige de fremtidige perkolatemissioner. For at kunne estimere sådanne fremtidige emissioner er det nødvendigt at forudsige både kvantiteten og kvaliteten af perkolatet. AV Miljø lossepladsen er inddelt i flere forskellige celler med varierende affaldssammensætning. Denne rapport fokuserer på tre udvalgte celler indeholdende slutdeponeret affald. For at estimere den langsigtede perkolatkvalitet bliver der ofte udført udvaskningstests i laboratoriet. Ved sådanne forsøg etableres der en sammenhæng mellem perkolatkoncentrationer og den akkumulerede vandmængde som har passeret igennem affaldsvolumenet – den såkaldte koncentration –L/S-sammenhæng (L= akkumuleret vandmængde(liter), S= affaldsmassen(kilogram)). For at kunne ekstrapolere laboratorieresultaterne til lossepladsen i fuld skala må der etableres en sammenhæng mellem fuldskala L/S-forhold og lossepladscellens alder. Til brug for dette må den akkumulative vandinfiltration bestemmes via en vandbalancemodel for lossepladscellen.

AV Miljø lossepladsen modtager affald med et lavt indhold af organisk materiale. Erfaringerne med perkolatsammensætning fra sådanne lossepladser er ret begrænsede. Internationalt har der i de senere år været en øget fokus på perkolaters indhold af specifikke organiske stoffer.

Formålet med dette projekt har været at estimere perkolatdannelsen fra tre typiske affaldsceller (celle 1.3, celle 1.5.1 og celle 2.2.2) ved hjælp af et lossepladshydrologisk modelværktøj, HELP. Perkolatdannelsen fra cellernes etablering og frem til nu er estimeret, ligesom den fremtidige perkolatdannelse fra de tre celler er beregnet. På basis af cellernes affaldsmængder er cellernes L/S-forhold endelig beregnet. Et yderligere formål var at karakterisere perkolatsammensætningen fra de tre celler, idet der er blevet fokuseret på basale vandkemiske parametre (pH, ledningsevne og anioner), makro kationer, spormetaller, generelt indhold af organisk stof, og udvalgte specifikke organiske stoffer.

Lossepladsen AV Miljø er beliggende på inddæmmet land i den nordlige del af Køge Bugt. Under lossepladsen findes et oprindeligt lag af moræne ler med en tykkelse på 7 meter. Herunder findes vandførende kalklag. De tre udvalgte affaldsceller indeholder forskelligt affald: Celle 1.3 indeholder blandet affald med en overvægt af industriaffald og forbrændingsegnet affald.. Celle 2.2.2 har primært modtaget industriaffald og sand fra sandfang. Celle 1.5.1 har langt overvejende modtaget restaffald fra frakmenteringsanlæg for biler og andre metalholdige affaldselementer. Under frakmenteringsaffaldet er deponeret et lag af slamaske.

Det lossepladshydrologiske modelværktøj, HELP, er en "quasi-todimensionel" model som beskriver vandstrømningen gennem et antal forudbestemte lag af jord og affald. Afhængig af typen af lag vil vandet enten strømme i en lodret retning (perkolations- og membranlag) eller i en primær vandret retning (drænlag). Modellen kræver som input lokale daglige meteorologiske data (nedbør, temperatur, solindstråling, mm.). Jord- og membran-karakteristika kan tages fra modellens database eller kan indateres manuelt. Den benyttede version af HELP – HELP 3.80 D – er en revideret version lavet i Tyskland. I versionen er håndteringen af frossen jord blevet forbedret til at kunne lave et mere retvisende beregning specielt under nordeuropæiske forhold.

Den gennemsnitlige årlige perkolatdannelse for perioden fra cellernes etablering til nu blev estimeret til 195-209 mm/år for de tre affaldsceller. Dette svarer til omkring 30% af

den totale nedbør. For den fremtidige perkolatdannelse er opnået estimater på 73 mm (celle 1.3), 111 mm (celle 1.5.1) og 116 mm (celle 2.2.2) gælden for de næste 20 år. Perkolatdannelsen svar til henholdsvis 11%, 17% og 18% af total nedbøren. Baseret på de estimerede perkolatdannelser er det nuværende L/S-forhold blevet beregnet ud fra den akkumulerede perkolatdannelse og den deponerede affaldsmængde. Affaldet i celle 1.3 havde det højeste L/S-forhold på 0,65 L/kg, mens L/S-forholdet for celle 1.5.1 og 2.2.2 var 0.3 L/kg.

Resultatet af perkolatanalysen viste perkolater med et generelt neutralt pH og et relativt lavt indhold af spormetaller (Zn, Cr, As, Co, Cu, Pb og Hg) på under 35 μg/L. Af de analyserede specifikke organiske stoffer synes bisphenol A er være det mest kritiske stof med koncentrationer op til 210 μg/L i celle 1.5.1. Diethylphthalat (DEP) og di-isobutylphthalat (DIBP) blev fundet i lave koncentrationer (1,8-3,1 μg/L). Koncentrationer af alkylphenoler, nonylphenoler, octylphenol og andre analyserede specifikke stoffer var generelt lavere i sammenligning til værdier fundet i litteraturen.

Summary

The generation of leachate is probably the emission with the longest duration from landfills and there is a need for predicting the future emissions. As a basis for such a prediction both the existing leachate quantity and quality are to be assessed. The AV Miljø Landfill is divided in several waste cells with different waste composition. This report focuses on three typical waste cells which have been filled for final storage of the waste. For long term evaluation of the leaching from waste cells often laboratory leaching tests are performed to establish a relationship between leached concentration and the accumulative volume of water which has passed through the waste volume in term of the concentration vs liquid-to-solid (L/S) ratio relationship. In order to extrapolate the laboratory results to full scale landfills a relationship between the L/S-ratio of the disposed waste and disposal time must be established. One part of this is to estimate the water infiltration to the waste cell by use of a water balance model.

Information about leachate quality from landfill cells containing wastes with lower organic content is lacking. Lately, there have been focus on the presence of specific organic pollutants, which may be leaching out of waste materials.

The objectives of this project were - through the application of the hydrological modeling tool, HELP – to estimate the leachate production at three typical cells, cell 1.3, 1.5.1 and 2.2.2. since the initiation of the cells and until today, to estimate the future leachate production at the three cells, and to determine the liquid-to-solid ratio (L/S) of the disposed waste. A second objective is to characterize the leachate quality according to basic water parameters (pH, electrical conductivity, anions), metals and trace metals, content of organic matter expressed as biological and chemical oxygen demand, and selected specific organic contaminants.

The AV Miljø landfill is situated on dammed land inside Køge Bay and the landfill base is constituted by the existing 7 meters of moraine clay, which overlies a chalk formation. Cell 1.3 contains mixed waste with an overweight of industrial waste and combustible waste. Cell 2.2.2 has mainly received industrial waste and sand from sandtraps. In contrast to this, the waste in cell 1.5.1 predominantly consists of shredding residues originating from metal scrapping of automobiles and electrical appliances. Besides the shredder waste, sludge ashes have been disposed of at cell 1.5.1 and constitute the bottom waste layer in the cell.

The HELP model used for the estimation of leachate production is a model for simulation of the water balance of landfill systems. It is a "quasi-two-dimensional" layer model that describes the water flow through a sequence of layers defined by the user. Depending on the layer type, the water flow through a specific layer is either vertical (percolation layer and membrane layer) or horizontal (drainage layer). The model requires climate data (precipitation, temperature and solar radiation) to be specified on a daily basis. Soil and membrane characteristics can be assigned by using the HELP database or be input manually. The applied version of the HELP model (HELP 3.80 D) is a revised version made in Germany. It has improved especially the handling of frozen soils to better reflect the specific Northern European situation.

The average annual leachate production for the period from initiation of the cells 1.3, 1.5.1 and 2.2.2 and until today was in average of 195-209 mm/year of leachate, corresponds to about 30% of the total precipitation. An estimation of the future leachate production at the 3 cells gives an average annual leachate production of 73 mm (cell 1.3), 111 mm (cell

1.5.1) and 116 mm (2.2.2) in the future 20 years. The leachate accounts for 11%, 17% and 18% of the precipitation respectively. Based on the estimated leachate production, the present liquid-to-solid ratio (L/S ratio) was calculated based on the accumulated leachate amounts and the waste amounts at the cells. Waste at cell 1.3 has the highest L/S-value of 0.65 l/kg, whereas the L/S ratio for waste in cells 1.5.1 and 2.2.2 is only 0.3 l/kg.

The results of the leachate analysis showed generally leachate with neutral pH-values and a content of heavy metals (Zn, Cr, As, Co, Cu, Pb and Hg) below 35 µg/l. Of the specific organic contaminants included in the characterization, bisphenol A seems to be the most critical compound with concentrations up to 210 µg/l in cell 1.5.1. Diethylphthalate (DEP) and di-isobutylphthalat (DIBP) were detected in low concentrations (1.8-3.1 µg/l) in the leachate samples. Concentrations of the alkylphenols, nonylphenol and octylphenol and other specific compounds generally low compared to literature values.

1. Introduction

The generation of leachate is probably the emission with the longest duration from landfills and there is a need for predicting the future emissions. As a basis for such a prediction both the existing leachate quantity and quality are to be assessed. The AV Miljø Landfill is divided in several waste cells with different waste composition. Several of the cells were temporary filled with waste which later has been removed for treatment elsewhere. This report focus on three typical waste cells which have been filled for final storage of the waste. For long term evaluation of the leaching from waste cells often laboratory leaching tests are performed to establish a relationship between leached concentration and the accumulative volume of water which has passed through the waste volume in term of the concentration vs liquid-to-solid (L/S) ratio relationship. In order to extrapolate the laboratory results to full scale landfills a relationship between the L/S-ratio of the disposed waste and disposal time must be established. One part of this is to estimate the water infiltration to the waste cell by use of a water balance model

The landfill, AV Miljø, situated in Hvidovre, Denmark, has been studied intensively regarding gas emissions from the disposed waste. In addition to these investigations, this report concerns the other main emission from landfills, namely leachate produced when precipitation infiltrates through the waste. Information about leachate quality from landfill cells containing wastes with lower organic content is lacking. Lately, there have been focus on the presence of specific organic pollutants, which may be leaching out of waste materials. This report investigate the presence of specific organic pollutants in the leachate from the three selected waste cells.

1.1 Objectives

Through the application of the hydrological modeling tool, HELP, the aims of this study are:

1) to estimate the leachate production at cells 1.3, 1.5.1 and 2.2.2. since the initiation of the cells and until today;
2) to estimate the future leachate production at the three cells
3) to determine the liquid-to-solid ratio (L/S) of the disposed waste. This is to be done based on waste amounts and the leachate production over time estimated under (1) and (2).

The uncertainty of the simulated water balance for the landfill cells will be assessed through performance of scenario and sensitivity analyses.

In addition to the hydrological evaluation, sampling of leachate from the 3 particular cells will be conducted in order to characterize the leachate quality according to

1) basic water parameters (pH, electrical conductivity, anions);
2) metals and trace metals;
3) content of organic matter expressed as biological and chemical oxygen demand;
4) selected specific organic contaminants

1.2 The field site

A thorough description of AV Miljø Landfill is given elsewhere e.g. Fredenslund, 2004; thus only additional information of relevance to the current objective is included here.

The landfill is situated on dammed land inside Køge Bay and the landfill base is constituted by the existing 7 meters of moraine clay, which overlies a chalk formation (AV Miljø, no year).
Figure *1* presents an overview of the disposal site. The locations of the three cells in focus (1.3, 1.5.1 and 2.2.2) are marked. These cells are all permanent cells where build-up of waste has been completed.
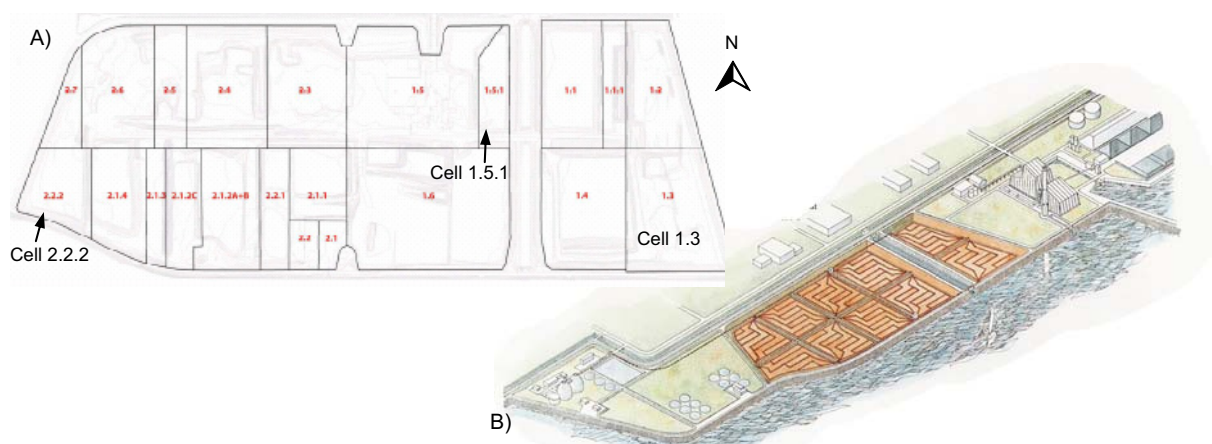
Figure 1. A) Site plan, AV Miljø Landfill. B) Sketch of the landfill design, AV Miljø (AV Miljø, No year)

A brief description of the cells in focus is given in the table below. Cell 1.3 contains mixed waste with an overweight of industrial waste and combustible waste. Cell 2.2.2 has mainly received industrial waste and sand from sandtraps. In contrast to this, the waste in cell 1.5.1 predominantly consists of shredding residues originating from metal scrapping of automobiles and electrical appliances. Besides the shredder waste, sludge ashes have been disposed of at cell 1.5.1 and constitute the bottom waste layer in the cell (AV Miljø, 2006).

Table 1. Description of disposal cell 1.3, 1.5.1 and 2.2.2 (AV Miljø, 2006; Fredenslund, 2004).

Cell	Active period	Cell area (m^2)	Waste amount (tonnes)	Main waste types	Final top covering
1.3	1992-1999	24,000	94,000	• Industrial waste • Combustible waste • Construction waste	1997-2001
1.5.1	1990-2000	7,200	47,000	• Shredder waste • Sludge ashes	
2.2.2	1992-2000 (Main period: 1998-2000)	10,500	41,000	• Industrial waste • Sand from sand traps	2003 (20 cm of top soil lacking)

Final top covering of the landfill cells consists of 20 cm of gravel (root blocker), followed by 80 cm of clayey cover soil and finally 20 cm of top soil. Top covering has been completed at cell 1.3 and initiated at cell 2.2.2, which only lacks the 20 cm of top soil. At cell 1.5.1 top covering has not been initiated, but is expected to be started within the next couple of years (AV Miljø, 2006).

A cross sectional view of the three cells is presented in Figure 2. The waste depth is approximately 5.5 meters at all cells.
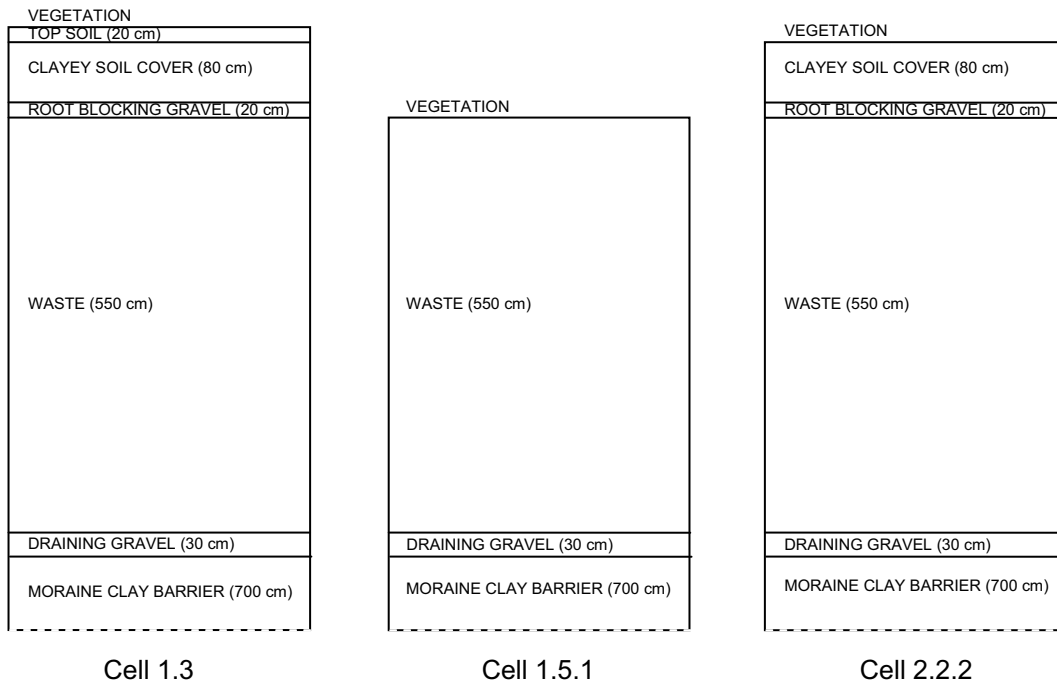
Figure 2. Cross sectional view of cells 1.3, 1.5.1 and 2.2.2 at AV Miljø Landfill

In cell 1.3 and 1.5.1 the waste has been built into horizontal layers. In cell 2.2.2 the waste has been built into layers with some tendency of sloping from the coast inwards (AV Miljø, 2006).

The vegetative cover of cell 1.3 is better than that of the other cells. At cell 2.2.2 the grass cover is very scarce with large areas of bare soil. Although no soil covering of the waste exists at cell 1.5.1, it does have a better grass cover than cell 2.2.2. The vegetative cover of the 3 cells is seen in Figure 3.

Leachate is sampled regularly at AV Miljø. The parameters included in characterization of the outlet from the site are seen in Table 2. Of the cells included in the present investigation only cell 1.5.1 is subjected to separate analysis. These analyses include the trace metals listed in the table.

Table 2. Parametres included in analyses of total outlet and leachate from cell 1.5.1

	Parametres included in analysis
Total outlet	Oil, sulfide, dry matter, BOD_5, COD, NH4-N, N_{total}, P_{total}, pH, conductivity, Cl^-, SO_4^{2-}, As, Pb, Cd, Cr, Fe, K, Cu, Hg, Mn, Ni, Ag, Sn; Zn, phenol number, CN^-, anionic surfactants
Cell 1.5.1	pH, oil, Pb, Cd, Cr, Cu, Hg, Ni

Figure 3. Left: Cell 1.3. View towards east. Mid: Cell 1.5.1 – view towards north. Right: Cell 2.2.2 – view towards south. 27-06-2006

On two occasions, the leachate has been analysed for the content of specific organic contaminants. In 2000 leachate from cell 1.5.1 was analysed for 7 PCBs, none of which were detected (AV Miljø, 2006). A screening of 7 phthalates was carried out for cell 2.2.2. This revealed a detection of 4 out of 7 phthalates with concentrations ranging from 1.7-64 µg/l. The highest concentration was found for diethylhexylphthalate (DEHP) (Cowi, 2002).

1.3 The Hydrologic Evaluation of Landfill Performance (HELP) model

The HELP model is a model for simulation of the water balance of landfill systems. It is a "quasi-two-dimensional" layer model that describes the water flow through a sequence of layers defined by the user. Depending on the layer type, the water flow through a specific layer is either vertical (percolation layer and membrane layer) or horizontal (drainage layer).

The model requires climate data (precipitation, temperature and solar radiation) to be specified on a daily basis. Soil and membrane characteristics can be assigned by using the HELP database or be input manually.

The following hydrological processes are included in the HELP simulation:

- Surface runoff
- Accumulation of precipitation as snow on the surface and snowmelt
- Evapotranspiration (potential and actual)
- Unsaturated vertical percolation
- Saturated lateral drainage
- Saturated percolation through barrier soil layers
- Flow through geomembranes
- Frozen soil
- Recirculation of leachate
- Subsurface inflow

14
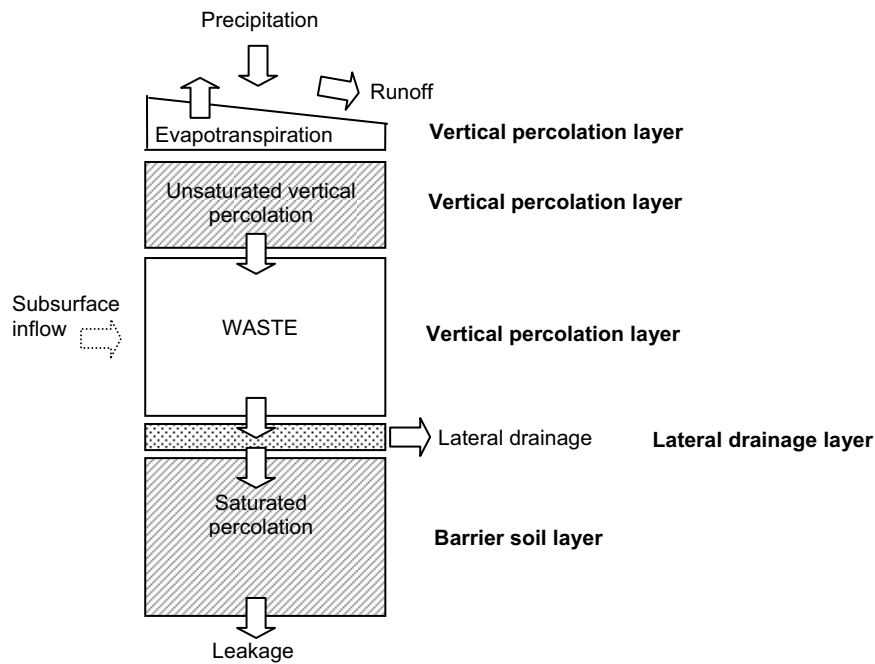
Figure 4. Example of a landfill profile setup and illustration of hydrological processes included in HELP (simplified)

The actual evapotranspiration calculated by HELP consists of three components: evaporation of surface water (intercepted water, snow, snowmelt), soil evaporation and plant transpiration.

Figure 4 shows an example of a landfill layer profile and the included hydrological processes modeled by HELP. The simulations are carried out by a one-day timestep and the output is available as daily values as well as monthly and yearly totals.

For further details regarding the HELP model refer to Berger (2004) and Schroeder & Berger (2004).

2. Methods and materials

2.1 Hydrological balance modeling

The leachate production will be modeled using the "Hydrological Evaluation of Landfill Performance" model described in the previous chapter. This model includes all important hydrological processes that occur in landfills and has an extensive database of soil and liner properties.

The applied version of the HELP model (HELP 3.80 D) is a revised version by Berger (2004). The revisions made include elimination of errors and enhancements of included processes in ealier versions. As an example, the submodel for simulation of frozen soil has been improved to be more realistic for German climate, where long periods of frozen soil are rare. Furthermore, with the revised model it is possible to simulate the ageing of a landfill by changing layer and vegetation properties during a simulation period. Other improvements compared to previous versions are replacement of submodels for actual evapotranspiration and unsaturated/saturated vertical flow in vertical percolation layers (Berger, 2004).

The model will be applied for each of the landfill cells 1.3, 1.5.1 and 2.2.2. The acquisition of input data regarding meteorological conditions and landfill design is described in the following. This is followed by a outline of the modeling strategy, which includes a number of modeling scenarios and a sensitivity analysis.

Climate data

An important data input for the HELP simulation is meteorological data. Data from the nearest available weather stations have been obtained from the Danish Meteorological Institute (DMI). See the table below for data specifications.

Precipitation data are recorded at Hvidovre Water works app. 3.7 km from AV Miljø. The nearest weather station recording temperature is Copenhagen Airport 11 km east of the landfill, whereas solar radiation could not be obtained from weather stations closer than Sjælsmark app. 40 km to the north of the landfill. Relative humidity and wind speed is obtained from the weather station at Copenhagen Airport.

Table 3. Details regarding climate data used for HELP simulations

Data	Weather station (Number, name)	Data type (unit)	Data sequence	Missing data
Precipitation	30318 Hvidovre Water works	Daily values (1/10 mm)	1/1 1979 – 31/12 2005	**1990**: 31/1, 10-11/2, 13-14/2, 19/2-6/3
Temperature	06180 Copenhagen Airport	Daily mean (1/10°C)	1/1 1987 – 31/12 2005	
Solar radiation	30188 Sjælsmark	Daily sum (MJ/m^2)	23/5 1986 – 31/12 2005	**1990**: 15/3, 23/3, 29/3, 4/8, 22-23/8, 16/11 **1991**: 30/8, 14-16/12 **1992**: 1-2/6, 1/8, 24/10, 9/12 **1993**: 20/1, 19/3, 27/3, 15-16/6 **1996**: 28/3 **1997**: 5/6 **1998**: 3/6 **2000**: 11/2 **2001**: 20/6 **2002**: 16-27/6, 2/8 **2003**: 16/3, 5-9/8, 12-13/9 **2005**: 16-19/1, 1-4/10.
Relative humidity	06180 Copenhagen Airport	Daily values (%)	1/1 1987 – 31/12 2005	
Wind speed	06180 Copenhagen Airport	Daily values (1/10 m/s – 10 m above ground)	1/1 1987 – 31/12 2005	

HELP requires a complete dataset for precipitation, temperature and solar radiation data. Missing precipitation records were thus replaced with zeros since only few data was missing (only for 1990). Missing solar radiation records were estimated taking the average value of the 3 previous and the 3 following days. No temperature data was missing in the dataset.

In order to estimate the evapotranspiration, the following additional data are required:

- Maximum leaf area index (LAI)
- Depth of the evaporative zone
- Growing season start day
- Growing season end day
- Average wind speed (km/h) at 2 meters height
- Relative humidity (quarterly average values)

The *maximum leaf area index* increases with increased vegetative cover and values from the HELP 3.80D manual (Schroeder & Berger, 2004) were used. During waste build-up, the surface is assumed to be bare with no vegetation and thus a LAI value of zero. LAI values have been assigned to the present vegetation at the three cells (see Table *4*). These values will be used for the last part of the simulated period after waste disposal has ended.

Table 4. Present vegetative cover at cells 1.3., 1.5.1 and 2.2.2 and corresponding leaf area index (LAI)

Cell	1.3	1.5.1	2.2.2
Vegetation	Fair stand of grass	Poor stand of grass	Poor stand of grass with spots of bare soil
LAI	2	1	0.7

Default values for the *depth of the evaporative zone* were taken from WHI (2001) to be 25 cm for bare soil, 56 cm for fair stand of grass and 99 cm for excellent stand of grass.

The *duration of the growing season* was taken to be the period of the year where the average day temperature exceeds 8°C, which is recommended for German conditions in Schroeder & Berger (2004). This results in a growing season from the beginning of May till the end of October (184 days). The *average wind speed* was calculated based on 1990-2005 data and converted from 10 to 2 meter above ground by the following formula (Schroeder & Berger, 2004):

$$U_{2m} = U_{10m} \frac{4.2}{\ln(10) + 3.5}$$

Quarterly average *relative humidity* values were calculated from 1990-2005 data.

Layer and soil data

For each cell the simulation period will start the initial year of the active period and end by the end of 2005. The layer profiles existing presently at the 3 cells are illustrated in Figure 2. It is however necessary to evaluate the development in the layer profiles since the beginning of the operation of the specific cell. In Appendix 1, an assessment of the development in layer thicknesses throughout the lifetime of the cells can be viewed. These estimations assume that the waste received in one year is distributed evenly across the cell surface. If top covering of a cell has taken place through a period of years, it is assumed that the activity is distributed evenly between the years.

The HELP simulation must be executed separately for each period of stationary layer thickness.

Therefore, in order to reflect the build-up of waste and cover material during the lifetime of the cell, it is necessary to divide the simulation into a number of subsimulations each representing approximately stationary layer profiles (see Table 5). Consequently, layer and climate input files are created for each simulation period.

Table 5. The HELP simulation for each cell is divided into a number of sub-simulations with stationary layer profiles.

	Simulation periods		
	Cell 1.3	**Cell 1.5.1**	**Cell 2.2.2**
1	1992	1990 - 1991	1992-1997
2	1993	1992	1998
3	1994 - 1996	1993	1999
4	1997	1994	2000 - 2002
5	1998	1995	2003-2005
6	1999	1996	
7	2000	1997	
8	2001 - 2005	1998	
9		1999	
10		2000 - 2005	

For each of the layers in the landfill profile a range of soil properties is required (total porosity, field capacity, wilting point, initial moisture and saturated hydraulic conductivity).

Additionally, for drainage layers, the slope of the drainage system and the maximum drainage length must be specified. At AV Miljø the slope of the drainage pipes are approximately 5‰ and the maximum drainage lengths are 200m, 170m and 130m respectively for cell 1.3, 1.5.1 and 2.2.2. In presence of geotextiles (which is not the case for AV Miljø landfill) the necessary data increases to also include pinhole densities, transmissivity etc.

The program contains a database with default soil property values. The soil properties for layers waste, gravel, clayey soil cover is selected from this database (see Appendix 1). As for the moraine clay bottom membrane, the hydraulic conductivity was chosen to be very low, since leakage through the moraine clay membrane is not expected due to the low hydraulic head maintained within the site by extensive pumping.

Surface runoff

The surfaces of the cells are approximately horizontal (level +4 m). Therefore, surface runoff is expected to be insignificant and will be neglected in the simulations. During waste build-up, the layers have been sloping at cell 2.2.2. This is, however, neglected in the simulations.

Subsurface inflow

The hydraulic head within the landfill is lower than for the surroundings in order to prevent leakage of leachate. Therefore groundwater and sea water from Køge Bay can flow into the site where it is collected together with the landfill leachate. The magnitude of the inflow has been estimated to be 0.011 m^3/m^2/yr (Fredenslund, 2004). This inflow is however neglected in the HELP simulation, since the water does not percolate through the waste and therefore does not affect the calculated L/S-ratio. In order to compare the simulated leachate amounts with observed leachate amounts, the inflow should be included.

Modeling strategy

A baseline scenario is modeled initially. This is followed by a number of additional scenarios with alterations of the waste data to account for (A) dead zones and channeling in the waste and (B) difference in water content of newly added and existing waste material. In scenario C, HELP will be used for a prediction of the future leachate generation at the three cells.

Baseline scenario

In the baseline scenario the properties of all waste material is represented by HELP waste type 18: Municipal Solid Waste. This is chosen in lack of alternatives, since the only waste types in HELP are MSW and three kinds of ash material. The initial moisture contents of the layers are estimated by HELP as steady state values. The resulting water content of the layers at the end of one simulation period are recorded and entered manually as initial water content for the subsequent simulation period. When the thickness of a specific layer is increased from one period to the next, the water content of the newly added layer material was assumed to be the equal to that of the pre-existing layer material. The initial water content of new layer types (e.g. soil covering) are estimated as HELP steady state values.

Further modeling scenarios

Three additional modeling scenarios have been simulated with HELP. The scenario settings are described below:

- SCENARIO A: Waste layers with dead zones and channeling

In scenario A, the waste type was changed to the HELP default waste type "MSW with dead zones and channeling". The active pore volume involved in drainage and storage of infiltration is assumed to be only 25% of the total possible volume. This causes shorter leachate retention times in the waste and a decrease in the water storage potential. The initial soil water content will be estimated as HELP steady state values.

- SCENARIO B: Initial water content of 0.1 for new waste material

In this scenario, an increasing layer depth from one period to the next, is represented in the layer design as addition of a new layer. In this way, the initial water content of the newly added material can differ from that of the existing material. This means, that if e.g the waste layer has been built up over 5 years, then a total of five waste layers will be present for the 5th simulation. The layer structure used in Scenario B is seen in Appendix 1. The water content of the "old" material is the value obtained by the end of the previous simulation step, whereas the water content of the "new" material is set to 0.1 (vol/vol).. This value is within the range of literature values for MSW reported in Christensen (1998) Since the field capacity of the waste is 0.292 (vol/vol) this gives a water deficit of the waste of 0.192. The initial moisture for drainage layers is chosen to be 0.1 as well, whereas for soil covering, the steady state model simulated values are used.

- SCENARIO C: Future leachate production (2006-2025)

In order to simulate the future leachate production it is necessary to determine the likely future changes regarding top covering and cover vegetation of the cells. Top covering of cell 1.5.1 is assumed to occur in 2008 and a continued improvement of the grass cover is assumed for all cells. The assumed development in vegetation and layer structure is outlined in Table 6.

Precipitation, temperature and solar radiation data for the period 2006-2025 is estimated using average daily values calculated from data from the period 1990-2005.

Table 6. Assumed changes in layer structure and vegetative cover in the period from 2006-2025. The assumed changes in layer structure are based on information from AV Miljø (2006).

	Scenario C: Future leachate production 2006-2025		
	Cell 1.3	**Cell 1.5.1**	**Cell 2.2.2**
Layer structure	Unchanged	20 cm root blocker (2008) 80 cm cover soil (2008)	Unchanged
Vegetation	2006-2012: Good stand of grass. 2013-2025: Excellent stand of grass	2006-2008: Poor stand of grass 2009-2012: Poor stand of grass 2013-2018: Fair stand of grass. 2019-2025: Good stand of grass	2006-2012: Poor stand of grass/bare soil 2013-2018: Fair stand of grass 2019-2025: Good stand of grass.

Sensitivity analysis

A sensitivity analysis will be performed to evaluate the sensitivity of the baseline scenario results and to identify the parameters that influence the model results the most.
The analysis consists of two parts:

Initially, the value of selected input parameters will be increased by 50% on at a time and a new HELP simulation will be performed. This will show, which parameters the model result mathematically is most sensitive towards.

Parameter values that are based on site data are believed to be less uncertain that those estimated from literature data. This is reflected in the second part of the sensitivity analysis, where HELP simulations will be performed using the minimum and maximum value of the uncertainty range of the specific parameter.

In both parts of the sensitivity analysis, the "effect" of the parameter change will be measured as the change (in %) of the accumulated leachate production during the entire simulation period.
Due to the large number of subsimulations required for each parameter change, the sensitivity analysis is done only for cell 1.3.

For each of the parameters in Table 7, the uncertainty is assessed, reflected in the maximum and minimum values given. Some comments on the assessment of the uncertainty range is given below.

The largest uncertainty (a factor of ± 10) is assessed to be associated with the hydraulic conductivities of the cover soil, waste and draining gravel.

Table 7. Parameter uncertain expressed as a multiplication factory

Parameter	Symbol	Base value	Maximum	Minimum
Precipitation	P	Uncorrected precipitation data from Hvidovre water works	Corrected precipitation (base value*1.21)	Base value * 0.90
Temperature	T	Data from Copenhagen airport	Base value * 1.10	Base value * 0.90
Solar radiation	R	Data from Sjælsmark	Base value * 1.20	Base value * 0.80
Hydraulic conductivity of layers (soil cover, waste, gravel)	K_{cover} K_{waste} K_{gravel}	2.5E-5 cm/s 1E-3 cm/s 3E-1 cm/s	Base value * 10	Base value * 0.1
Wind speed at 2 meters above ground		Average value of 14.5 km/h based on 1990 – 2005 data from Copenhagen airport.	Base value * 1.10	Base value * 0.90
Humidity		Average quaternary values based on 1990 – 2005 data from Copenhagen airport.	Base value * 1.10	Base value * 0.90
Depth of evaporative zone	d_{ez}	Default values from WHI (2001) Bare soil: 25 cm Fair stand of grass: 56 cm	Base value * 1.5	Base value * 0.5

The precipitation data used for the baseline simulation are uncorrected values. This is chosen based on the experiences by Berger, who found that the uncorrected data gives a better agreement between modeled and measured leachate amounts, whereas the use of corrected precipitation data tends to cause an overestimation of the leachate production (Berger 2000; Berger 2006). It is, however a fact, that the measured precipitation data contains systematic errors due to sheltering of the rain gauges. Therefore the maximum daily precipitation values have been set to the corrected precipitation data. On an annual basis this gives an increase of 21% in the volume of precipitated water. Further details on calculation of corrected precipitation values are given in Appendix 2.

The minimum precipitation values are set to be 10% below the base value. For the temperature data, wind speed and humidity the uncertainty is likewise set to ± 10%. Since solar radiation data have been measured farthest away from the site, the uncertainty of this parameter was set to be larger than other climate data (± 20%). The uncertainty of the depth of the evaporative zone is assessed to be quite uncertain (± 50%), since it is not based on site data.

Calculation of L/S-ratio

The liquid-to-solid ratio (L/S) is calculated as the accumulated leachate volume ($V_{leachate\_acc}$) divided by the mass of disposed waste (M_{waste}):

$$L/S(t) = \frac{V_{leachate\_acc}(t)}{M_{waste}}$$

Since the waste has been received over a period of years, and therefore represent different ages, the L/S- ratio will vary throughout the landfill cell according to the age of the waste. The resulting L/S-ratio is therefore given as an interval for each cell.

2.2 Leachate quality

Leachate sampling

Leachate samples were collected from AV Miljø Landfill in May and July 2006. From cell 1.3 leachate is drained separately to the pumping station P1, where sampling could be done directly from a tap. Leachate from cell 1.5.1 and 2.2.2 is mixed with leachate from other cells when drained to the pumping station. Therefore leachate sampling from these cells was done at the leachate collection wells.

At cell 2.2.2 a 12 volt submersible pump was used to lift the water the approximately 8 meters to the surface. pH and conductivity was measured in a flow cell and sampling was done after stabilization of these parameters.

At cell 1.5.1 pumping was attempted but failed due to the much lower water depth in this collection well. A suction method using a vacuum system was attempted as well, but was not found to be optimal, since this sampling method resulted in suction of thick black sludge. Therefore samples at 1.5.1 were taken by lowering a sampling container down under the outlet pipe. In this way, only the "fresh" leachate was sampled. The sampled leachate therefore only comes from one of the 3 main leachate pipes leading leachate into the collection well. Since the waste build-up is homogenous within the cell (sludge ashes overlain by shredder waste), this is believed to be of minor importance.

From each cell a total of approximately 5 liters (May) and 2 liters (July) of leachate was sampled.
Samples for analysis of organic contaminants were collected in 1000 mL glass flasks with teflon caps, metals in 125 mL acid-rinsed flasks and anions, COD and BOD in 500 mL plastic bottles. Adequate sample containers were provided by Analytica AB and samples were subsequently delivered to Analytica for further analysis.

Analyses

All analyses except pH and electrical conductivity, which were measured in the field, were carried out by Analytica AB.

The chemical analysis of inorganic parameters covered anions (chloride, sulfate and ammonia) and a long range of metals. The anion analyses were carried out according to ISO standard procedures.

Samples for metal analysis were digested with nitric acid (HNO_3) except for Ag, where hydrochloric acid (HCl) was used. I.e. the metal determination includes both dissolved and suspended metal species.

Concentrations of the metals Ca, Fe, K, Mg, Na, S, Ba and Mn were determined using Inductively Coupled Plasma-Atomic Emission Spectrometry, (ICP-AES). For a range of the metals (Al, As, Cd, Co, Cr, Cu, Ni, Pb, Zn) it was necessary to use a high-solution ICP technique (ICP-SFMS) due to interference caused by the high chloride concentrations. With this method the analytic signals are separated, which gives a more accurate determination/ high sensitivity determination. Hg concentrations were determined using atomic fluorescence spectroscopy (AFS).

In addition to the inorganic parameters a selection of specific organic contaminants was included in the leachate characterization. These were chosen based the findings from a literature study of organic pollutants found in landfill leachate in Europe and Japan within the last 7 years. A summary of the findings is tabulated in Appendix 3. Pollutants from landfills containing other waste types than MSW (construction waste, different types of industrial waste) were given more attention, when choosing the contaminants to be included in the leachate characterisation.

The literature study showed that endocrine disrupting chemicals (EDCs) are an important group of emerging xenobiotic organic contaminants in landfill leachate. The EDCs is a heterogeneous group of chemicals commonly used for industrial purposes, i.e. as synthethic detergents, additives in plastic and paint, pharmaceuticals and as flame retardants. Four groups of compounds were selected:

- Bisphenol A
- Phthalates (10 compounds)
- Brominated flame retardants (13 compounds)
- Alkylphenols (2 compounds)

Table 8 contains the full list of specific contaminants included in the analysis and the method applied for analysis. The sources to these selected contaminants are described briefly below:

Table 8. Specific organic contaminants included in leachate characterization

Group/compound	Compounds included in analysis	Method
Phthalates	• Dimethyl phthalate (DMP) • Diethyl phthalate (DEP) • Di-n-propyl phthalate • Di-n-butyl phthalate (DBP) • Di-isobutyl phthalate • Di-pentyl phthalate • Di-n-octyl phthalate • Di-(2-ethylhexyl) phthalate (DEHP) • Butylbenzyl pthalate (BBP) • Di-cyclohexyl pthalate	Extraction with n-hexan, GC-MS
Bisphenol A	• Bisphenol A	Solid-phase extraction GC-MSD
Brominated flame retardants	• TetraBDE • BDE 47 • PentaBDE • BDE 99 • BDE 100 • HexaBDE • HeptaBDE • OctaBDE • NonaBDE • DecaBDE • Tetrabrom bisphenol-A (TBBA) • Decabrom biphenyl (DeBB) • Hexabrom cyclododecan (HBCD)	Extraction with toluene, GC-MS
Alkylphenols	• 4-nonylphenol • 4-tert-octylphenol	Extraction with n-hexan, GC-MS

Bisphenol A and phthalates are widely used plastizisers and their occurrence in landfill leachate can hence be ascribed to landfilling of polymer products.

Electric and electronic equipment is an important source for brominated flame retardants (BFRs). Plastic, textiles and building materials are other sources to BFRs in landfill leachate. These compounds can either end up in leachate through direct disposal of electrical appliances, plastic or textiles in landfills or they can be contained in incineration residues disposed of in landfills. Polybrominated diphenyl ethers (PBDEs) is a large group of brominated flame retardants. Other BFRs include Tetrabrom bisphenol-A (TBBA), Decabrom biphenyl (DeBB) and Hexabrom cyclododecan (HBCD).

The alkylphenols included in the leachate characterization are nonylphenol and octylphenol. These compounds originate from biodegradation of alkylphenol ethoxylates contained in non-ionic surfactants, detergents and personal care products.

Apart from the specific organic contaminants, the content of dissolved organic material in the leachate will be evaluated through analyses of biological oxygen demand (BOD_5) and chemical oxygen demand (COD_{Cr}).

3. HELP simulations: Results and discussions

3.1 Water balance for the disposal cells 1.3, 1.5.1 and 2.2.2

The hydrologic balance has been estimated through the application of the HELP model, the objective being to estimate the quantity of leachate produced and subsequently estimate the liquid-to-solid ratio (L/S ratio) of the disposed waste.

Baseline scenario

The water budget simulated by HELP for the baseline sceanario for cell 1.3, 1.5.1 and 2.2.2 is presented in Figure 5 - Figure 7. The components of the water budget presented in the figures are precipitation (P), actual evapotranspiration (E_a), lateral drainage ($L_{lateral}$) and change in water storage (ΔS). Since surface runoff and subsurface inflow is disregarded and vertical leakage through the landfill base is negligible, the water balance for the landfill system simplifies to:

$$P - E_a - L_{lateral} = \Delta S$$

ΔS is the total change in water storage, which HELP calculates as the sum of the change in water stored in soil, stored as interception and stored as snow. For the present system, the change in water stored in soil is the dominant component of these. The individual magnitudes of the components of ΔS can be seen in the full water balance placed in Appendix 4, which also includes the model calculated potential evapotranspiration.

The annual leachate production varies between 90 and 390 mm/year and the fluctuations in the leachate production clearly follow that of the precipitation, which represents the water inflow to the system. Thus, the simulated minimum and maximum leachate production for each cells occurs in the year of minimum and maximum precipitation which is 1996 and 1994 respectively.
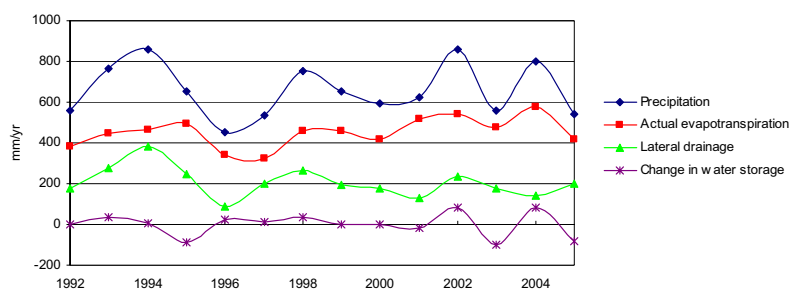
Figure 5. Water balance for cell 1.3 at AV Miljø simulated by HELP
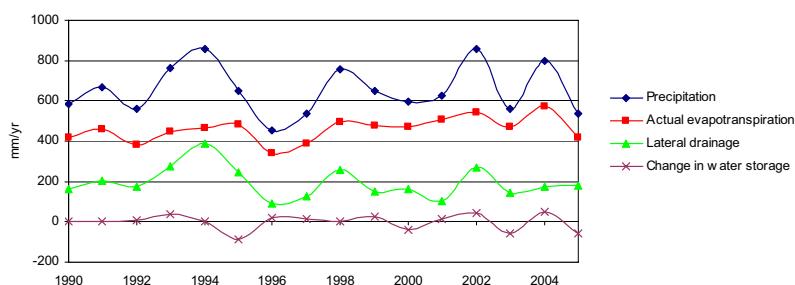
Figure 6. Water balance for cell 1.5.1 at AV Miljø simulated by HELP
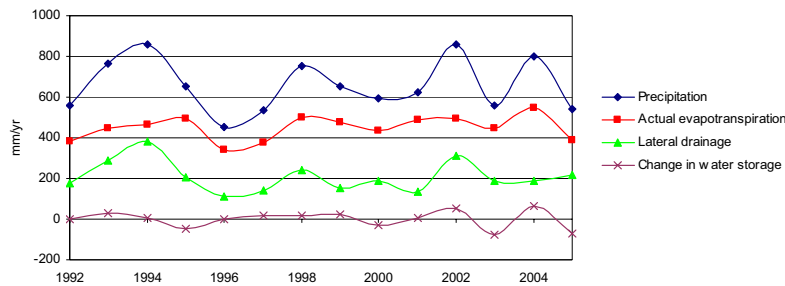
Figure 7. Water balance for cell 2.2.2 at AV Miljø simulated by HELP

A summary of the water budget for cell 1.3, 1.5.1 and 2.2.2 respectively is presented in Table *9*, where annual average values of the components of the water balance have been calculated. This is done for the full simulation period as well as *during build-up* and *after build-up*. The build-up period refers to period where build-up of waste and top covering has taken place and no cover vegetation is present at the cell. In the period *after build-up* presence of surface vegetation is included in the simulations. When considering the entire modeling period the annual average precipitation is app. 650 mm of which app. 450 mm (68-70%) is evapotranspirated. The remaining 200 mm (30-32%) infiltrates through the waste and results in leachate production.

During the build-up period the evapotranspiration constitutes 65-67% of the precipitation, this increases to 73-75% in the period after build-up. The higher evapotranspiration is caused by the presence of surface vegetation. In response to the increase of the actual evapotranspiration a decreasing tendency is observed for the leachate production. This tendency is most pronounced for cell 1.3 and 1.5.1 and less for cell 2.2.2, which has the poorest cover vegetation.

Table 9. Average annual water budget in mm/year (% of P) for the baseline scenario. The build-up period refers to the period in which build up of waste and soil covering has taken place

	P	R	E_a	$L_{lateral}$	$L_{leakage}$	ΔS
Cell 1.3						
Total period (1992-2005)	657 (100%)	0	451 (69%)	206 (31%)	1 (0.1%)	-1 (-0.1%)
During build-up (1992-2000)	646 (100%)	0	421 (65%)	223 (35%)	1 (0.1%)	2 (0.3%)
After build-up (2001-2005)	676 (100%)	0	506 (75%)	176 (26%)	1 (0.1%)	-6 (-0.9%)
Cell 1.5.1						
Total period (1990-2005)	653 (100%)	0	459 (70%)	195 (30%)	1 (0.1%)	-1 (-0.1%)
During build-up (1990-1999)	647 (100%)	0	436 (67%)	208 (32%)	1 (0.1%)	3 (0.3%)
After build-up (2000-2005)	663 (100%)	0	497 (73%)	172 (26%)	1 (0.1%)	-7 (-1.1%)
Cell 2.2.2						
Total period (1992-2005)	657 (100%)	0	448 (68%)	209 (32%)	1 (0.1%)	-1 (-0.1%)
During build-up (1992-2002)	664 (100%)	0	445 (67%)	212 (32%)	1 (0.1%)	7 (1.0%)
After build-up (2003-2005)	632 (100%)	0	460 (73%)	199 (31%)	1 (0.1%)	-27 (-4.3%)

P: Precipitation, R: Surface runoff, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water

3.2 Further modeling scenarios

Scenario A: Waste with dead zones and channeling

In this scenario, the active volume for drainage and storage of infiltration has been reduced by 75% in order to represent waste material with dead zones and significant

channeling, which could be a relevant situation at AV Miljø Landfill. This results in an initial soil water content of 0.07 Thus, the initial steady state soil water content is only 0.07 compared to 0.28 in the baseline scenario.

The result of this simulation is shown in Figure 8 - Figure 10 (the green curve). Compared to the baseline scenario (the black curve), it is evident that at cell 1.3 an increasing leachate production is mainly ascribed to the first part of the simulation period (1992-1996). The lower water content of the waste material, which is uncovered until 1996, causes a significantly decreasing evapotranspiration during this period, which combined with the faster flow through the waste, causes an increased leachate production.
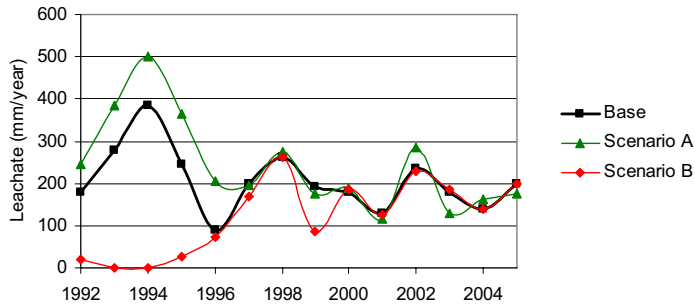
Figure 8. Leachate production at cell 1.3 for Scenario A (Waste with dead zones and channeling) and Scenario B (Initial water content of 0.1 for new waste material)
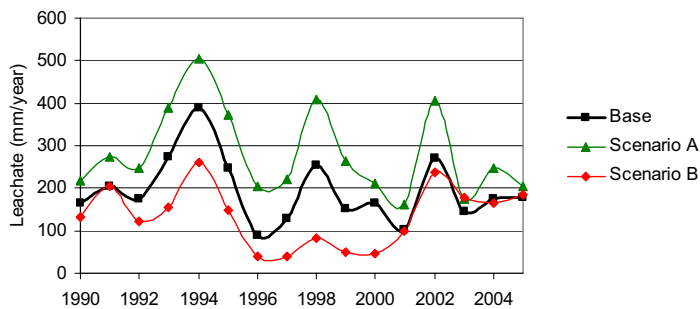
Figure 9. Leachate production at cell 1.5.1 for Scenario A (Waste with dead zones and channeling) and Scenario B (Initial water content of 0.1 for new waste material)
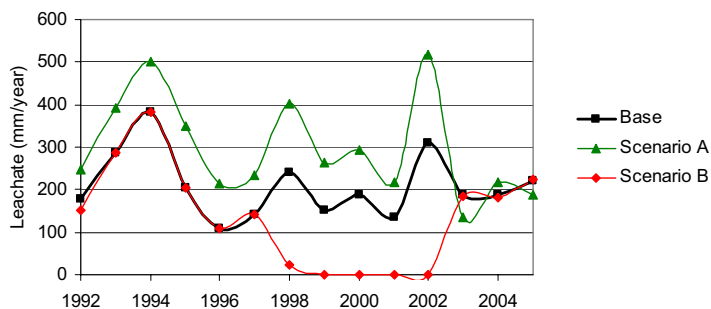
Figure 10. Leachate production at cell 2.2.2 for Scenario A (Waste with dead zones and channeling) and Scenario B (Initial water content of 0.1 for new waste material)

For cell 1.5.1, which is uncovered, Scenario A gives an increased leachate production virtually throughout the period as seen from Figure 9.

An increased leachate production is also seen for cell 2.2.2. As for cell 1.3, the increase is primarily restricted to the period prior to capping of the cell, which took place in 2003.

29

Seen over the entire modeled period, the leachate production now constitutes 37-45% of the precipitation. The total leachate amount has increased by 18% for cell 1.3 and 42-46% for cell 1.5.1 and 2.2.2 respectively. Thus, the water balance changes very significantly in this scenario. Table 10 summarizes the water budget for Scenario A.

Table 10. Average annual water budget in mm/year (% of P) for Scenario A. The build-up period refers to the period in which build up of waste and soil covering has taken place

	P	R	E_a	$L_{lateral}$	$L_{leakage}$	ΔS
Cell 1.3						
Total period (1992-2005)	657 (100%)	0	412 (63%)	244 (37%)	1 (0.1%)	1 (-0.1%)
During build-up (1992-2000)	646 (100%)	0	360 (56%)	282 (44%)	1 (0.1%)	3 (0.5%)
After build-up (2001-2005)	676 (100%)	0	506 (75%)	174 (26%)	1 (0.1%)	-4 (-1.1%)
Cell 1.5.1						
Total period (1990-2005)	653 (100%)	0	370 (56%)	282 (44%)	1 (0.1%)	1 (-0.1%)
During build-up (1990-1999)	647 (100%)	0	334 (52%)	310 (48%)	1 (0.1%)	3 (0.4%)
After build-up(2000-2005)	663 (100%)	0	430 (65%)	234 (35%)	1 (0.1%)	-3 (-0.4%)
Cell 2.2.2						
Total period (1992-2005)	657 (100%)	0	358 (55%)	298 (45%)	1 (0.1%)	0
During build-up (1992-2002)	664 (100%)	0	331 (50%)	330 (50%)	1 (0.1%)	3 (0.4%)
After build-up (2003-2005)	632 (100%)	0	460 (73%)	180 (29%)	1 (0.1%)	-8 (-1.3%)

P: Precipitation, R: Surface runoff, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water

Scenario B: Initial water content of 0.1 for new waste material

In this scenario, the increase of a layer thickness is simulated by adding a new layer. In this way it is possible to have a different initial moisture of the newly added material, than for the pre-existing waste material. The initial water content of new waste material is set to 0.1 (vol/vol), which results in a water deficit of 0.19 (vol/vol). The resulting water balances are illustrated in Figure 8 - Figure 10 (the red curve) and summarized in table 11.

As seen in Figure 8, the leachate production at cell 1.3 is very low during the initial 4 years. In this period, the infiltrating water is used to compensate for the water deficit in the waste. From 1997 onwards no further waste is disposed of and the leachate production for the rest of the period is nearly equal to that of the baseline scenario.

At cell 1.5.1, waste has been built up during the period from 1990 to 1999. The lower initial water content of the received waste compared to the baseline scenario results in an increased water storage and a lower leachate production during the period with waste build-up. As expected, the leachate production in this scenario approximates that of the baseline scenario in the period from 2000 and onwards (See Figure 9).

Table 11. Average annual water budget in mm/year (% of P) for Scenario B. The build-up period refers to the period in which build up of waste and soil covering has taken place

	P	R	E$_a$	L$_{lateral}$	L$_{leakage}$	ΔS
Cell 1.3						
Total period (1992-2005)	657 (100%)	0	449 (68%)	122 (19%)	1 (0.1%)	86 (13%)
During build-up (1992-2000)	646 (100%)	0	418 (65%)	91 (14%)	1 (0.1%)	137 (21%)
After build-up (2001-2005)	676 (100%)	0	506 (75%)	176 (26%)	1 (0.1%)	-6 (-1%)
Cell 1.5.1						
Total period (1990-2005)	653 (100%)	0	455 (70%)	134 (21%)	1 (0.1%)	63 (10%)
During build-up (1990-1999)	647 (100%)	0	430 (66%)	123 (19%)	1 (0.1%)	94 (15%)
After build-up (2000-2005)	663 (100%)	0	497 (75%)	152 (23%)	1 (0.1%)	12 (2%)
Cell 2.2.2						
Total period (1992-2005)	657 (100%)	0	446 (68%)	135 (21%)	1 (0.1%)	75 (11%)
During build-up (1992-2002)	664 (100%)	0	442 (67%))	118 (18%)	1 (0.1%)	103 (16%)
After build-up (2003-2005)	632 (100%)	0	460 (73%)	198 (31%)	1 (0.1%)	-26 (-4%)

P: Precipitation, R: Surface runoff, E$_a$: Actual evapotranspiration, L$_{lateral}$: Leachate collected from drainage layer, L$_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water

The model result of Scenario B for cell 2.2.2 is seen in Figure 10. During 1993-1997 no new waste has been received at the cell. The leachate production in this period is therefore unchanged in comparison to the baseline scenario. The waste has primarily been received in the period from 1997-2000 and the model result indicates that leachate is not produced until 2003 due to build up of water in the waste material. The leachate production from 2003-2005 resembles that of the baseline scenario.

In this scenario, the evapotranspiration constitutes 68-70% of the precipitation, which is the same as in the baseline scenario. However, only 19-21% of the precipitation results in formation of leachate, whereas the remaining 10-13% is stored as soil water especially in the waste material.   . The accumulated leachate amount for the entire simulation period has been decreased by 34-41% compared to the baseline scenario.

Scenario C: Future leachate production (2006-2025)

The future leachate production at the three cells have been modeled by assuming that climate conditions for the period 2006-2025 correspond to average climate conditions from the period 1990-2005. Covering of cell 1.5.1 is assumed to take place in 2008. The vegetation quality is enhanced during the simulation as described in Table 6.

The results from the HELP simulations (see Figure 11 - Figure 13) demonstrate a stepwise increase in evapotranspiration as a response to the stepwise vegetation improvement. Thus, due to the higher evapotranspiration, the leachate production exhibits a decrease over the simulated period and reaches a level of approximately 65 mm/year (cell 1.3) and 90 mm/year (cell 1.5.1 and 2.2.2) in 2025.
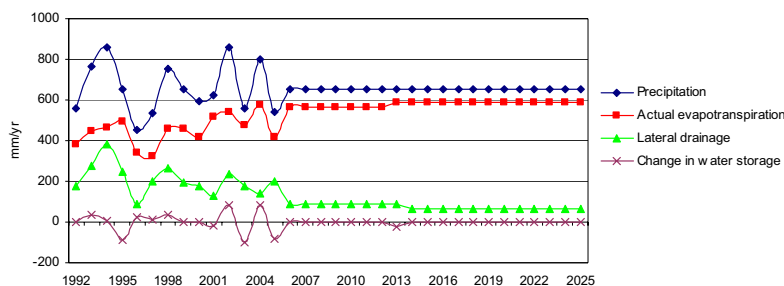
Figure 11. Water balance for cell 1.3 1992-2025
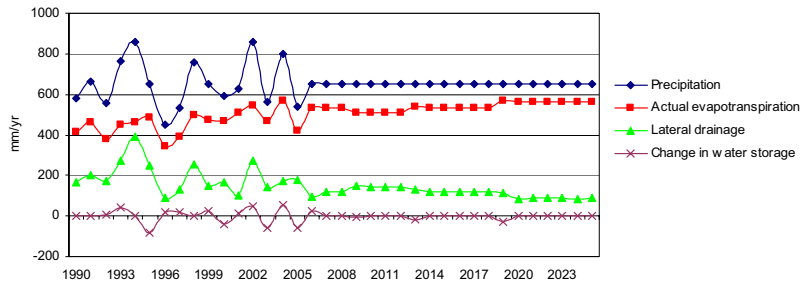
Figure 12. Water balance for cell 1.5.1 1990-2025
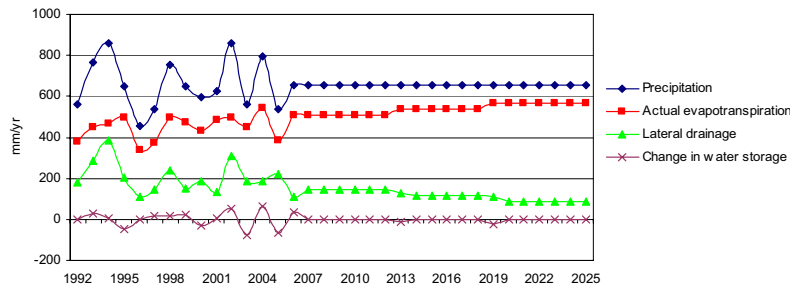
Figure 13. Water balance for cell 2.2.2 1992-2025

3.3 Sensitivity analysis

The sensitivity of the model results has been investigated by performing a sensitivity analysis. In the first step of the analysis input parameter values have initially been increased one at a time by 50% and a new HELP simulation has been executed. This part of the analysis serves to investigate which parameters the model mathematically is most sensitive towards.

In order to include the fact that the different parameters have different uncertainties the parameters have been changed to a) the assessed minimum value and b) the assessed maximum value in the second step of the analysis. This will identify the parameters, that impact the current model result the most.

The effect of a parameter change is calculated as the change in the accumulated leachate production in the baseline scenario. Due to the large number of subsimulations required for each parameter change, the sensitivity analysis has only been performed for cell 1.3.

Figure 14 depicts the impact of increasing each parameter by 50% one at a time. The analysis reveals that the precipitation, P, is the parameter, by far, that exert the largest influence on the modeled leachate production. An increase of 50% of the daily precipitation values causes a drastic increase of 90% in the leachate production at cell 1.3. Since the actual evapotranspiration does not increase accordingly, i.e. only by 30%, the effect of increasing the precipitation is very large.

The remaining parameters all causes a response that is well below 50% change, humidity being the most profound causing a leachate increase of 25%. This is followed by wind speed (8% decrease), evaporative zone depth (4% decrease) and temperature (3% decrease). The hydraulic conductivities of the layers as well as the solar radiation and the parameters associated with the vegetation (LAI and growing season) only exerts minimal change in the leachate production when increased by 50%.
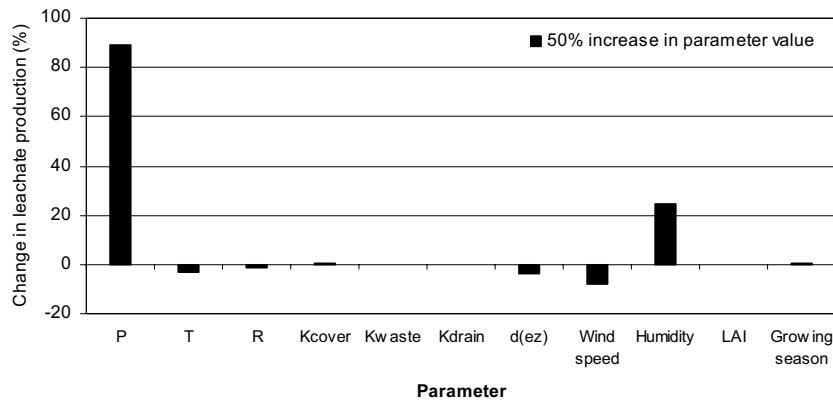
Figure 14. Sensitivity of the HELP model results when increasing a parameter value by 50%

The uncertainty associated with determination of the parameters used for the HELP simulation is assessed in Table 7 and varies significantly between the parameters. The suggested minimum and maximum value for each parameter will be used to illustrate the effect on the model result that arises from the actual parameter uncertainty.

As seen in Figure 15, the maximum precipitation, which represents corrected precipitation values, is the parameter that influence the result the most (42% increase). This is followed by the minimum depth of the evaporative zone (22% increase) and the minimum humidity (20% decrease).

The minimum hydraulic conductivity of the waste causes a 10% increase. Inexplicably, the maximum solar radiation causes an increase to the result, however minimally.
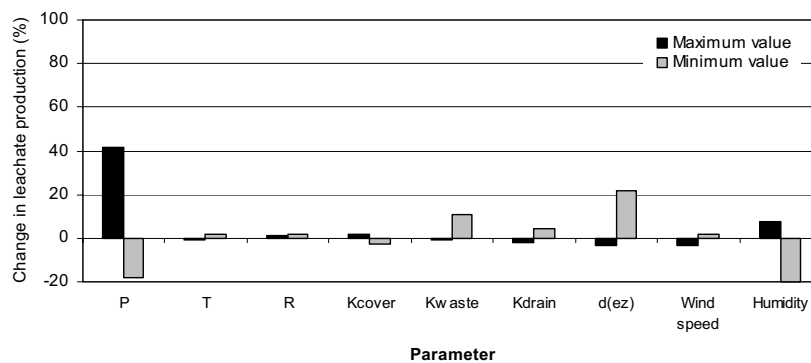
Figure 15. Sensitivity of the HELP model results when changing a parameter to its maximum and minimum value

The initial water content and porosity of the disposed waste have not been included in the sensitivity analysis. Scenario A and B, however, illustrated the significance of these parameters. In Scenario A, a 75% decrease of the porosity caused an increased initial leachate production at cell 1.3 of 18% and in Scenario B, the leachate production decreased by 42% when the initial water content of the waste was decreased by 65%.

3.4 L/S ratio

Based on the HELP simulation results, the liquid-to-solid ratio can be computed by dividing the accumulated leachate amounts with the waste amount of the specific cell.

Since the waste in the cells has been disposed over a period of years the L/S ratio will be higher for the older waste and lower for the younger waste.

The leachate amounts used for these calculations are the results obtained in the baseline scenario as well as the estimated future leachate production. Figure 16 - Figure 18 shows the predicted development in the L/S ratio since the start of disposal and until 2005.

An average L/S value has been calculated using the amount of leachate produced since the average disposal year of the waste. Furthermore a minimum and maximum L/S-value has been calculated assuming that all waste is disposed of in the initial and final year of the main disposal period of the specific cell. Due to the long disposal period for cell 1.5.1, the largest range in L/S value is found for waste in this cell.
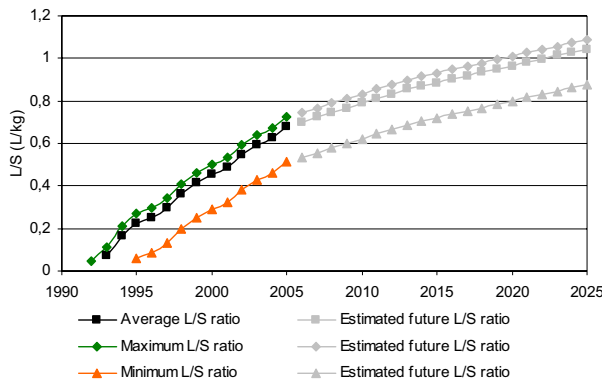
Figure 16. L/S ratio for waste in Cell 1.3. The average disposal year is 1993 and waste disposal has mainly taken place from 1992-1995.
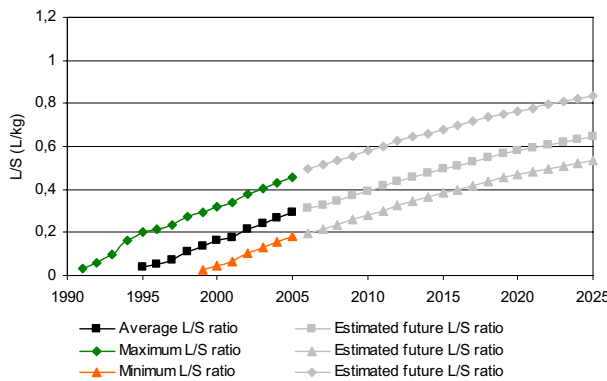
Figure 17. L/S ratio for waste in Cell 1.5.1. The average disposal year is 1995 and waste disposal has mainly taken place from 1991-1999.
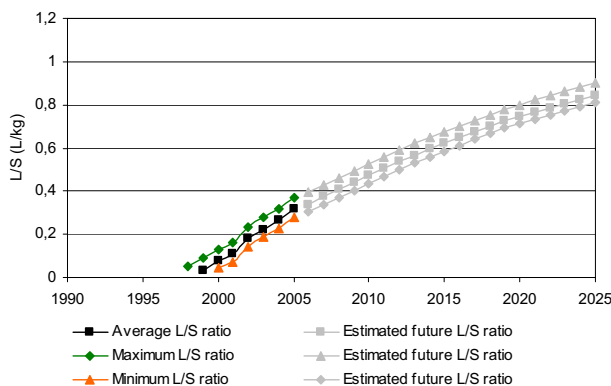
Figure 18. L/S ratio for waste in Cell 2.2.2. The average disposal year is 1995 and waste disposal has mainly taken place from 1998-2000.

The L/S ratios obtained by the end of 2005 and 2025 together with the corresponding maximum and minimum values are summarized in Table 12. As expected, currently the highest L/S value (0.65 l/kg) is found for the waste in cell 1.3, which was also the first cell to be finalized. The L/S ratio of waste in cells 1.5.1 and 2.2.2 is currently 0.30 l/kg. In 2025, the average L/S ratio of waste in cell 1.3 is forecasted to have increased to app. 1 l/kg, whereas it will be 0.68 l/kg and 0.85 l/kg for waste in cell 1.5.1 and 2.2.2 respectively.

Table 12. Average L/S ratios obtained using the leachate production simulated by HELP in the baseline scenario. The reported range for the L/S value describes the variation in the L/S value due to different ages of the waste in each cell.

Cell	L/S ratio 2005 (l/kg) Average value (range)	L/S ratio 2025 (l/kg) Average value (range)
1.3	0.68 (0.51-0.73)	1.04 (0.88-1.09)
1.5.1	0.30 (0.18-0.46)	0.65 (0.53-0.81)
2.2.2	0.31 (0.28-0.37)	0.85 (0.81-0.90)

The L/S ratios in Table 12 were calculated based on the model simulated leachate amounts for the baseline scenario. Taking into consideration the uncertainty of the input parameters as seen through the scenario and sensitivity analyses, the leachate amount can be significantly higher or lower. The accumulated leachate amounts as simulated in Scenario A and B are plotted in Figure 19 and Figure 20 together with the baseline scenario.
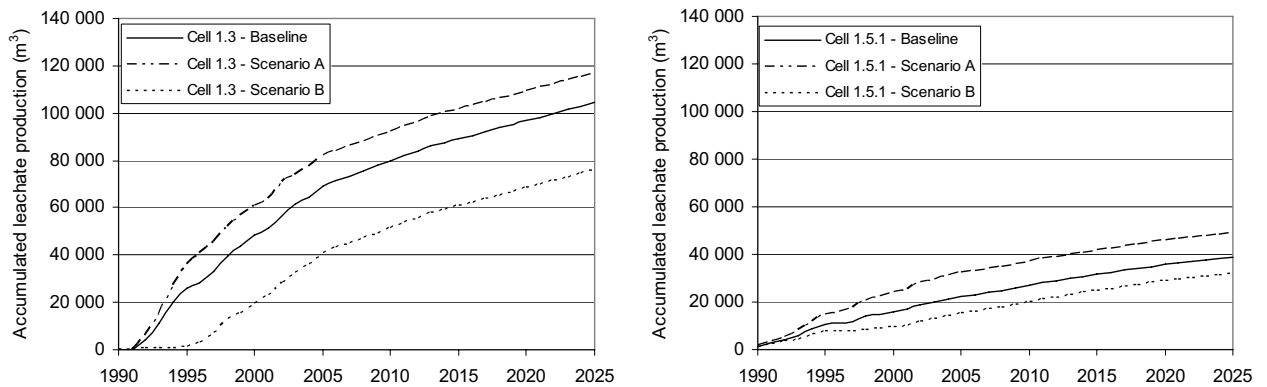
Figure 19. Accumulated leachate production Cell 1.3 and Cell 1.5.1. Results from baseline scenario, Scenario A and B.
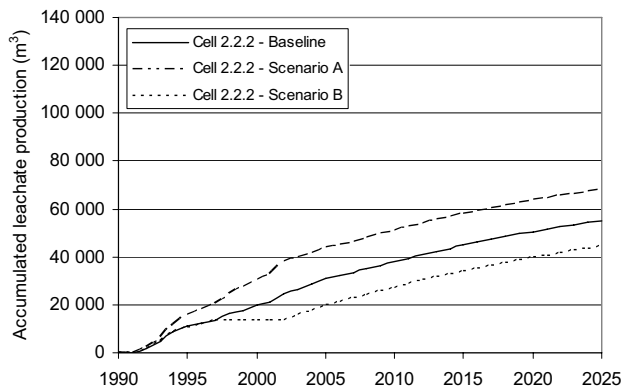
Figure 20. Accumulated leachate production Cell 2.2.2 Results from baseline scenario, Scenario A and B.

If, instead, the results from Scenario A or B are used for calculation of the L/S ratio, this will cause an average increase of 20% and decrease of 30% respectively in the L/S ratios for 2005. For the 2025 L/S ratio the Scenario A results are in average 15% higher and Scenario B results 30% higher.

4. Leachate characterization: Results and discussion

The analytic results obtained for the leachate sampled May and July 2006 from cells 1.5.1, 1.3 and 2.2.2 are summarized in table 13. The results will be commented and discussed in the following.

4.1 pH, conductivity, anions and ammonia

The pH values of the leachate ranged from slightly acidic (cell 1.3) to slightly alkaline (cell 1.5.1), whereas the leachate in cell 2.2.2 showed pH-values very close to neutral (Figure 21). The electrical conductivity ranged from 6.70-11.42 mS/cm, with the highest values found for cell 2.2.2.
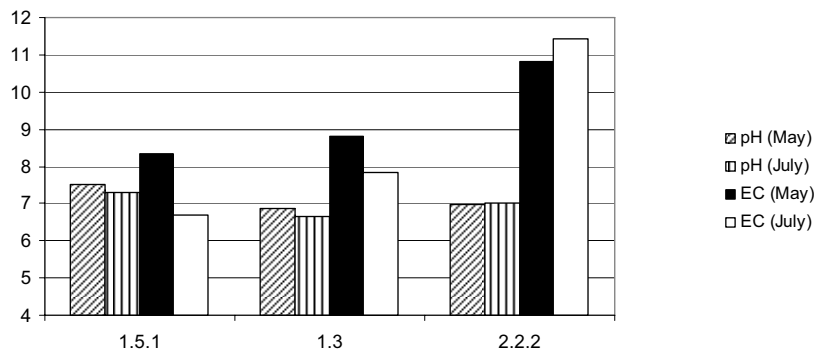
Figure 21. pH and electrical conductivity (EC) in mS/cm in leachate samples from cell 1.5.1, 1.3 and 2.2.2

The highest conductivity found in leachate from cell 2.2.2. This can partly be explained by a higher anion concentration of chloride and sulfate as seen in Figure 22. The ammonia concentration is lower for cell 2.2.2 than the other cells. The high chloride concentration in leachate in cell 2.2.2 is consistent with the low L/S ratio found for the waste in this cell, which means that the removal of dissolved compounds by leaching is only in its initial stage. The L/S of the waste in cell 1.5.1 is at the level as in cell 2.2.2; this is however not reflected in the chloride concentration, which was found to be lower in this cell, than in the other. This can possibly be due to the composition of the disposed waste.
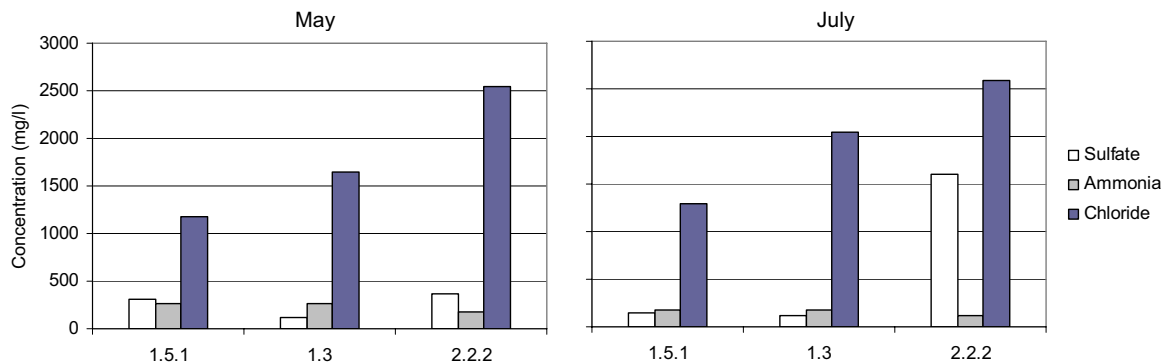
Figure 22. Concentrations of the sulfate, ammonia and chloride in leachate samples from cell 1.5.1, 1.3 and 2.2.2

4.2 Biological and chemical oxygen demand

The content of dissolved organic material in the leachate can be expressed by the chemical oxygen demand (COD), whereas only the readily biodegradable part is covered in the biological oxygen demand (BOD_5). The BOD_5 values are generally low in the leachate and range from 41-250 mg/l and the chemical oxygen demand range from 340-1190 mg/l. The highest COD and BOD values are found for cell 1.5.1. The BOD/COD ratio in the leachate is found to be quite low: 0.06-0.2. This indicates that the majority of the organic matter contained in the leachate is not readily biodegradable.

4.3 Metals/sulfur

In order to illustrate the metal content in the leachate samples graphically, the metals have been divided into 4 groups according to their concentration level. These are

1. High concentration metals: Ca, K, Na, Mg and S (42-1880 mg/l)
2. Iron and manganese: Fe and Mn (0.15-12.5 mg/l)
3. Low concentration metals: Al, Ni and Ba (24-1000 μg/l)
4. Trace metals: Zn, Cr, As, Co, Cu, Pb and Hg (0.02-35 μg/l)

The metal concentrations found in the leachate samples from the three cells are illustrated in Figure 23 (group 1 and 2) and Figure 24 (group 3 and 4).

High concentration metals and sulfur: Ca, K, Na, Mg and S

Leachate from cell 2.2.2 has the highest abundance of the high concentration metals. Sodium is found in the highest concentrations followed by calcium. The concentration levels are similar for May and July samples, except for calcium and sulfur concentration from cell 2.2.2 which is significantly higher in July.

Iron and Manganese

As for the high concentration metals, the highest iron and manganese concentrations are seen for cell 2.2.2. The very low iron concentrations found for cell 1.5.1 is in accordance with the fact, that this cell contains shredder waste, from which iron and other metals have been recovered during the shredding process. Furthermore, the higher pH of leachate from cell 1.5.1 will cause a larger part of the iron and manganese to be present in particulate form and precipitate.

Low concentration metals: Al, Ni and Ba

The very low aluminium content in leachate from cell 1.5.1 might also be due to the low pH as well as some extent of recovering of aluminium during shredding. Nickel, however, is not recovered from the waste and is found in high concentrations in leachate from this cell. Leachate from cell 2.2.2 has a significantly higher content of aluminium than leachate from the other cells and in leachate from May, a high barium content is seen as well.
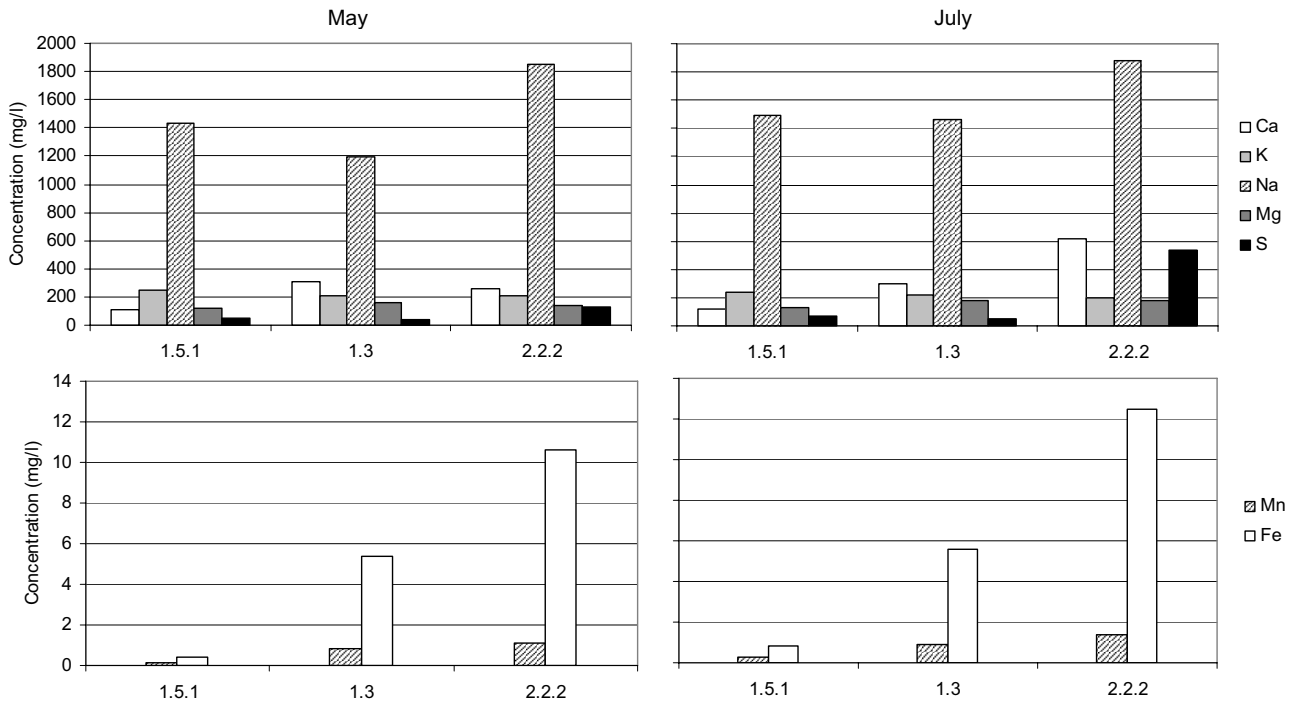
Figure 23. Metal concentrations (Group 1 and 2) in leachate samples from cell 1.5.1, 1.3 and 2.2.2

Trace metals: Zn, Cr, As, Co, Cu, Pb and Hg

For the trace metals a tendency of higher concentrations is again seen for cell 2.2.2. The number of trace metals detected in cell 1.3 is smaller than for the other cells, i.e. only 3 of 7 trace metals were present. At cell 1.5.1 all trace metals are detected, however in concentrations lower than for cell 2.2.2. Mercury is not included in *Figure 24*, since it has only been detected in cell 1.5.1 (July samples).
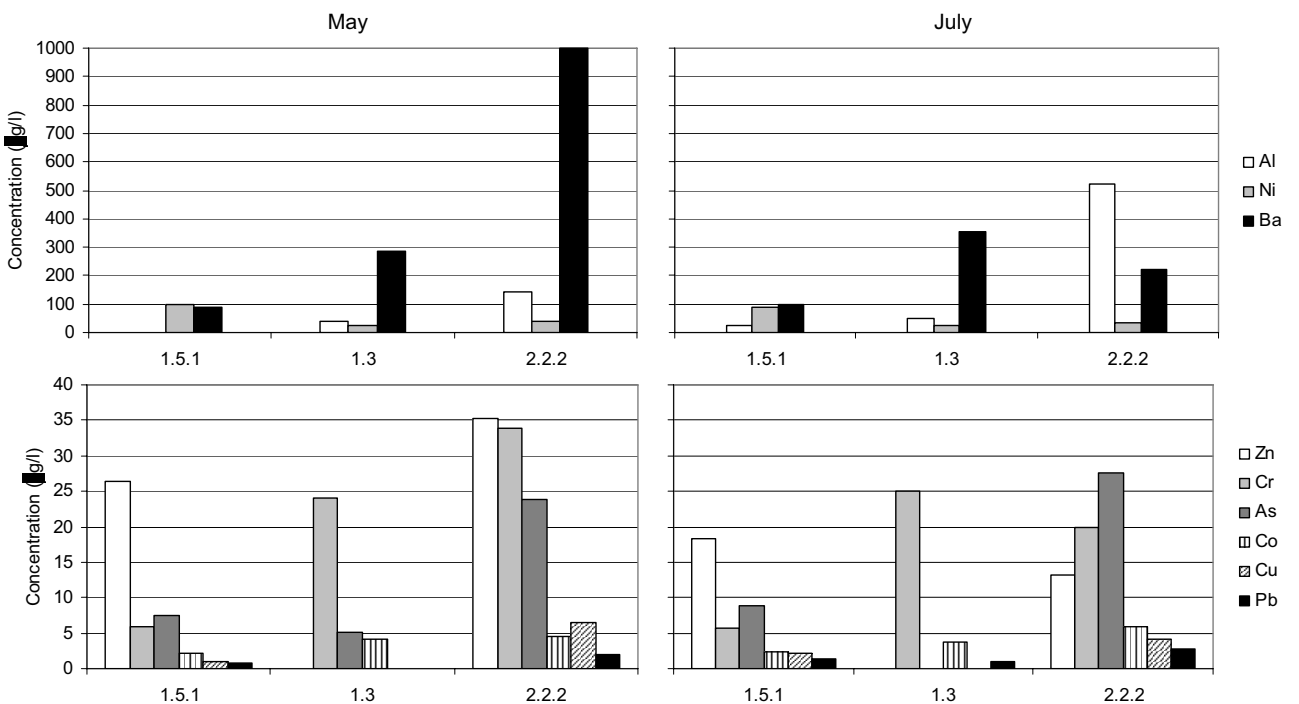
Figure 24. Metal concentrations (Group 3 and 4) in leachate samples from cell 1.5.1, 1.3 and 2.2.2

4.4 Specific organic contaminants

Of the specific organic contaminants included in the leachate characterisation, bisphenol A, is the compound found in the highest concentrations. Due to the low levels of the other compounds these were excluded from analyses of leachate collected in July.

The highest concentrations of bisphenol A was measured in leachate from cell 1.5.1 and ranged from 200-210 μg/l. Bisphenol A concentrations in leachate from cell 1.3 and 2.2.2 ranged from 2.6-29 μg/l. The observed concentrations of this compound are within ranges previously reported in the literature (see Appendix 3). The significant concentration levels of this compound are noteworthy due to its classification as an endocrine disrupting chemical.

In each cell, one out of the 10 the phthalates included in the analysis, were detected. In cell 1.5.1, di-ethylphthalate (DEP) was found in a concentration of 3.1μg/l.

Di-isobutylphthalate (DIBP) was found in both cell 1.3 and 2.2.2 in concentrations of 1.8 and 2.9 μg/l respectively. Di-(2-ethylhexyl) phthalate (DEHP) has previously been measured in leachate from cell 2.2.2 in concentration of 64μg/l. In the present study, the compound was however not detected. The phthalate concentrations in the present investigation are in the low range of those reported in landfill leachate in the literature, where DEP has been discovered in concentrations from 1-60μg/l. Findings of DIBP in landfill leachate have, however, not been reported in the literature.

The brominated flame retardants BDE 47 and BDE 99 were detected in the leachate. BDE 47 and BDE 99 was found in leachate from cell 2.2.2 in a concentrations of 0.2 ng/l and 0.18 ng/l respectively. Furthermore 0.13 ng/l of BDE 99 was found in leachate from cell 1.3. The remaining 12 brominated flame retardants were below detection limits. As opposed to what could have been expected, due to the shredder waste in cell 1.5.1, no BFRs were detected in leachate from this cell

Only few studies of the occurrence of brominated flame retardants in landfill leachate exist in the literature. These studies report the concentration as the sum of polybrominated byphenyls (ΣPBDEs), which has been reported in the range from below detection to 5 ng/l. For comparison, one of the studies report individual concentrations of BDE 47 to range from 0.011-0.017ng/l, whereas BDE 99 not is detected (see appendix 3)..

4-Nonylphenol concentrations of 0.94-1.29 μg/l was measured; with the highest concentrations observed in leachate from cell 1.3. 4-tertoctylphenol was also found in the highest concentrations in cell 1.3 and overall ranged from 0.098-0.45 μg/l. The observed concentrations of nonylphenol are low compared to literature values, where concentrations range from 2.8-7 μg/l.

Table 13. Analytical results of leachate analyses from cell 1.3, 1.5.1 and 2.2.2 at AV Miljø.

	Unit	Cell 1.3			Cell 1.5.1			Cell 2.2.2		
		May	July	SD	May	July	SD	May	July	SD
pH		6.87	6.66	0.1	7.52	7.30	0.2	6.97	7.02	0.0
EC	mS/cm	8.82	7.83	0.7	8.35	6.70	1.2	10.80	11.42	0.4
Ca	mg/l	311	302	6.4	108	121	9.2	263	620	252.4
Fe	mg/l	5.36	5.6	0.2	0.398	0.857	0.3	10.6	12.5	1.3
K	mg/l	207	219	8.5	245	234	7.8	208	196	8.5
Mg	mg/l	157	184	19.1	120	131	7.8	137	183	32.5
Na	mg/l	1190	1460	190.9	1430	1490	42.4	1850	1880	21.2
S	mg/l	42.4	52.5	7.1	54.6	70.4	11.2	132	536	285.7
Al	µg/l	39.4	51.7	8.7	<20	26.9		143	522	268.0
As	µg/l	5.05	<6		7.53	8.87	0.9	23.8	27.6	2.7
Ba	µg/l	284	356	50.9	89.9	99.4	6.7	1000	223	549.4
Cd	µg/l	<0,05	<0,05		<0,05	0.118		<0,05	0.0602	
Co	µg/l	4.08	3.69	0.3	2.12	2.28	0.1	4.46	5.92	1.0
Cr	µg/l	24	25.1	0.8	5.86	5.64	0.2	33.8	19.9	9.8
Cu	µg/l	<1	<1		1.01	2.18	0.8	6.53	4.14	1.7
Hg	µg/l	<0,02	<0,02		<0,02	0.0248		<0,02	<0,02	
Mn	µg/l	851	902	36.1	155	280	88.4	1130	1400	190.9
Ni	µg/l	24.1	25.5	1.0	97.4	90.3	5.0	39.2	34.3	3.5
Pb	µg/l	<0,6	1.02		0.695	1.4	0.5	1.93	2.78	0.6
Zn	µg/l	<4	<4		26.5	18.3	5.8	35.3	13.3	15.6
SO_4^{2-}	mg/l	115	123	5.7	305	153	107.5	366	1610	879.6
NH4-N	mg/l	264	176	62.2	270	172	69.3	172	120	36.8
Cl^-	mg/l	1650	2050	282.8	1170	1290	84.9	2550	2590	28.3
CODCr	mg/l	410	410	0.0	1190	890	212.1	51	340	204.4
BOD	mg/l	41	85	31.1	77	150	51.6	58	65	4.9
Dimethyl phthalate (DMP)	µg/l	<1,0			<1,0			<1,0		
Diethyl phthalate (DEP)	µg/l	<1,0			**3.1**			<1,0		
Di-n-propyl phthalate	µg/l	<1,0			<1,0			<1,0		
Di-n-butyl phthalate (DBP)	µg/l	<1,0			<1,0			<1,0		
Di-isobutyl phthalate (DIBP)	µg/l	**1.8**			<1,0			**2.9**		
Di-pentyl phthalate	µg/l	<1,0			<1,0			<1,0		
Di-n-octyl phthalate	µg/l	<1,0			<1,0			<1,0		
Di-(2-ethylhexyl) phthalate (DEHP)	µg/l	<1,0			<1,0			<1,0		
Butylbenzyl pthtalate (BBP)	µg/l	<1,0			<1,0			<1,0		
Di-cyclohexyl pthtalate	µg/l	<1,0			<1,0			<1,0		
Bisphenol A	µg/l	**9.6**	**29**	13.7	**200**	**210**	7.1	**21**	**2.6**	13.0
TetraBDE	µg/l	<0,0010			<0,0010			<0,0010		
BDE 47	µg/l	<0,0001			<0,0001			**0.0002**		
PentaBDE	µg/l	<0,0010			<0,0010			<0,0010		
BDE 99	µg/l	**0.00013**			<0,0001			**0.00018**		
BDE 100	µg/l	<0,0001			<0,0001			<0,0001		
HexaBDE	µg/l	<0,0020			<0,0020			<0,0020		
HeptaBDE	µg/l	<0,0040			<0,0040			<0,0040		
OctaBDE	µg/l	<0,0050			<0,0050			<0,0050		
NonaBDE	µg/l	<0,010			<0,010			<0,010		
DecaBDE	µg/l	<0,010			<0,010			<0,010		
Tetrabrom bisphenol-A (TBBA)	µg/l	<0,0050			<0,0050			<0,0050		
Decabrom biphenyl (DeBB)	µg/l	<0,010			<0,010			<0,010		
Hexabrom cyclododecan (HBCD)	µg/l	<0,010			<0,010			<0,010		
4-nonylphenol	ng/l	**1290**			**962**			**937**		
4-tert-octylphenol	ng/l	**453**			**98**			**246**		
BOD/COD		0.10	0.21		0.06	0.17		1.14	0.19	

SD: Standard deviation between measurements made in May and July

5. Conclusion

The average annual leachate production for the period from initiation of the cells 1.3, 1.5.1 and 2.2.2 and until today was simulated using HELP. The resulting water balance showed that an annual average of 195-209 mm of leachate has been generated during this period. This corresponds to 30-32% of the precipitation.

Under the assumption, that dead zones and significant channeling is present in the waste causes the modeled leachate production to increase to account for 37-45% of the precipitated water (Scenario A). Assuming a lower initial water content of the newly added waste material than for the existing waste causes a delay and/or a decrease in leachate formation during periods of waste build-up. In this scenario only 19-21% of the precipitation results in leachate formation, since 10-13% is used for replenishment of the water deficit in the waste.

An estimation of the future leachate production at the 3 cells has been simulated under the assumption that meteorological conditions are similar to those of 1990-2005. This gives an average annual leachate production of 73 mm (cell 1.3), 111 mm (cell 1.5.1) and 116 mm (2.2.2) in the future 20 years. The leachate accounts for 11%, 17% and 18% of the precipitation respectively.

The liquid-to-solid ratio (L/S ratio) was calculated based on the accumulated leachate amounts and the waste amounts at the cells. Waste at cell 1.3 has the highest L/S-value of 0.65 l/kg, whereas the L/S ratio for waste in cells 1.5.1 and 2.2.2 is only 0.3 l/kg.

The scenario and sensitivity analyses showed that the precipitation as well as the initial moisture and porosity of the waste are the parameters that impact the leachate production the most. Due to uncertainty in these parameters, the simulated leachate amounts and hence the calculated L/S values for 2005 can vary approximately +20%/-30%.

The highest concentration of anions and metals is generally found in leachate from cell 2.2.2. This is in correspondence with the low L/S ratio found for the waste in this cell. For cell 1.5.1 the L/S ratio, too was found to be low. This is in correspondence with high concentration of macro metals and anions. However, low concentrations were found for especially iron, manganese and aluminum, which partly may be ascribed the higher pH.

Trace metals were especially abundant in leachate from cell 2.2.2 and 1.5.1, whereas only few of the trace metals were detected in leachate from cell 1.3.

Of the specific organic contaminants included in the characterization, bisphenol A seems to be the most critical compound with concentrations up to 210 µg/l in cell 1.5.1. Diethylphthalate (DEP) and di-isobutylphthalat (DIBP) were detected in low concentrations (1.8-3.1 µg/l) in the leachate samples. The brominated flame retardants BDE 47 and 99 were detected in leachate from cell 1.3 and 2.2.2. At cell 2.2.2 , the sum of polybrominated byphenyls (ΣPBDE) was 0.38 ng/l. Concentrations of the alkylphenols nonylphenol and octylphenol were highest in leachate from cell 1.3 but concentration levels were generally low compared to literature values.

6. References

AV Miljø (2006). Svend Erik Christensen and Jonas Nedenskov, AV Miljø, Hvidovre, Denmark.

AV Miljø (no year). Etablering af affaldsdeponi. Pamphlet published by AV Miljø.

Berger, K. (2006). Email correspondence with Dr. Klaus Berger, University of Hamburg, Institute of Soil Science.

Berger, K. (2004). The Hydrological Evaluation of Landfill Performance (HELP) Model. Engineering Documentation for HELP 3.80 D – Enhancements Compared to HELP 3.07 .

Berger, K. (2000). Validation of the hydrologic evaluation of landfill performance (HELP) model for simulating the water balance of cover systems. Environmental Geology 39 (11) 2000.

Christensen, T.H. (ed.) (1998). Affaldsteknologi. Teknisk Forlag.

Cowi (2002). AV Miljø. Klassificering af affald deponeret på AV Miljø. Februar 2002.

Fredenslund, A.M. (2004). Deponeringsanlægget AV Miljø. Baggrundsrapport. Environment & Resources DTU.

Schroeder, P.R. & Berger, K. (2004). Das Hydrologic Evaluation of landfill Performance (HELP) Modell. Benutzerhandbuch für die deutsche Version 3.

WHI (2001). WHI UnSat Suite User's Manual. 1-D Unsaturated Zone Flow and Transport Modeling Using SESOIL, VLEACH, PESTAN and Visual HELP. Waterloo hydrogeologic.

Additional literature used for literature study in Appendix 3

Asakura, H., Matsuto, T., Tanaka, N. (2004) Behavior of endocrine-disrupting chemicals in leachate from MSW landfill sites in Japan. Waste Management 24 (2004) 613–622

Baun, A., Ledin, A., Reitzel, L.A., Bjerg, P.L., Christensen, T.H. (2004). Xenobiotic organic compounds in leachates from ten DanishMSW landfills—chemical analysis and toxicity tests. Water Research 38 (2004) 3845–3858.

Behnisch, P.A., Fujii, K., Shizaki, K., Kawakami, I., Sakai, S. (2001). Estrogenic and dioxin-like potency in each step of a controlled landfill leachate treatment plant in Japan. Chemosphere 43 (2001) 977-984.

Haarstad K. (2006). Målinger av utvalgte miljøgifter i sigevann. Haarstad et al. unpublished. Email correspondence with Ketil Haarstad, Senior researcher, Bioforsk Jord og miljø, Norway.

Haarstad, K., Eggen, T., Borch, H., Mæhlum, T. (2005). New pollutants in Norwegian leachates. Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium.

Jonsson, S, Ejlertsson, J., Ledin, A, Mersiowskyc, I., Svensson, B.H. (2003). Mono- and diesters from o-phthalic acid in leachates from different European landfills. Water Research 37 (2003) 609–617.

Osako, M., Kim, Y., Sakai, S. (2004). Leaching of brominated flame retardants in leachate from landfills in Japan. Chemosphere 57 (2004) 1571–1579.

Paxéus, N. (2000). Organic compounds in municipal landfill leachates. Water Science and Technology 42 (2000) 323-333.

Riediker, S., Suter, M. J.-F., and Giger, W. (2000).Benzene- and naphthalenesulfonates in leachates and plumes of landfills. Water Resources 34 (2000) 2069-2079.

Schwarzbauer, J., Heim, S., Brinker, S., Littke, R. (2002).Occurrence and alteration of organic contaminants in seepage and leakage water from a waste deposit landfill. Water Research 36 (2002) 2275–2287.

Yamamoto, T., Yasuhara, A., Shiraishi, H., Nakasugi, O. (2001).Bisphenol A in hazardous waste landfill leachates. Chemosphere 42 (2001) 415-418

Appendices

Appendix 1: Soil and layer data

Profiles of landfill cells

Cell 1.3

Waste build-up
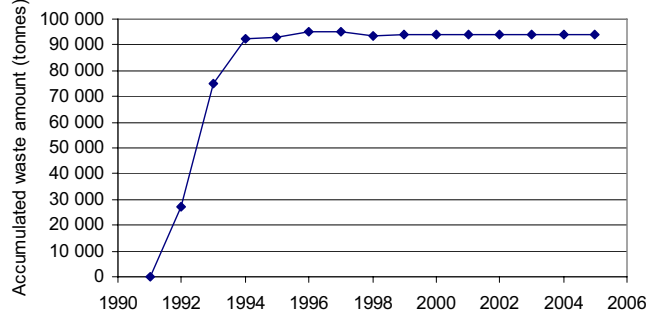
Estimated waste and cover depth
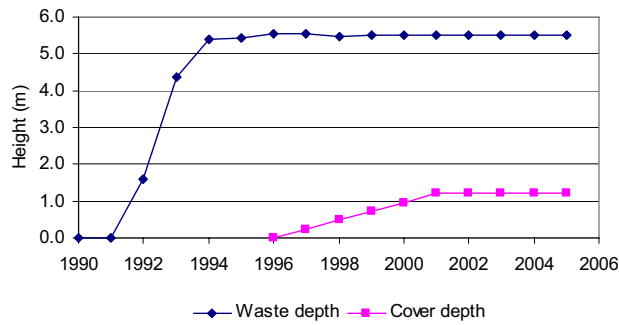
Layer profiles for sub periods

Cell 1.3		Layer thicknesses (cm)						Evaporative zone depth (cm)	Maximum LAI
Simulation periods	# years	Top soil	Soil cover	Gravel	Waste	Gravel	Moraine clay		
1	1992	1				159	30	700	25	0
2	1993	1				437	30	700	25	0
3	1994-1996	3				539	30	700	25	0
4	1997	1		4	20	550	30	700	25	0
5	1998	1		28	20	545	30	700	25	0
6	1999	1		52	20	550	30	700	25	0
7	2000	1		76	20	550	30	700	25	0
8	2001-2005	5	20	80	20	550	30	700	56	2
9	2006-2012	7	20	80	20	550	30	700	78	3.5
10	2013-2025	13	20	80	20	550	30	700	99	5

Cell 1.5.1

Waste build-up
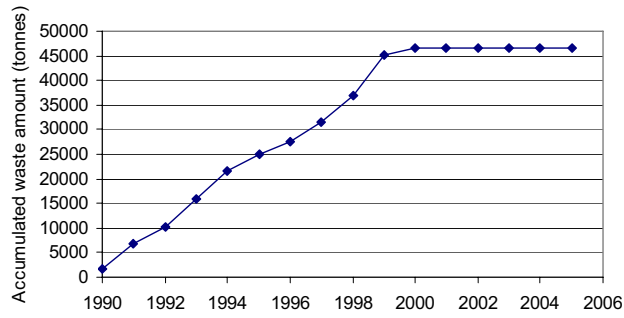
Estimated waste depth
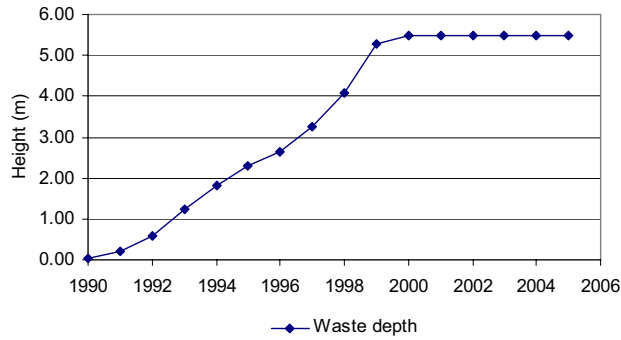
Layer profiles for sub periods

| Cell 1.5.1 | | Layer thicknesses (cm) | | | | | | Evaporative | |
Simulation periods	# years	Top soil	Soil cover	Gravel	Waste	Gravel	Moraine clay	zone depth (cm)	Maximum LAI
1	1990-1991	2				12	30	700	25	0
2	1992	1				57	30	700	25	0
3	1993	1				123	30	700	25	0
4	1994	1				182	30	700	25	0
5	1995	1				229	30	700	25	0
6	1996	1				264	30	700	25	0
7	1997	1				324	30	700	25	0
8	1998	1				406	30	700	25	0
9	1999	1				529	30	700	25	0
10	2000-2005	6				550	30	700	35	1
11	2006-2008	3		80	20	550	30	700	35	1
12	2009-2012	4		80	20	550	30	700	35	2
12	2013-2018	6		80	20	550	30	700	56	2
13	2019-2025	7		80	20	550	30	700	78	3.5

Cell 2.2.2

Waste build-up
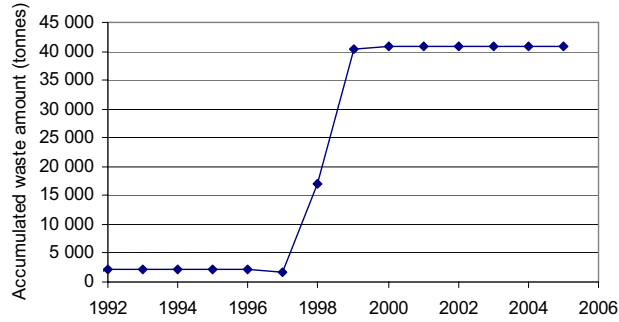
Estimated waste and cover depth
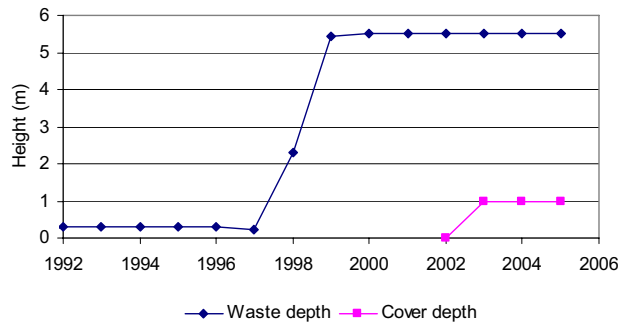
Layer profiles for sub periods

Cell 2.2.2		Layer thicknesses (cm)						Evaporative zone depth (cm)	Maximum LAI
Simulation periods	# years	Top soil	Soil cover	Gravel	Waste	Gravel	Moraine clay		
1	1992-1997	6				29	30	700	25	0
2	1998	1				229	30	700	25	0
3	1999	1				543	30	700	25	0
4	2000-2002	3				550	30	700	25	0
5	2003-2005	3		80	20	550	30	700	30	0.7
6	2006-2012	7		80	20	550	30	700	35	1
8	2013-2018	6		80	20	550	30	700	56	2
9	2019-2025	7		80	20	550	30	700	78	3.5
10										

Layer properties

Layer description (1): General properties — Layer description (2): Drainage and other properties

Layer	Layer type (1-4)	No. Soil texture	Total porosity (vol/vol)	Field capacity (vol/vol)	Wilting P. (vol/vol)	Init. Moist (vol/vol)	Saturated hyd. Conduct. (cm/s)	Drainage lenght (m)	Drain slope (%)	Leachate recirc. (%)	Recirc. to layer (#)	Subs. Inflow (mm/yr)
Top soil	1	7	0.473	0.222	0.104		5.20E-04					
Clayey soil	1	14	0.479	0.371	0.251		2.50E-05					
Gravel (root blocker)	1	21	0.397	0.032	0.013		3.00E-01					
Waste	1	18	0.671	0.292	0.077		1.00E-03					
Gravel (drainage layer. 1-8 mm)	2	21	0.397	0.032	0.013		3.00E-01	170	0.5			
Gravel (drainage layer. 1-8 mm)	2	21	0.397	0.032	0.013		3.00E-01	200	0.5			
Gravel (drainage layer. 1-8 mm)	2	21	0.397	0.032	0.013		3.00E-01	130	0.5			
Moraine clay (bottom membrane)[1]	3	24	0.365	0.305	0.202		1.90E-09					
Waste with dead zones and channeling		19	0.168	0.073	0.019		1.00E-03					

[1] A low saturated hydraulic conductivity of the moraine clay is chosen due to the intense pumping, that prevents leakage.

Layer types

1	Vertical percolation layer
2	Lateral drainage layer
3	Barrier soil layer
4	Geomembrane layer

Profiles of landfill cells (Scenario B)

Cell 1.3

Cell 1.3		Layer thicknesses (cm)													Evaporative zone depth (cm)	Maximum LAI
		Top soil	Soil cover 1	Soil cover 2	Soil cover 3	Soil cover 4	Soil cover 5	Gravel	Waste 1	Waste 2	waste 3	Waste 4	Gravel	Moraine clay		
Simulation periods	# years															
1 1992	1								159				30	700	25	0
2 1993	1								278	159			30	700	25	0
3 1994-1996	3		4						102	278	159		30	700	25	0
4 1997	1		4					20	11	102	278	159	30	700	25	0
5 1998	1		24	4				20	11	102	278	159	30	700	25	0
6 1999	1		24	24	4			20	11	102	278	159	30	700	25	0
7 2000	1		24	24	24	4		20	11	102	278	159	30	700	25	0
8 2001-2005	5	20	4	24	24	24	4	20	11	102	278	159	30	700	56	2

Cell 1.5.1

Cell 1.5.1		Layer thicknesses (cm)															Evaporative zone depth (cm)	Maximum LAI
		Top soil	Soil cover	Gravel	Waste 1	Waste 2	Waste 3	Waste 4	Waste 5	Waste 6	Waste 7	Waste 8	Waste 9	Waste 10	Gravel	Moraine clay		
Simulation periods	# years																	
1 1990-1991	2				12										30	700	25	0
2 1992	1				45	12									30	700	25	0
3 1993	1				66	45	12								30	700	25	0
4 1994	1				58	66	45	12							30	700	25	0
5 1995	1				47	58	66	45	12						30	700	25	0
6 1996	1				35	47	58	66	45	12					30	700	25	0
7 1997	1				61	35	47	58	66	45	12				30	700	25	0
8 1998	1				82	61	35	47	58	66	45	12			30	700	25	0
9 1999	1				123	82	61	35	47	58	66	45	12		30	700	25	0
10 2000-2005	6				21	123	82	61	35	47	58	66	45	12	30	700	35	1

Cell 2.2.2

Cell 2.2.2		Layer thicknesses (cm)									Evaporative zone depth (cm)	Maximum LAI
		Top soil	Soil cover	Gravel	Waste 1	Waste 2	Waste 3	Waste 4	Gravel	Moraine clay		
Simulation periods	# years											
1 1992-1997	6				29				30	700	25	0
2 1998	1				200	29			30	700	25	0
3 1999	1				314	200	29		30	700	25	0
4 2000-2002	3				7	314	200	29	30	700	25	0
5 2003-2005	3	80		20	7	314	200	29	30	700	30	0.7

Appendix 2: Climate data

Evapotranspiration data

Parameter	Value	Unit	Comment
Growing season start day	121	Julian day	May 1st to November 1st. Period with mean day temperature > 8°C
Growing season end day	305	Julian day	
Average wind speed	14.5	km/h	Average wind speed measured at Copenhagen Airport 1990-2005. Converted to 2 meters height.
First quarter relative humidity	85	%	
Second quarter relative humidity	74	%	Average quarterly relative humidities measured at Copenhagen Airport 1990-2005
Third quarter relative humidity	77	%	
Fourth quarter relative humidity	87	%	

Leaf area indices

Vegetation class	Maximum LAI [1]
Bare soil	0
Poor stand of grass	1
Fair stand of grass	2
Good stand of grass	3.5
Excellent stand of grass	5
Shrub	4-8
Deciduous forest	7-15
Coniferous forest	10-20

[1] Values from Schroeder & Berger (2004)

Correction of precipitation data

The measured precipitation P_G is corrected by using the formula:

$$P_C = (1 + K) \cdot P_G$$

Where P_C is the corrected precipitation value and (1+K) is a correction factor which depends on the shelter category of the specific rain gauge, see table below.

Standard values of precipitation corrections, K (%), for aerodynamic effect and wetting error as a function of shelter class and month of year

Shelter class	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly average
A	29	30	26	19	11	9	8	8	9	10	17	26	16
B	41	42	35	24	13	11	10	10	11	14	23	37	21
C	53	53	45	29	12	13	12	12	13	17	29	48	27

This means that if 5 mm of rain has been measured at Hvidovre Waterworks (shelter class B) in September 8, 1998, this number must be multiplied by a correction factor of 1.11 to find the actual precipitation.

Appendix 3: Organic contaminants in landfill leachate (a literature study)

A literature study has been carried out to investigate the specific organic contaminants found in landfill leachate. The study has focused especially on identifying contaminants occurring in new landfill types without disposal of municipal solid waste and covers the recent 7-year period. Reported contaminants and corresponding concentration ranges are summarized in the following table.

	Group	Compounds	Use	Concentration range detected in leachate (µg/l)	Landfill without MSW	Potential adverse effects
1	Phenols	• Bisphenol A	• Plasticizer • Fungiside • Coating of metal cans	**Japan** (Asakura et al., 2004): 0.13-224 (Landfill B) **Germany** (Schwarzbauer et al., 2002): **4200** **Japan** (Behnisch et al, 2001): 0.13 **Japan** (Yamamoto et al., 2001): 1.3-17200 (Median: 269) **Sweden** (Paxéus, 2000): 4-15 (Landfill A and B)	X (Landfill B) ÷ X (Industrial waste) X (Hazardous waste) X (Landfill A and B)	Endocrine disrupter
2	Phthalates	• Di-(2-ethylhexyl)pthtalate (DEHP) • Di-n-butylphthalate (DBP) • Diethyl phthalate (DEP) • Butylbenzylphthalate (BBP)	• Plasticizer	**Danmark** (Baun et al. 2004): **BBP**: 2, **DEHP**: 1-3, **DEP**: 60 **Japan** (Asakura et al., 2004): **DEHP**: 9.6-39 (Landfill B), **DBP**: 3-15, **DEP**: 1-8.4, **BBP**: 0.7-7.8 (Landfill A and B) **Sweden** (Jonsson et al., 2003): **DEHP**: 5-9, **DBP**: 1-23, **DEP**: 1-11, **BBP**: 2-5 **Germany** (Jonsson et al., 2003): **DEHP**: ≤20, **DBP**: 4-19, **DEP**:11-33, **BBP**: 7 **Italy** (Jonsson et al., 2003): **DEHP**: 88-460, **DBP**: 6-10, **DEP**:7-27 **Sweden** (Paxéus, 2000): **DEHP**: 97-346, **DBP**: 2, **BBP**: 1-2 (Landfill A and B)	÷ X (Landfill B) ÷ ÷ ÷ X (Landfill A and B)	Endocrine disrupter
3	Polychlorinated biphenyls	• PCB 28, 52, 101, 118, 138, 153, 180	• Incineration ash	**Japan** (Behnisch et al., 2001): **PCB**:0.046	X (Industrial waste)	Endocrine disrupter
4	Brominated flame retardants	• Polybrominated diphenyl ethers - PBDEs • Tetrabrombisphenol A (TBBA) • Decabrom biphenyl (DeBB) • Hexabrom cyclododecan (HBCD)	• Electrical appliances • Building materials • Textiles	**Japan** (Osako et al, 2004): ∑**PBDE-47,-99,-100**:b.d. – 0.004. **BDE 47**: 0.000011-0.000017 **Norway** (Haarstad et al, 2006): ∑**PBDE-28, 47,49+71, 66, 77, 85, 99,100, 119, 139, 153, 154, 183, 196, 206, 209**: 0.00253-0.00506	X ?	Endocrine disrupter
5	Pharmaceuticals	• Ibuprofene • Naproxene • Propyphenazone	• Pharmaceuticals	**Norway** (Haarstad et al., 2005): Ibuprofene: 0.06-0.5, Naproxene: 0.02-2 **Germany** (Schwarzbauer et al., 2002): **Propyphenazone**: 110-140	÷ ÷	Endocrine disrupter
7	Pesticides	• MCPP • Dichlorprop • MCPA	• Pesticides	**Denmark** (Baun et al., 2004): **MCPP**: 0.8-150 (9/10 landfills), **Dichlorprop**: 0.3-5.2 (8/10 landfills), **MCPA**: 0.2-9,1 (3/10 landfills)	÷	
8	Alkylphenolethoxylates/ degradation products (APEs/APs)	• Nonylphenol (NP) • Nonylphenolethoxylate (NPEO1) • Octylphenol (OP)	• Non-inoic surfactants • Industrial cleaning • Personal care products	**Denmark** (Baun et al., 2004): **NP**: 6.3-7 (2/10 landfills) **Japan** (Behnisch et al, 2001): **NP**: 2.8 **Sweden** (Paxéus, 2000): **NP**: 3-4 **NPEO1**: 3-5 (Landfill A and B)	÷ X (Industrial waste) X (Landfill A and B)	Endocrine disrupter
9	Chlorinated solvents	• PCE		**Denmark** (Baun et al., 2004): **PCE**: 6.9 (1/10 landfills)		

	Group	Compounds	Use	Concentration range detected in leachate (µg/l)	Landfill without MSW	Potential adverse effects

10	Aromatic sulfonates/sulfonamides	• Benzenesulfonateamides
		  - N-butylbenzenesulfonamid (NBBS)
		  - Diphenylsulfone
		  - N-ethyl-4-methyl-Benzenesulfonamide
		• Naphtalensulfonater (NS)
			Benzenesulfonater:
			• Azo dyes
			• optical brighteners
			• detergents
			• concrete plasticizers
			• sulfonamide plasticizers
				Germany (Schwarzbauer et al., 2002): **NBBS**: 590, **diphenylsulfone**: 32
				Sweden (Paxéus, 2000): **NBBS** 39-78, **N-ethyl-4-methyl-Benzenesulfonamide**: 2-8
				Switzerland (Rediker et al, 2000): levels not reported
					÷
					X (Landfill A and B)
					X
						NBBS: neurotoxic

11	Organotins	• Tributylin (TBT) • Triphenyltin (TPT)	• Antifoulig agents –ship paint			Endocrine disrupter

Appendix 4: HELP results

Baseline scenario

Cell 1.3

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1992	559	0	4507	380	179	1	0	0	0	0	0
1993	763	0	3837	447	278	1	38	38	0	0	0
1994	857	0	4332	465	385	1	7	7	0	0	0
1995	650	0	4365	494	244	1	-89	-93	0	5	0
1996	453	0	3920	341	89	1	22	27	0	-5	0
1997	536	0	4345	326	200	1	10	10	0	0	0
1998	755	0	3597	459	263	1	33	33	0	0	0
1999	651	0	4271	458	193	1	0	0	0	0	0
2000	594	0	3905	416	178	1	0	0	0	0	0
2001	625	0	4169	516	128	1	-20	-46	0	26	0
2002	860	0	4064	542	235	1	83	107	2	-26	0
2003	560	0	4263	478	179	1	-97	-97	0	0	0
2004	798	0	3694	574	139	1	84	83	1	0	0
2005	539	0	3979	419	199	1	-80	-96	-1	16	0
Sum	*9200*	*0*	*57247*	*6314*	*2889*	*8*	*-11*	*-30*	*2*	*16*	*0*
Annual average	*657*	*0*	*4089*	*451*	*206*	*1*	*-1*	*-2*	*0*	*1*	*0*
%	*100*	*0*	*622*	*69*	*31*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Cell 1.5.1

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1990	582	0	3837	416	165	1	0	0	0	0	0
1991	665	0	3562	459	204	1	1	1	0	0	0
1992	559	0	4507	380	174	1	5	5	0	0	0
1993	763	0	3837	447	275	1	40	40	0	0	0
1994	857	0	4332	465	389	1	3	3	0	0	0
1995	650	0	4365	485	249	1	-84	-89	0	5	0
1996	453	0	3920	343	89	1	21	21	0	0	0
1997	536	0	4345	389	130	1	16	16	0	0	0
1998	755	0	3597	498	255	1	3	3	0	0	0
1999	651	0	4271	475	152	1	24	24	0	0	0
2000	594	0	3905	471	164	0	-41	-43	1	0	0
2001	625	0	4169	508	102	0	14	-11	-1	26	0
2002	860	0	4342	543	270	1	46	69	2	-26	0
2003	560	0	4356	470	145	0	-56	-55	0	0	0
2004	798	0	3694	570	175	1	52	51	1	0	0
2005	539	0	3992	421	178	0	-60	-75	0	16	0
Sum	*10447*	*0*	*65030*	*7340*	*3114*	*9*	*-15*	*-38*	*3*	*21*	*0*
Annual average	*653*	*0*	*4064*	*459*	*195*	*1*	*-1*	*-2*	*0*	*1*	*0*
%	*100*	*0*	*622*	*70*	*30*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Cell 2.2.2

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1992	559	0	4507	380	179	0	0	0	0	0	0
1993	763	0	3837	447	286	0	29	29	0	0	0
1994	857	0	4332	465	384	1	8	8	0	0	0
1995	650	0	4365	494	204	1	-48	-53	0	5	0
1996	453	0	3920	341	110	1	1	6	0	-5	0
1997	536	0	4345	376	143	1	16	16	0	0	0
1998	755	0	3597	498	242	1	15	15	0	0	0
1999	651	0	4271	475	153	1	23	23	0	0	0
2000	594	0	3905	434	188	1	-29	-29	0	0	0
2001	625	0	4169	487	134	1	4	-22	0	26	0
2002	860	0	4342	495	311	1	54	80	0	-26	0
2003	560	0	4356	447	188	1	-75	-77	2	0	0
2004	798	0	3694	546	189	1	63	62	1	0	0
2005	539	0	3992	387	220	1	-68	-84	0	16	0
Sum	*9200*	*0*	*57631*	*6270*	*2930*	*8*	*-8*	*-26*	*2*	*16*	*0*
Annual average	*657*	*0*	*4117*	*448*	*209*	*1*	*-1*	*-2*	*0*	*1*	*0*
%	*100*	*0*	*626*	*68*	*32*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Scenario A

Cell 1.3

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1992	559	0	4507	312	247	1	0	0	0	0	0
1993	763	0	3837	342	386	1	35	35	0	0	0
1994	857	0	4332	347	499	1	10	10	0	0	0
1995	650	0	4365	347	366	1	-63	-68	0	5	0
1996	453	0	3920	237	207	1	9	13	0	-5	0
1997	536	0	4345	326	196	1	13	13	0	0	0
1998	755	0	3597	459	276	1	20	20	0	0	0
1999	651	0	4271	458	176	1	16	16	0	0	0
2000	594	0	3905	416	189	1	-11	-11	0	0	0
2001	625	0	4169	516	117	1	-9	-35	0	26	0
2002	860	0	4064	542	286	1	32	56	2	-26	0
2003	560	0	4263	478	129	1	-47	-47	0	0	0
2004	798	0	3694	574	163	1	60	59	1	0	0
2005	539	0	3979	419	176	1	-56	-72	-1	16	0
Sum	*9200*	*0*	*57247*	*5771*	*3411*	*8*	*10*	*-9*	*2*	*16*	*0*
Annual average	*657*	*0*	*4089*	*412*	*244*	*1*	*1*	*-1*	*0*	*1*	*0*
%	*100*	*0*	*622*	*63*	*37*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Cell 1.5.1

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1990	582	0	3837	363	218	1	0	0	0	0	0
1991	665	0	3562	389	275	1	1	1	0	0	0
1992	559	0	4507	312	248	1	-2	-2	0	0	0
1993	763	0	3837	342	389	1	32	32	0	0	0
1994	857	0	4332	347	503	1	7	7	0	0	0
1995	650	0	4365	338	372	1	-61	-65	0	5	0
1996	453	0	3920	238	203	1	11	11	0	0	0
1997	536	0	4345	298	221	1	16	16	0	0	0
1998	755	0	3597	347	408	1	0	0	0	0	0
1999	651	0	4271	365	264	1	22	22	0	0	0
2000	594	0	3905	401	212	1	-20	-21	1	0	0
2001	625	0	4169	446	162	1	16	-10	-1	26	0
2002	860	0	4342	445	407	1	7	32	2	-26	0
2003	560	0	4356	405	173	1	-19	-19	0	0	0
2004	798	0	3694	519	248	1	30	29	1	0	0
2005	539	0	3992	366	204	1	-31	-47	0	16	0
Sum	*10447*	*0*	*65030*	*5922*	*4507*	*10*	*9*	*-14*	*2*	*21*	*0*
Annual average	*653*	*0*	*4064*	*459*	*282*	*1*	*1*	*-1*	*0*	*1*	*0*
%	*100*	*0*	*626*	*56*	*44*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Cell 2.2.2

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1992	559	0	4507	312	247	1	0	0	0	0	0
1993	763	0	3837	343	393	1	28	28	0	0	0
1994	857	0	4332	347	501	1	8	8	0	0	0
1995	650	0	4365	347	349	1	-46	-51	0	5	0
1996	453	0	3920	237	215	1	1	5	0	-5	0
1997	536	0	4345	285	235	1	15	15	0	0	0
1998	755	0	3597	347	401	1	7	7	0	0	0
1999	651	0	4271	365	263	1	23	23	0	0	0
2000	594	0	3905	323	293	1	-23	-23	0	0	0
2001	625	0	4169	390	217	1	17	-9	0	26	0
2002	860	0	4342	341	518	1	0	26	0	-26	0
2003	560	0	4356	447	136	1	-23	-25	2	0	0
2004	798	0	3694	546	219	1	32	31	1	0	0
2005	539	0	3992	387	187	1	-35	-51	0	16	0
Sum	*9200*	*0*	*57631*	*5016*	*4172*	*8*	*4*	*-15*	*2*	*16*	*0*
Annual average	*657*	*0*	*4117*	*358*	*298*	*1*	*0*	*-1*	*0*	*1*	*0*
%	*100*	*0*	*626*	*55*	*45*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Scenario B

Cell 1.3

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1992	559	0	4507	356	20	0	183	183	0	0	0
1993	763	0	3837	447	0	0	316	316	0	0	0
1994	857	0	4332	465	0	0	392	392	0	0	0
1995	650	0	4365	494	26	0	130	126	0	5	0
1996	453	0	3920	341	74	1	37	41	0	-5	0
1997	536	0	4345	326	171	1	39	39	0	0	0
1998	755	0	3597	459	263	1	34	34	0	0	0
1999	651	0	4271	458	85	1	107	107	0	0	0
2000	594	0	3905	415	185	1	-7	-7	0	0	0
2001	625	0	4169	516	127	1	-18	-44	0	26	0
2002	860	0	4064	542	228	1	89	114	2	-26	0
2003	560	0	4263	478	186	1	-104	-104	0	0	0
2004	798	0	3694	574	139	1	84	84	1	0	0
2005	539	0	3979	419	200	1	-80	-96	-1	16	0
Sum	*9200*	*0*	*57247*	*6290*	*1702*	*7*	*1201*	*1183*	*2*	*16*	*0*
Annual average	*657*	*0*	*4089*	*449*	*122*	*0*	*86*	*84*	*0*	*1*	*0*
%	*100*	*0*	*622*	*68*	*19*	*0*	*13*	*13*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Cell 1.5.1

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1990	582	0	3837	415	132	1	34	34	0	0	0
1991	665	0	3562	459	204	1	1	1	0	0	0
1992	559	0	4507	356	122	0	81	81	0	0	0
1993	763	0	3837	447	153	0	162	162	0	0	0
1994	857	0	4332	465	261	1	131	131	0	0	0
1995	650	0	4365	485	149	1	15	10	0	5	0
1996	453	0	3920	329	39	0	85	85	0	0	0
1997	536	0	4345	368	39	0	129	129	0	0	0
1998	755	0	3597	498	81	0	176	176	0	0	0
1999	651	0	4271	475	50	0	127	127	0	0	0
2000	594	0	3905	471	46	0	77	75	1	0	0
2001	625	0	4169	508	100	0	16	-9	-1	26	0
2002	860	0	4342	543	239	1	77	101	2	-26	0
2003	560	0	4356	470	178	0	-89	-88	0	0	0
2004	798	0	3694	571	165	1	62	61	1	0	0
2005	539	0	3992	421	186	1	-67	-83	0	16	0
Sum	*10447*	*0*	*65030*	*7280*	*2144*	*7*	*1015*	*992*	*3*	*21*	*0*
Annual average	*653*	*0*	*4064*	*455*	*134*	*0*	*63*	*62*	*0*	*1*	*0*
%	*100*	*0*	*626*	*68*	*21*	*0*	*11*	*11*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Cell 2.2.2

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
1992	559	0	4507	356	151	0	52	52	0	0	0
1993	763	0	3837	447	286	0	29	29	0	0	0
1994	857	0	4332	465	384	1	8	8	0	0	0
1995	650	0	4365	494	204	1	-48	-53	0	5	0
1996	453	0	3920	341	110	1	1	6	0	-5	0
1997	536	0	4345	376	143	1	16	16	0	0	0
1998	755	0	3597	498	23	0	235	235	0	0	0
1999	651	0	4271	475	0	0	177	177	0	0	0
2000	594	0	3905	434	0	0	160	160	0	0	0
2001	625	0	4169	487	0	0	138	112	0	26	0
2002	860	0	4342	495	1	0	365	391	0	-26	0
2003	560	0	4356	447	186	1	-74	-76	2	0	0
2004	798	0	3694	546	183	1	68	68	1	0	0
2005	539	0	3992	387	226	1	-74	-90	0	16	0
Sum	*9200*	*0*	*57631*	*6246*	*1897*	*5*	*1052*	*1034*	*2*	*16*	*0*
Annual average	*657*	*0*	*4117*	*446*	*135*	*0*	*75*	*74*	*0*	*1*	*0*
%	*100*	*0*	*626*	*68*	*21*	*0*	*11*	*11*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Future Scenario

Cell 1.3

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
2006	653	0	4021	566	88	1	-1	-3	2	0	0
2007	653	0	4021	565	87	1	0	0	0	0	0
2008	653	0	4016	565	87	1	1	1	0	0	0
2009	653	0	4021	565	89	1	-1	-1	0	0	0
2010	653	0	4021	565	88	1	0	0	0	0	0
2011	653	0	4021	565	88	1	0	0	0	0	0
2012	653	0	4016	565	87	1	1	1	0	0	0
2013	653	0	4021	590	87	1	-24	-27	2	0	0
2014	653	0	4021	589	63	1	0	0	0	0	0
2015	653	0	4021	589	63	1	0	0	0	0	0
2016	653	0	4016	589	63	1	1	1	0	0	0
2017	653	0	4021	589	65	1	-1	-1	0	0	0
2018	653	0	4021	589	63	1	0	0	0	0	0
2019	653	0	4021	589	64	1	0	0	0	0	0
2020	653	0	4016	589	63	1	1	1	0	0	0
2021	653	0	4021	589	65	1	-1	-1	0	0	0
2022	653	0	4021	589	63	1	0	0	0	0	0
2023	653	0	4021	589	64	1	0	0	0	0	0
2024	653	0	4016	589	63	1	1	1	0	0	0
2025	653	0	4021	589	65	1	-1	-1	0	0	0
Sum	*13065*	*0*	*80388*	*11615*	*1461*	*12*	*-24*	*-28*	*5*	*0*	*0*
Annual average	*653*	*0*	*4019*	*581*	*73*	*1*	*-1*	*-1*	*0*	*0*	*0*
%	*100*	*0*	*615*	*89*	*11*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Cell 1.5.1

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil\ water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
2006	653	0	4021	534	96	0	23	21	2	0	0
2007	653	0	4021	534	119	0	0	0	0	0	0
2008	653	0	4016	534	119	0	0	0	0	0	0
2009	653	0	4021	509	150	1	-7	-9	2	0	0
2010	653	0	4021	509	144	1	0	0	0	0	0
2011	653	0	4021	509	144	1	0	0	0	0	0
2012	653	0	4016	508	144	1	1	1	0	0	0
2013	653	0	4021	536	132	1	-16	-18	2	0	0
2014	653	0	4021	536	117	1	0	0	0	0	0
2015	653	0	4021	536	117	1	0	0	0	0	0
2016	653	0	4016	535	117	1	1	1	0	0	0
2017	653	0	4021	536	117	1	-1	-1	0	0	0
2018	653	0	4021	536	117	1	0	0	0	0	0
2019	653	0	4021	566	114	1	-27	-29	2	0	0
2020	653	0	4016	565	86	1	1	1	0	0	0
2021	653	0	4021	566	88	1	-1	-1	0	0	0
2022	653	0	4021	565	87	1	0	0	0	0	0
2023	653	0	4021	565	87	1	0	0	0	0	0
2024	653	0	4016	565	87	1	1	1	0	0	0
2025	653	0	4021	565	89	1	-1	-1	0	0	0
Sum	*13065*	*0*	*80388*	*10808*	*2272*	*11*	*-26*	*-35*	*8*	*0*	*0*
Annual average	*653*	*0*	*4019*	*540*	*114*	*1*	*-1*	*-2*	*0*	*0*	*0*
%	*100*	*0*	*615*	*83*	*17*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil\ water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.

Cell 2.2.2

Water budget (mm/year)

Year	P	R	E_{pot}	E_a	$L_{lateral}$	$L_{leakage}$	ΔS	$\Delta S_{soil water}$	$\Delta S_{interception}$	ΔS_{snow}	Balance
2006	653	0	4021	509	112	1	32	30	2	0	0
2007	653	0	4021	509	144	1	0	0	0	0	0
2008	653	0	4016	508	144	1	1	1	0	0	0
2009	653	0	4021	509	144	1	-1	-1	0	0	0
2010	653	0	4021	509	144	1	0	0	0	0	0
2011	653	0	4021	509	144	1	0	0	0	0	0
2012	653	0	4016	508	145	1	1	1	0	0	0
2013	653	0	4021	536	131	1	-14	-16	2	0	0
2014	653	0	4021	536	117	1	0	0	0	0	0
2015	653	0	4021	536	117	1	0	0	0	0	0
2016	653	0	4016	535	117	1	1	1	0	0	0
2017	653	0	4021	536	117	1	-1	-1	0	0	0
2018	653	0	4021	536	117	1	0	0	0	0	0
2019	653	0	4021	566	113	1	-26	-29	2	0	0
2020	653	0	4016	565	86	1	1	1	0	0	0
2021	653	0	4021	566	88	1	-1	-1	0	0	0
2022	653	0	4021	565	87	1	0	0	0	0	0
2023	653	0	4021	565	87	1	0	0	0	0	0
2024	653	0	4016	565	87	1	1	1	0	0	0
2025	653	0	4021	565	89	1	-1	-1	0	0	0
Sum	*13065*	*0*	*80388*	*10731*	*2330*	*12*	*-8*	*-14*	*6*	*0*	*0*
Annual average	*653*	*0*	*4019*	*537*	*116*	*1*	*0*	*-1*	*0*	*0*	*0*
%	*100*	*0*	*615*	*83*	*17*	*0*	*0*	*0*	*0*	*0*	*0*

P: Precipitation, R: Surface runoff, E_{pot}: Potential evapotranspiration, E_a: Actual evapotranspiration, $L_{lateral}$: Leachate collected from drainage layer, $L_{leakage}$: Leachate leaking through bottom membrane, ΔS: Total change in stored water, $\Delta S_{soil water}$: Change in water stored in soil, $\Delta S_{interception}$: Change in water stored as interception, ΔS_{snow}: Change in water stored as snow.