A water balance model for landfill De Kragge II

Supporting the development of a sustainable aftercare approach

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by

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to obtain the degree of Master of Science
at the Delft University of Technology
to be defended publicly on Wednesday May 9th 2018 at 15.00.

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Project duration:	September 2017 – May 2018	
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Cover image: Photo of landfill De Kragge II, reprinted from Google Maps (n.d.)

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TU Delft

Preface

Before you lies my thesis “A water balance model for landfill De Kragge II: Supporting the development of a sustainable aftercare approach”. It has been written to fulfil the graduation requirements of the master track Geo-Engineering at the faculty of Civil Engineering and Geosciences at the University of Technology in Delft. I was engaged in researching and writing this thesis from September 2017 to May 2018.

This research is part of a project in which landfill sustainability is increased with treatment performed by the TU Delft. The coming years the results of the project will be analysed. As preparation, I made a water balance model for one of the project locations using baseline measurement data. During my master I gained interest in the field of geohydrology and this the main reason why this research topic interested me so much. In addition its relation to environmental aspects made me exited about this subject. The water balance model can be coupled with chemical reactions inside the landfill, leading to information about ex-filtrating contaminations. If the project succeeds, landfills will be less harmful for the environment in the future. This project is executed in collaboration with different companies including Attero. Attero maintains one of the project location, De Kragge II on which my research is focussed.

I would like to thank my graduation committee: Timo Heimovaara, André van Turnhout, Julia Gebert and Thom Boogaard, for guiding me during this research. Their thoughts and ideas helped me reflect on and improve my work throughout the process. Especially, I would like to thank André for his help, feedback and never ending patience. In addition I would like to thank Sylwia Kowalska, Hans Hertog and Frank Simons for answering all my questions regarding the data collection and construction of De Kragge II.

I would also like to thank my family and friends for their support during my study time in Delft.

L. Vermeijden
Delft, May 2018

Summary

Landfills are full of contaminated material, which could be harmful for the environment. To reduce the risks of pollutants entering the environment, a watertight base layer and an impermeable cover layer isolate the waste. These layers have to be maintained eternally, which is very costly. To move towards a more sustainable landfill aftercare, Dutch landfill operators have started three demonstration projects, to reduce leachate concentration in 10 years. At one of the projects, this is attempted by recirculation of leachate, which in the long term, reduces the concentrations of pollutants in the leachate. During the project the reduction of emissions via leachate is measured, but in order to make this project successful, it also has to be proofed that the emissions are reduced permanently. To proof that the emission via leachate is permanently reduced a model is required which enables to predict how remaining mass in the landfill will be emitted via leachate, based on time series of leachate quantity and quality.

This research focusses on adapting the prediction models, created for two demonstration projects, to describe the water balance for the third demonstration field at De Kragge II in Bergen op Zoom. Compared with the other two projects, the water balance for this field is a bit more complicated, since it has a different layout of the drainage system and lateral flow to and from adjacent fields is possible. The aim of this research is to model the water dynamics in the landfill with minimal uncertainty.

Available input and output data are: rainfall, evaporation potential, leachate levels and leachate outflow, available for the pilot field and the adjacent compartment. The leachate outflow is controlled by valves, level meters and pumps in the flow system, also the operator has influence on which compartment is drained. Another complication with the outflow data is that the data from weighed trucks transporting the leachate indicate that sometimes leachate was directly pumped from the landfill, herewith bypassing the flowmeter.

The model consists of three layers, a recultivation-, waste- and drainage layer. In the recultivation layer infiltration into the waste layer is calculated by balancing rainfall, evapotranspiration and storage. The water volume infiltrating the waste layer is distributed stochastically, according to a travel time distribution, that discretizes the infiltrated water to faster and slower moving regimes. In the drainage layer model, the balance of water inflow, leachate outflow, sideflow and storage is calculated. Resulting in a volume of water ex-filtrating the landfill. To evaluate model uncertainty, visual and quantative criteria are used. The fits of modelled on measured data is used as a visual check. The quantitative analysis consists of evaluating the Kullback-Leibler divergence and the marginalized likelihood. The Kullback-leibler divergence estimates how much information is gained from the parameters, while the marginalized likelihood determines the balance between information content and complexity.

In order to find a model that describes the water dynamics with minimal uncertainty, three different model implementations were evaluated. In the first approach both leachate level and outflow were used for calibration with measured data. Evaluation of the model performance showed that the outflow could not be determined with acceptable error. This was indicated by large standard deviations of the model and measurement error with respect to outflow measurements. Likely the reason for this is the gap in the water balance and the erratic patterns in the outflow data. A second approach was therefore modelled in which only the leachate levels were fitted with measured data and the outflow data was given as input. This increased the leachate level fits slightly, also the quantitative criteria showed that approach 2 is better than approach 1. Some of the parameters of approach 2 had large uncertainty and the model is quite complex given the available measured data. Therefore a third, simpler and faster model was implemented. In this model the waste layer calculations were simplified using the circular convolution function of MATLAB. This function calculates the travel time distribution continuously instead of discretizing the function over given retention times, which was done in the first two approaches. This model approach gave the best leachate level fits. The Kullback-leibler divergence indicated higher information content compared to approach 2.

In addition, each approach was evaluated with different model scenarios in which the waste compartments where either coupled or uncoupled. For each approach the uncoupled models performed visually and quantitatively better than the coupled models.

Approach 2 gave the best insight in the water dynamics given its complexity, shown by the higher values for the marginalized likelihood. Approach 3 gave the best fits, of the leachate levels, the highest D_{KL} values and is the fastest model. From these results it would be advised to use approach 3 to analyse the water dynamics of the landfill. Given the results of the different scenarios, it would be advised to use the uncoupled models for the analysis of water dynamics inside the landfill, since these models showed the best fits, highest D_{KL} and marginalized likelihood values.

Based on the obtained results, the following insights could be drawn about the landfill dynamics. The sideflow between the two compartments is about 5 to 25 m^3/day. The model showed that water in the landfill, flows fast from the cover layer to the drainage layer. The infiltration flux of the recultivation layer model seemed to be dominated by rainfall and evaporation. Therefore this model could be simplified by omitting water storage and flow through the layer.

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Nomenclature

Abbreviations

EC	Electrical conductivity	
DREAM	DiffeRential Evolution Adaptive Metropolis	
pdf	Probability density function	

Parameters

A	Area	[m^2]
β	Fraction between slow and fast moving water	[-]
dS	Change in storage	[m^3]
Δz_{root}	Thickness of the recultivation layer	[m]
dL	Change in leachate level	[m]
E_{pot}	Evapotranspiration potential	[m/d]
f_{crop}	Crop factor	[-]
f_{water}^{ini}	Initial water fraction	$[\frac{kgwater}{kgdryweight}]$
H	Parameterset	[-]
h_{dike}	Dike height	[m]
K	Hydraulic conductivity	[m/d]
k	Permeability	[m^2]
L	Leachate level	[m]
$L(H\|\tilde{y})$	Likelihood of the parameters	[-]
m	Empirical shape parameter	[-]
μ	Mean	[d],[m],[m^3]
n	Amount of mobile travel times	[-]
N	Number of measurements	[-]
ϕ	Porosity	[-]
$p(H)$	Prior probability of H	[-]
$p(H\|\tilde{y})$	Posterior probability of H given the model	[-]
q	Water flux	[m/d]
Q	Water flow	[m^3]
S_{eff}	Effective Saturation	[-]
σ	Standard deviation	[d],[m],[m^3]
τ	Retention time	[d]
θ	Volumetric water content	[-]
$\tilde{y}$	Modelled data	[-]
y	Measured data	[-]

Subscripts

$base$	Baseflow
c_n	Compartment n
$drain$	Drainage layer
$evap$	Evaporation
$fast$	Fast moving water
in	Initial
inf	Infiltration
im	Immobile
$level$	Leachate level
lf	Landfill
m	Mobile
out	Outflow
res	Residual
$rain$	Rainfall
rec	Recultivation layer
sat	Saturated
$side$	Sideflow
$slow$	Slow moving water
t	Time
TE	Total error
$waste$	Waste layer

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1 Introduction

We all produce a lot of waste. This waste is thrown in a garbage bin and picked up by a waste processing company. But what happens after that? Currently most of your waste is incinerated, but in the past it was most likely to end up in a landfill (Werkgroep Afvalregistratie, 2016). In the Netherlands there are hundreds of landfills of which some are still operating. These landfills are full of contaminated material. The main pollutants inside landfills are chloride, methane, carbon dioxide and metals. These pollutants are of greatest concern, because high concentrations are present in water ex-filtrating the landfill. When this polluted water gets in contact with the environment it could be harmful. To reduce environmental risks, landfills should be handled with care.

1.1. Recent developments

Before the 90's, there were no laws or regulations on dumping waste. This changed with the publication of four guidelines, between 1991 and 1997, containing requirements regarding landfill construction (Ministerie van VROM, 1991; Heidemij Adviesbureau, 1993a,b; IWACO B.V., 1997). The aim of these guidelines is to:

1. Keep pollutants inside the waste
2. Capture produced gas
3. Keep the leachate (polluted water) quantity from the landfill low
4. Make sure diffusion of solute transport from the landfill to the environment is low

A modern landfill design takes into account these aspects. A schematisation of such a landfill structure is shown in Figure 1.1. Before dumping the waste, a watertight base layer and drainage system have to be constructed at the site. When the landfill is full, the site has to be closed. This is done by placing an impermeable cover layer. The watertight base layer and impermeable cover layer isolate the waste from the environment and pollutants are kept inside. Produced leachate and gas is collected.

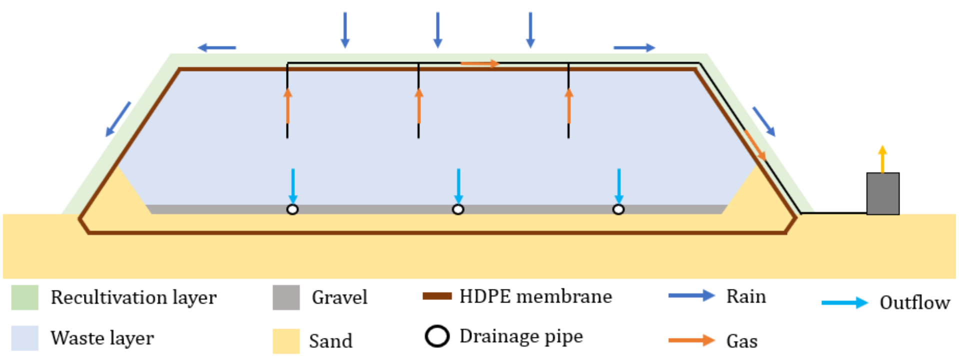

Figure 1.1: A schematisation of the structure of a modern landfill.

During construction and after closure the landfill needs to be controlled by the operator according to an aftercare protocol (art. 8.49 Wet MB 2017). The aftercare consists of collection, purification and transportation of the leachate, collecting the gas formed inside the landfill and check if pollutants end up in the environment. The current setup of aftercare is not an ideal solution for taking care of our waste. The main disadvantages of the aftercare protocol are:

1. Aftercare of landfills is very costly
2. The aftercare is a never ending process
3. Re-use of the landfill site after landfilling is restricted
4. In time the cover layer should be replaced (every 75 years)
5. There will always be a risk for the environment
6. Passing along the aftercare to future generations

The past few years different companies and universities came up with a new idea for the aftercare. Landfills could be treated to reduce the concentrations of pollutants in the leachate, instead of keeping our waste isolated form the environment (Introductie Duurzaam Stortbeheer, 2017). This treatment would consist of air or leachate infiltration, reducing the emission potential of the landfill. Emission potential is a term describing the possibility of mass of pollutants present inside the landfill to flow out. It has been shown in lysimeter experiments that treatment reduces the concentrations of pollutants in leachate (Valencia et al., 2011; Brandstätter et al., 2015). Concentrations in the leachate of the lysimeter experiments are likely reduced by creating more optimal conditions inside for (bio)degradation such as higher temperatures, increased moisture content and improved mixing of micro-organisms or other substrates. Since, the emission potential was reduced in lysimeter experiments due to treatment, it is expected that reduction is also possible with landfill treatment. A reduction of the emission potential of a landfill will result in it being harmless for the environment and aftercare could be ended.

Before this new idea could be applied, it should be tested. As part of a feasibility study, full scale experiments are performed at three different landfill sites for a period of ten years (Verengiging van Afvalbedrijven, 2014; Vereniging Afvalbedrijven, 2015). The landfills of Braambergen and Wieringermeer are treated with air, while De Kragge II (compartment 3) is treated with leachate infiltration followed by aeration. The high amount of organic matter at De Kragge II requires a different treatment method compared to the other locations. The goal is to reduce the emission potential at these pilot locations such that after ten years it is permanently lower than the regulated values.

The government has already agreed that a cover layer will no longer be required if the feasibility study proves its effectiveness (Rijksoverheid, 2011). If successful, treatment will be carried out at other landfills too. Fifteen landfills in the Netherlands have been qualified as potential locations, which means that the treatment could be performed on these landfills without adjustments. For these fifteen landfills, installation of a cover layer and aftercare might no longer be necessary, resulting in large financial savings.

1.2. Research question

To convince the regulators that this new idea works, it must be proven that the emission potential of the landfill is permanently low. Estimating emission potential from landfill samples is costly and very difficult, because of the large heterogeneity of the landfill. Therefore, van Turnhout (2017) developed a model which enables the estimation of the emission potential of a landfill based on time series of leachate quantity and quality. The model couples hydrological and biochemical processes, in order to estimate the internal state variables such as water content and storage. Measured data on leachate quantity is used to calibrate the model. The modelling approach has been calibrated and tested for data from the pilots at Braambergen and Wieringermeer. However, due to a different layout of the drainage system at De Kragge II, the model needs to be modified for investigation of the emission potential at De Kragge II. At De Kragge II leachate outflow is controlled, while at Braambergen and Wieringermeer leachate is able to flow out at all times.

In order to proof the reduction of the emission potential after the experiment, estimated emission potential is compared with baseline measurement data. These measurements were performed over a period of five years before infiltration started (June 2012 - June 2017). This research focusses on developing a description of the water balance at de Kragge II, using the baseline measurement data. Because pollutants ex-filtrate the landfill via leachate, a good understanding of the water balance is needed to estimate the emission potential.

For modelling the water balance of De Kragge II, the base model of Braambergen and Wieringermeer will be adapted. Different adaptations are implemented to find the model description with minimal error and uncertainty. Model error is evaluated based on inferred parameters. The model uses an algorithm, called DREAM, to optimize parameters within a given range. The probabilities of the parameters indicates model uncertainty. This research aims to answer the following research question:

Which modelling adaptation allows insight in the water dynamics of compartment 3 of De Kragge II, with minimal uncertainty?

1.3. Report outline

Chapter 2 gives a detailed description of different landfill hydrology modelling methods. Chapter 3 gives background information about the landfill site. In Chapter 4 the water balance model used to describe the processes inside the landfill is explained. The data processing before implementation in the model is described in Chapter 5. A check of the water balance error is given in Chapter 6. In Chapter 7, the model results are interpreted. Chapter 8 concludes on the research and provides recommendations for further improvements of the model.

2

Background information: Modelling landfill hydrology

There are different approaches to model the hydrology of a landfill. In this chapter the main modelling approaches found in literature will be discussed.

In 1994 Peyton and Schroeder developed the Hydrological Evaluation of Landfill Performance (HELP) model for modelling the water balance of cover and bottom liner systems (Schroeder et al., 4526). This is still a popular method in recent landfill modelling (Alslaibi et al., 2013; Berger, 2015). The HELP model calculates leachate discharge from balancing precipitation, evapotranspiration, run-off and storage in the waste layer. It uses empirical equations for the calculation of evapo-transpiration and run-off, and it calculates storage based on the concept of field capacity (Fellner and Brunner, 2010). This method assumes homogeneity of the waste, which makes it a good method for estimating water fluxes over a long time period. However homogeneity is a shortcoming when analysing short time periods. In this case peaks in flow data, coming from water flowing through preferential paths, can not be modelled.

More recent modelling approaches account for preferential flow paths in landfills (Fellner and Brunner, 2010; Tinet et al., 2011). A dual-porosity model assumes that the medium consists of two regions, one associated with the macro pores and the other with fine pores. Different dual-porosity methods are available. They mainly differ in implementation of water flow in and between the two pore regions (Šimůnek et al., 2003). A dual-porosity model is a deterministic model based on fundamental equations. It uses the Richards equation to describe water flow and the convection-dispersion equation for solute transport. The hydraulic properties of the macro and fine pore systems are described using the analytical functions of van Genuchten. Both regions have different porosities and volumes. Dual-porosity models account for the physical and biochemical complexity of landfill systems, but require significant amount of data. The complexity of this modelling method results in large uncertainty. This makes calibrating such models difficult and sometimes even impossible.

Also finite element programs are used to model landfill hydrology, for example HYDRUS. With HYDRUS, the water flow is modelled by Richards equation and solute transport is modelled with Fickian's Advection-Dispersion equation (Anwar and Thien, 2015). HYDRUS permits the user to choose between five different analytical models for the hydraulic properties which are: Brooks and Corey, van Genuchten, Vogel and Císlerová, Kosugi, and Durnet. Finite element programs have the same disadvantages as dual-porosity models.

Besides deterministic modelling approaches, landfills can also be modelled stochastically using transfer functions (Zacharof and Butler, 2004; Rosqvist et al., 2005; Botter et al., 2011; Hrachowitz et al., 2016). The retention time of water in the landfill is determined stochastically. In this way also preferential flow paths are taken into account. Contrary to dual-porosity models, less landfill data is needed for calibration. Unknown landfill parameters are determined within the model. The main disadvantage of the existing stochastic models is that solute transport is not or to a lesser extent taken in to account.

3

De Kragge: Landfill specifics

De Kragge is an area for the use of waste storage in Bergen op Zoom. It consists of two landfills that have been constructed next to each other. Figure 3.1 shows the site of De Kragge. De Kragge I has been constructed by the municipality of Bergen op Zoom and De Kragge II has been constructed by waste processing company Attero. Currently both landfills are maintained by Attero.

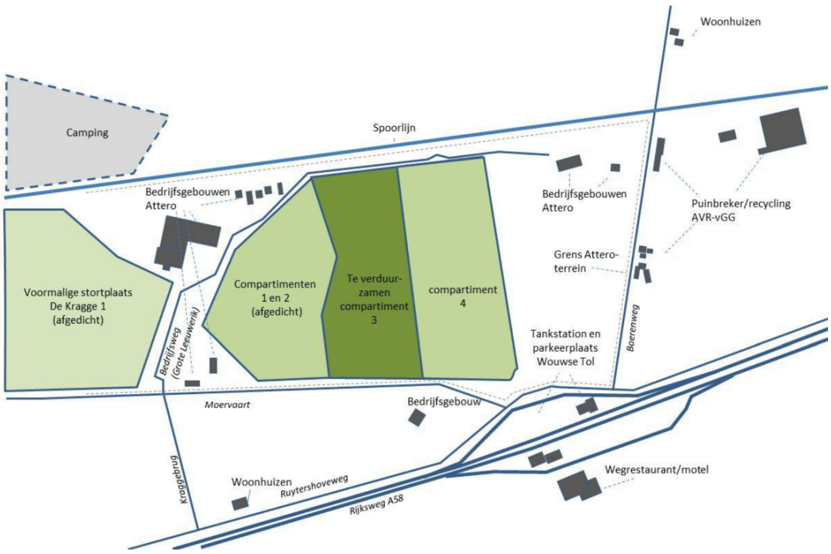

Figure 3.1: Top view of De Kragge site, showing both landfills and the division of De Kragge II in different compartments. Reprinted from Vereniging Afvalbedrijven (2015).

3.1. Landfill structure

This research focusses on landfill De Kragge II. This landfill was in operation from 1990 to 2009. Waste has been deposited in four different compartments (Figure 3.1). Compartment 1, 2 and a small part of compartment 3 are covered with an impermeable cover layer. Detailed information about the compartments dimensions are shown in table 3.1.

A base layer has been installed below the waste of all compartments. The structure of the base layer is shown schematically in Figure 3.2. The quality of the groundwater in the monitoring wells is measured twice a year. If the HDPE membrane fails, and pollutants from the landfill leak through the membrane, this will be noticed during the groundwater quality check and appropriate actions should be taken. The drainage pipes, constructed 25 meter apart from each other, transport the leachate from the waste layer to a collection pit. The landfill has been build on a slope with an inclination of around 0.4 degrees. The different compartments are separated by 2 meter high dikes (Hernández et al., 2016).

Table 3.1: Field data of De Kragge II per compartment. Data provided by Attero and adapted from Oonk (2014)

Compartment	Landfilling period	Waste Volume (m^3)	Base area (m^2)	Cover area (m^2)
1	1990 - 1993	86,047	12,514	13,037
2	1990 - 1993	453,705	33,460	34,355
3	1993 - 1998	851,561	56,137	57,593 Of which is covered: 5,450
4	1998 - 2007	622,421	58,206	61,012

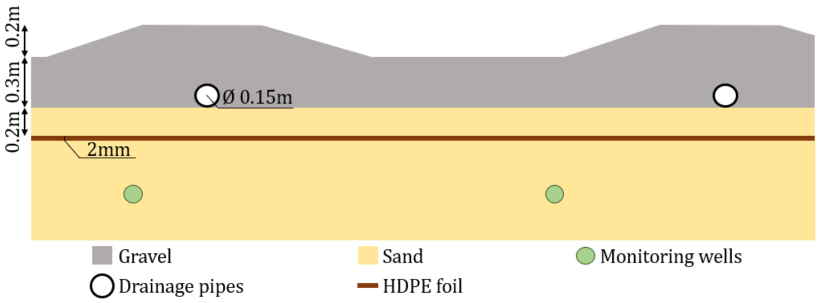

Figure 3.2: The structure of a watertight base layer from bottom to top: A layer of sand below the landfill with monitoring wells inside, the watertight HDPE membrane, a layer of sand and a layer of gravel, with leachate drainage pipes in it.

The impermeable cover layer consists of 4 layers, visualised in Figure 3.3. The construction rules are described in the guideline for cover systems (Ministerie van VROM, 1991). The profiling layer directly on top of the waste corrects for differential settlements, prevents sharp parts of the waste being able to cut through the impermeable layer and is the foundation layer for the impermeable layer. The impermeable layer can be created in three ways: 1) using a synthetic material like a geo-membrane, 2) using a mineral, like a sand-bentonite mixture or a clay layer, or 3) a combination of both. Rainwater runs off into ditches around the landfill. The ditches have been made impermeable using a 2 mm thick HDPE membrane. On compartment 3 and 4, where no cover layer is placed, there is only a recultivation layer with a thickness of around 30 cm.

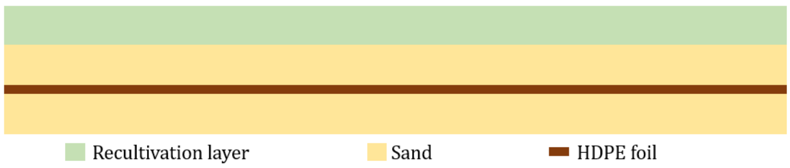

Figure 3.3: The structure of a water resistant cover layer from bottom to top: A sand layer being the foundation for the water resistant layer above it, a sand layer with rain water drainage pipes, a recultivation layer.

3.2. Leachate collection system

During the baseline measurement period, the collected leachate of De Kragge II was transported by truck to the leachate purification plant of Zevenbergen. In June 2017, Attero started to adapt the leachate collection system in light of the pilot project. For this research the old leachate collection system is relevant. The flow system of leachate from the landfill site to the truck is a complex system with multiple pump pits shown in Figure 3.4. Each compartment has its own collection pit, located in the landfill toe. The bottom of the collection pits are at the same level as the landfill liner. Because of the inclination of the landfill the bottom of the collection pits differ in height relative to NAP.

Each compartment has its own drainage system (⌀150mm). A detailed drawing of the drainage system can be found in Appendix A. The drains in the landfill come together at a collection drain (⌀160mm) ending in the collection pit. Inside the collection pits of compartment 3 and 4, the leachate level and the electrical conductivity (EC) have been monitored. The measurements started in 2012, as part of

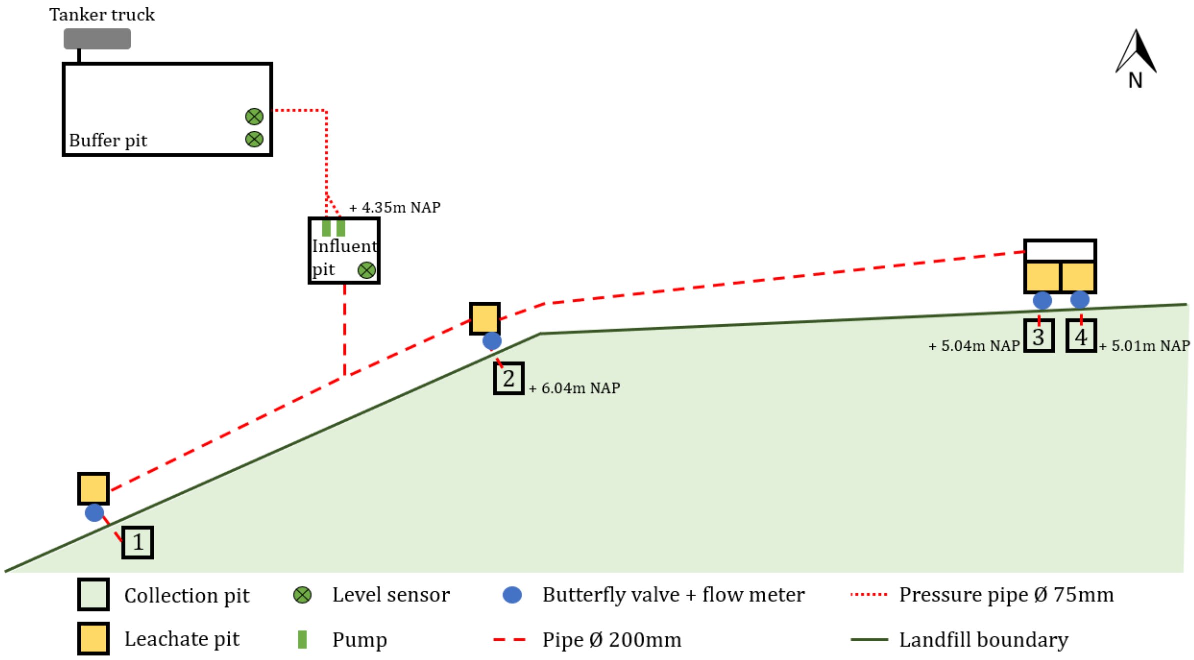

Figure 3.4: A map of the the leachate system at De Kragge II. Leachate flowing from the landfill to the truck passes multiple pits, valves and a flowmeter. Water level measurements are placed in collection pits 3 and 4.

collecting baseline measurement data. Because leachate can flow freely to the collection pits, the leachate level in the pits is a good representation of the leachate level inside the landfill. A section drawing of the collection pit of compartment 3 is shown in Figure B.1 in Appendix B.

Next to the collection pit a leachate pit is located just outside the landfill. Compartment 3 and 4 have a combined leachate pit consisting of three chambers. A separate chamber for both compartment 3 and 4 and a mixed chamber where the leachate of both compartments is gathered. A section- and horizontal section drawing of the leachate pit of compartment 3 and 4 is shown in Figures B.2 and B.3 in Appendix B. The flow from the collection pit to the leachate pit is controlled by a butterfly valve and a flowmeter, which registers the amount of leachate passing.

Water can flow to the mixed chamber due to an opening in the wall. Through a pipe (⌀200mm) the leachate flows from the mixed chamber, via the leachate pit of compartment 2, to the third pit, the influent pit. This pit in the system collects the leachate from all four compartments. From here the leachate is pumped to the leachate buffer pit, where the tanker truck collects the leachate.

3.2.1. Outflow control

When the tanker truck collects the leachate, the level in the buffer pit drops. Two sensors located inside the buffer pit register the level. If the first sensor reaches a predetermined value the first pump in the influent pit turns on. The second sensor is assigned to a lower water level and turns on the second pump. Both pumps have the same pumping rate of 2.78 L/s. A water level sensor is also located in the influent pit. When the first pump is turned on, the water level in the influent pit drops, automatically the valves to all compartments are opened. Depending on the water level inside the compartments, the operator can also manually open and close specific valves. With this, the operator could give priority to compartments with high levels. Depending on the water level in the landfill the pressure on the valve can be very high. If this pressure is high, completely opening the valve would result in leachate spraying out of the landfill. To prevent this, the valve itself can determine how far it should be opened.

In the past, the flow system has sometimes been bypassed. The leachate was then taken directly from the collection pit. In this case the flowmeter did not register the water flow. There is no record of the moments the system was bypassed. However, each truck leaving the landfill site has to be weighed.

So comparing the data of the flowmeter with data from the weighed trucks could give better insight in the amount of water that has been bypassing the flowmeter.

Taking the whole flow system into account it could be stated that the outflow (rate) of water from the landfill depends on different factors in this system, being:

1. The water level in the landfill
2. The water level in the influent pit
3. The pump(s) being on or off
4. The opening area of the valve
5. The duration of opening the valve
6. The operator’s actions

4

Methodology

The water balance model takes into account the water fluxes present in the landfill. Figure 4.1 shows the three layers of the landfill and the water fluxes. Because the outflow valves of a compartment can be closed off for a longer period of time, the water levels inside the landfill could become higher than the dike, resulting in overflow to adjacent compartments.

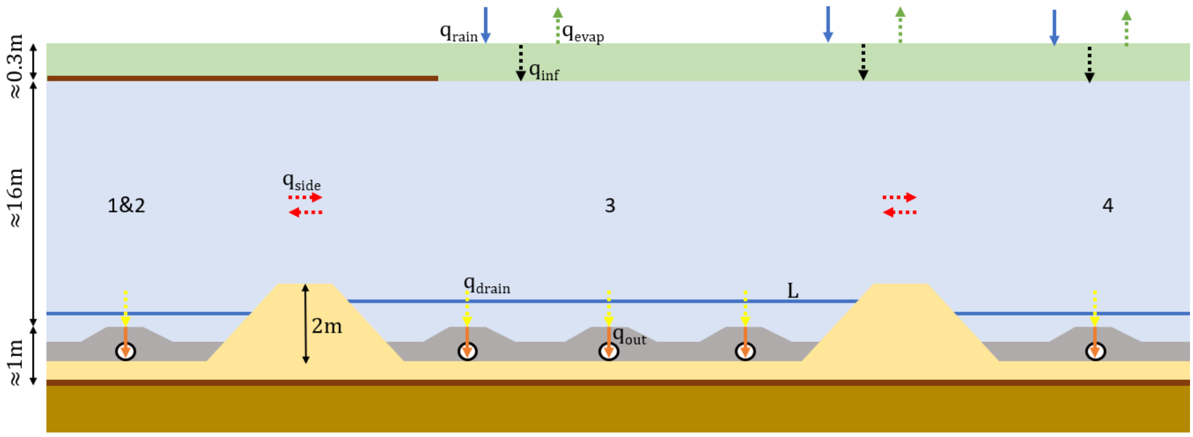

Figure 4.1: All water fluxes in landfill De Kragge II. On the cover layer rain falls and water evaporates. The black arrows indicate the infiltration flux into the waste layer. In the waste layer water flows from top to bottom. Above the dikes water is able to flow laterally from one compartment to the other (red arrows). The yellow arrows indicate water exfiltrating the waste layer into the drainage layer. In the drainage layer water is collected in drainage pipes and transported out of the landfill (orange arrows).

4.1. The model

The model made for Braambergen and Wieringermeer will be adapted in three ways. The first modelling approach will be explained in detail. For approaches 2 and 3, the differences to approach 1 will be explained.

4.1.1. Approach 1

The concept of the water balance model is given in Figure 4.2. Rain falls and water infiltrates into the recultivation layer (q_{rain}). The infiltration flux into the waste layer (q_{inf}) is determined by balancing rainfall, evapotranspiration, infiltration and storage. The water volume infiltrating the waste layer is distributed stochastically according to a travel time distribution that follows a bimodal lognormal distribution. The travel time distribution is discretized over given retention times. The value corresponding to the second-last value of the retention time (n), indicates the transition from the mobile to the immobile water phase. The travel time indicates how fast water is flowing from the infiltration layer into the drainage layer. The way that the retention times are discretized, would accumulate water in the immobile phase, this is solved with a baseflow. From the immobile phase water is exchanged to the mobile phase via this baseflow. In the drainage layer model, the balance of water inflow, leachate outflow, sideflow and storage is calculated. Resulting in a volume of water ex-filtrating the landfill.

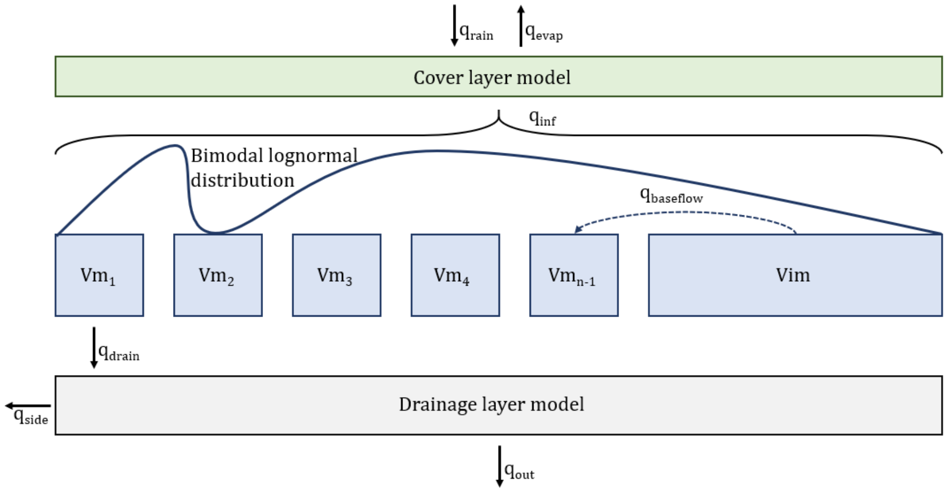

Figure 4.2: The concept of the water balance model with three layers.

Recultivation layer

The rain falling on the landfill infiltrates into the recultivation layer and drains into the waste layer. The infiltration flux into the waste layer is calculated by Equation 4.1. Where K_{sat}^{inf} is the saturated hydraulic conductivity of the recultivation layer and m_{inf} is the empirical shape parameter. The effective saturation (S_{eff}) of the recultivation layer is calculated according to Van Genuchten (Equation 4.2). Where, θ_{in}, $\theta_{res,rec}$ and $\theta_{sat,rec}$ are the initial-, residual- and saturated water content. The saturated water content is calculated based on $\theta_{res,rec}$, according to Equation 4.3. In this Equation, c is a factor between 0 and 1.

$$q_{inf} = -K_{sat}^{inf} \cdot {S_{eff}}^{m_{inf}} \tag{4.1}$$

$$S_{eff} = max \begin{cases} 0 \\ \frac{\theta_{in} - \theta_{res,rec}}{\theta_{sat,rec} - \theta_{res,rec}} \end{cases} \tag{4.2}$$

$$\theta_{sat,rec} = c \cdot (1 - \theta_{res,rec}) \tag{4.3}$$

From the calculation of q_{inf} the water content for the next day is estimated (Equation 4.4). For this calculation the model needs the input values from rainfall and potential evaporation flux, respectively q_{rain} and E_{pot}. The evaporation flux, q_{evap}, is estimated by multiplying E_{pot} with the crop factor (f_{crop}), according to Equation 4.5. Δz_{root} is the depth to which plants can take up water.

$$\frac{d\theta}{dt} = \frac{q_{rain} - q_{inf} + q_{evap}}{\Delta z_{root}} \tag{4.4}$$

$$q_{evap} = E_{pot} \cdot f_{crop} \tag{4.5}$$

There are three cases for which the calculated values of q_{inf} and/or q_{evap} are corrected:

1. If the estimated water content would become higher than the saturated water content, the layer 'flows over'. In this case the excess rainfall is directly shunted to the infiltration flux (Equation 4.6)

$$q_{inf} = -K_{sat}^{inf} \cdot {S_{eff}}^{m_{inf}} + (\theta - \theta_{sat,rec}) \cdot \frac{\Delta z_{root}}{dt} \tag{4.6}$$

2. If the estimated water content would be smaller than zero and the initial water content is larger than the residual water content, the water drains to fast. The calculated infiltration flux is too large and is reduced (Equation 4.7).

$$q_{inf} = (\theta - \theta_{res,rec}) \cdot \frac{\Delta z_{root}}{dt} \tag{4.7}$$

3. If only the estimated water content would be smaller than zero, too much water evaporates. The evaporation flux is too large and is reduced (Equation 4.8).

$$q_{evap} = E_{pot} \cdot f_{crop} + \theta \cdot \frac{\Delta z_{root}}{dt} \tag{4.8}$$

Waste layer
The infiltrated water (q_{inf}) is distributed following a bimodal lognormal distribution. Using a bimodal distribution allows fast and slow moving water, accounting for preferential flow paths in the landfill (Tinet et al., 2011). The probability density function (pdf) depending on the residence time (τ) and the stochastic parameters is given in Equation 4.9.

$$f(\tau) = \frac{\beta}{\tau\sigma_{fast}\sqrt{2\pi}} \cdot e^{\frac{-(ln\tau - \mu_{fast})^2}{2\sigma_{fast}^2}} + \frac{1-\beta}{\tau\sigma_{slow}\sqrt{2\pi}} \cdot e^{\frac{-(ln\tau - \mu_{slow})^2}{2\sigma_{slow}^2}} \tag{4.9}$$

Where β is the fraction between fast and slow moving water and μ and σ are the mean and standard deviation of the fast and slow moving water residence times. In order to determine the amount of water entering the drainage layer (Q_{drain}), the infiltration flux from the recultivation layer is multiplied with the landfill area (A_{lf}) and the pdf (Equation 4.10):

$$Q_{drain} = A_{lf} \cdot \int_0^t q_{inf}(t-\tau) \cdot f(\tau) d\tau \tag{4.10}$$

Because the travel time distribution is finite, a rest term is introduced. This is the immobile water part. All water that is left after distribution is added to the immobile water part. Water is able to drain from the immobile part to the mobile part. This baseflow is calculated according to Equation 4.11.

$$q_{base} = -A_{lf} \cdot K_{sat}^{base} \cdot \left(\frac{\theta_{im} - \theta_{res,im}}{\theta_{sat,im} - \theta_{res,im}}\right)^{m_{base}} \tag{4.11}$$

Drainage layer
The first flux in the drainage layer is Q_{drain}. The second flux comes from the flow between compartments (Q_{side}) and the last flux is the outflow of leachate out of the landfill (Q_{out}). Because the outflow rate depends on multiple factors that are unknown, such as the level in the influent pit and the operator's actions, the outflow is calculated based on the leachate level in the landfill and a factor D (Equation 4.12). All the unknown factors are merged into this one factor D.

$$Q_{out} = D \cdot L \tag{4.12}$$

The flow between compartments depends on the leachate level in both compartments and a factor k_{side}. k_{side} is a combined factor for the landfill hydraulic conductivity (m/d) and the flow distance (m). As example the side flow from compartment 3 to 4 is given in Equation 4.13.

$$Q_{side} = k_{side} \cdot (L_{c_3} - L_{c_4}) \tag{4.13}$$

The storage inside the drainage layer is calculated according to Equation 4.14. Where ϕ_{drain} is the porosity of the drainage layer. Since the water levels can rise above the drainage layer, ϕ_{drain} is a combination of the drainage layer and waste layer porosities. The new leachate level in the drainage layer is calculated as shown in equation 4.15. The estimated leachate level is the sum of the leachate level of the previous day and the change of the leachate level during the day.

$$\frac{dL}{dt} = \frac{Q_{drain} + Q_{side} - Q_{Out}}{A_{lf} \cdot \phi_{drain}} \tag{4.14}$$

$$L_{t+1} = L_t + dL \tag{4.15}$$

4.1.2. Approach 2

The idea behind modelling the outflow is to be able to predict future outflow. However, because of the complexity of the leachate system predicting outflow is difficult. In addition, when modelling the outflow is made too simplistic it could be too difficult to calculate the outflow. So it was concluded that the outflow data is to erratic to be used as fitting data. Therefore, in approach 2 the outflow was given as input value. Compared to the first approach, in this case only the leachate level is fitted with measured data.

4.1.3. Approach 3

Discretizing Equation 4.10 is very complex and time consuming. Therefore, the third approach uses a simpler method to calculate the drainage flux from the waste layer. It uses the circular convolution function of MATLAB. This MATLAB function calculates the travel time distribution continuously. The travel time is infinite and therefore no baseflow is needed. With this implementation, the amount of unknown parameters is reduced and calculation speed is increased. The reduction of unknown parameters improves model certainty.

4.2. Parameter optimization

The different parameters given in the previous sections are optimized within the model. The model uses Baye's theorem to determine the posterior probability of the parameters (H) based on the prior probability ($p(H)$) and the likelihood function ($L(H|\tilde{y})$) according to Equation 4.16 (Vrugt, 2016).

$$p(H|\tilde{y}) = p(H) \cdot L(H|\tilde{y}) \tag{4.16}$$

The posterior probability is calculated using the DiffeRential Evolution Adaptive Metropolis (DREAM) toolbox developed by Vrugt (2016). It uses the Markov Chain Monte Carlo (MCMC) simulation to sample the prior distribution. The Metropolis hasting rule is used to determine the acceptance rate of the proposed parameter set.

The likelihood function is used to describe the plausibility of a parameter set. In this model, the natural logarithmic Gaussian likelihood function is used (Equation 4.17). The Gaussian likelihood function is a good first approximation when nothing is known about the likelihood.

$$ln(L(H|\tilde{y})) = -\frac{N}{2} \cdot ln(2\pi) - \sum ln(\sigma_{TE}) - \frac{1}{2} \cdot \sum \left(\frac{\tilde{y} - y}{\sigma_{TE}}\right)^2 \tag{4.17}$$

Where N is the length of the likelihood vector, σ_{TE} is the sum of the measurement and model error, y is the measured data and $\tilde{y}$ is the modelled data.

4.3. Model scenarios

For each model approach four different scenarios were implemented. The main goal of this research is to create a water balance for compartment 3 of De Kragge II. Therefore the first scenario is a model for compartment 3. Information about the adjacent compartment was given as input. To get insight in the differences between compartment 3 and 4, the same model was implemented for compartment 4. This scenario is referred to as scenario 2.

Scenario 1 and 2 are not closed water balances, since the water flow to the adjacent compartment can act as a sink term. To be able to model a closed water balance and get better insight in the flow between compartments, also two coupled scenarios were made. In these models the recultivation layers of both compartments have the same parameters, this was possible because in reality they have similar thickness and are made of the same material. The first coupled scenario is referred to as scenario 3. In this scenario the waste of both compartments are similar. This results in one formulation of the travel time distribution. Since the volumes of both compartments are different, the parameters to calculate the baseflow are optimized for both compartments separately. For the drainage layer, the porosity of the compartments can differ. For the second coupled model, referred to as scenario 4, the waste is assumed to be different. This scenario was implemented after analysing the results of scenario 1 and 2, which gave different results for the waste layer parameters. The difference between scenario 3 and 4 is that for scenario 4 the travel time distribution parameters are optimized for both compartments separately.

In this report the scenarios will be first named after the implemented approach. The second number indicates the modelled scenario. For example, scenario 2.1 is the model for approach 2 and scenario 1.

5

Model input data

In this chapter the input data for the model will be shown and discussed.

5.1. Weather data

The weather data is taken from two KNMI weather stations. Weather station Westdorpe and Gilze-Rije respectively 40 kilometre south west and 45 kilometre east of Bergen op Zoom. The data of both weather stations is averaged. The average daily rainfall and evapotranspiration potential is given in Figure 5.1.

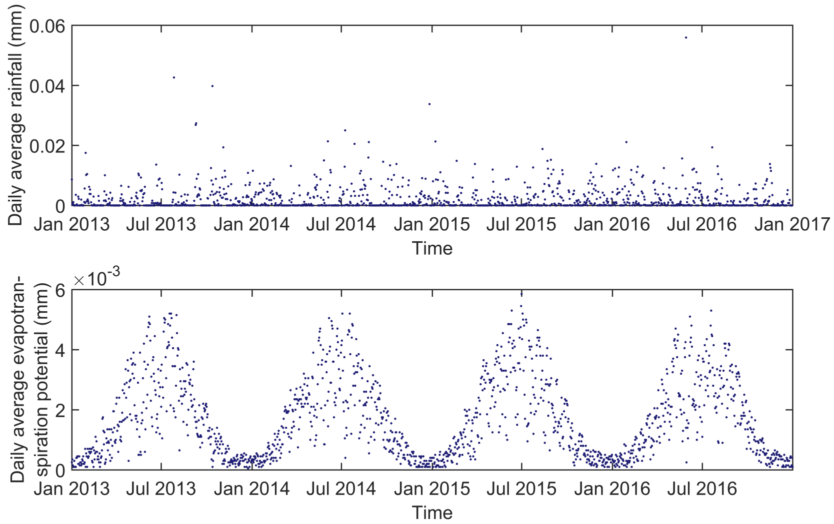

Figure 5.1: The daily average rainfall and evapotranspiration potential from weather stations Gilze-Rije and Westdorpe.

5.2. Site measurements

At the site, the outflow and leachate level are measured every 10 minutes. Figure 5.2 shows the leachate outflow and level for compartment 3 and 4. When water is ex-filtrating the landfill, the leachate level drops immediately. This shows that there is no delay between level changes and outflow. The figure also shows an irregular pattern of outflow. This irregularity is caused by the valves and pumps in the system, controlling the outflow. When the valves are closed, the water levels rise, so the storage increases.

Since the data on rainfall and evaporation is only logged daily, the model has to be based on daily data. Therefore the outflow and leachate levels have to be transformed to daily values. As consequence, the correlation between leachate level and outflow smooths out.

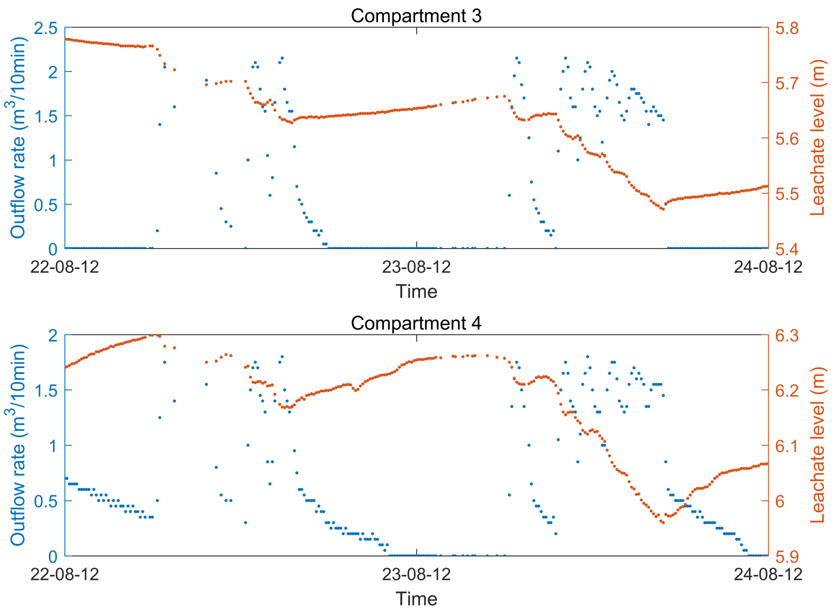

Figure 5.2: The outflow and leachate level of compartment 3 and 4 for two specific days.

5.2.1. Outflow

The flowmeter measurements of compartment 3 and 4 are stored cumulatively in excel sheets. The difference in cumulative outflow over a day is the daily outflow rate. The daily outflow for compartment 3 and 4 over the modelling period is given in Figure 5.3. The outflow shows a layered pattern. This makes clear that the influence of the valves and pumps in the leachate system are significant.

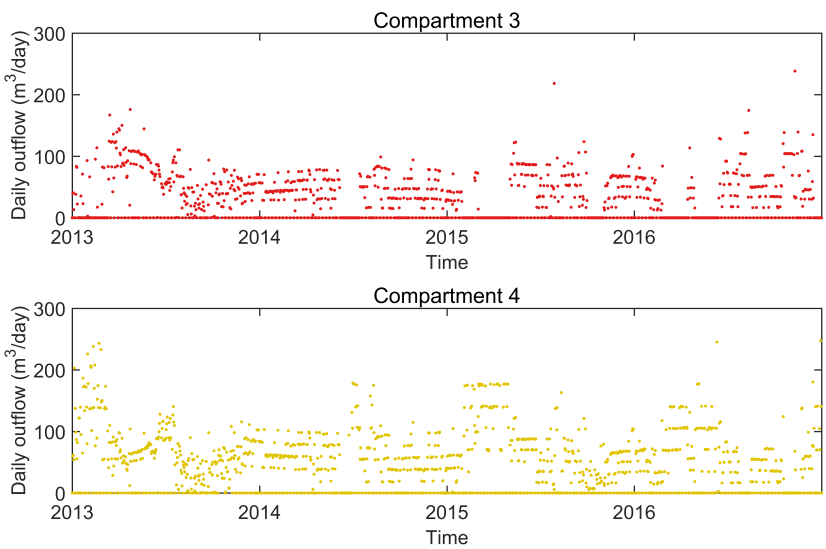

Figure 5.3: The daily outflow of compartment 3 and 4.

Each truck leaving the landfill site filled with leachate has to be weighed. Figure 5.4 shows the cumulative outflow of compartment 3 and 4 in total and the truck data. This data shows a difference of 4282,60 m^3. It must be noted that leachate from compartment 1 and 2, although very little, is not included in this data. With an average outflow of 56 m^3/d for compartment 3 and 71 m^3/d for compartment 4, this error is equivalent to 60-76 days of outflow.

Figure 5.5 shows the difference between truck data and flowmeter data. There are multiple explanations for the differences between truck and flowmeter data. The points corresponding to June and July 2013

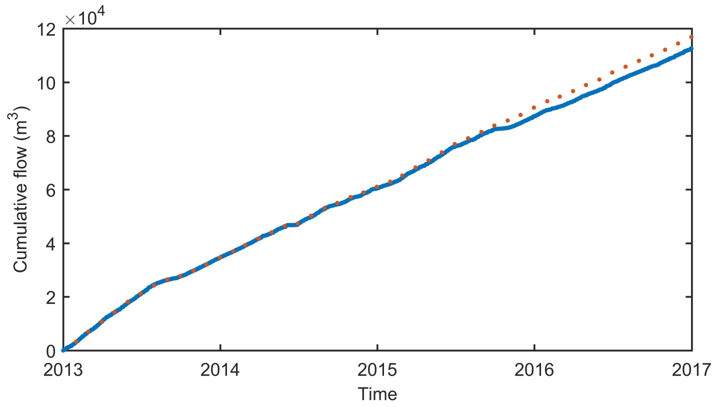

Figure 5.4: The cumulative outflow measured by flowmeter (bue) and truck weight (red).

have the same but opposite values. It seems that in this period water that has been flowing out of the landfill in June is registered in the truck data in July. The larger difference in the winter of 2015-2016 may be explained by the installation of equipment for the pilot project. In this period the flow system of compartment 3 and 4 was changed and leachate was not able to flow through the system. Therefore leachate was collected directly from the collection pit. Aside from these extreme differences there is always a small difference between truck and flowmeter data. This difference could be due to an error in the pump. It is known that the pump has not been calibrated on a regular basis.

In the current model no corrections are made for the differences in leachate volume between truck and flowmeter data.

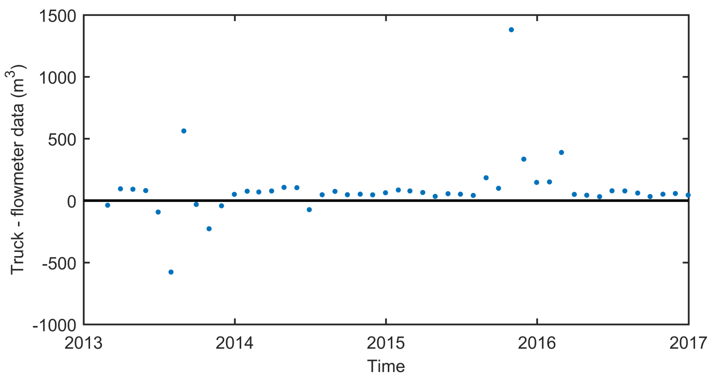

Figure 5.5: The difference between truck and flowmeter data over time.

5.2.2. Leachate level

Input values for the leachate level calculation are the measurements at the beginning of the day. Figure 5.6 shows the measured leachate levels for compartment 3 and 4 and the dike level. There are three periods where the water levels in the landfill are above the dike between compartment 3 and 4. In these time periods water will be able to flow between compartments. Most of the time the water level in compartment 4 is higher than in compartment 3. So the main flow will be expected to go towards compartment 3. The dike between compartment 2 and 3 is 8.04 meter above N.A.P.. Because the level in compartment 3 never reaches this height, water flow towards compartment 2 is not included in the model. The water level in compartment 2 is always below the dike, therefore there is no flow possible from compartment 2 to compartment 3.

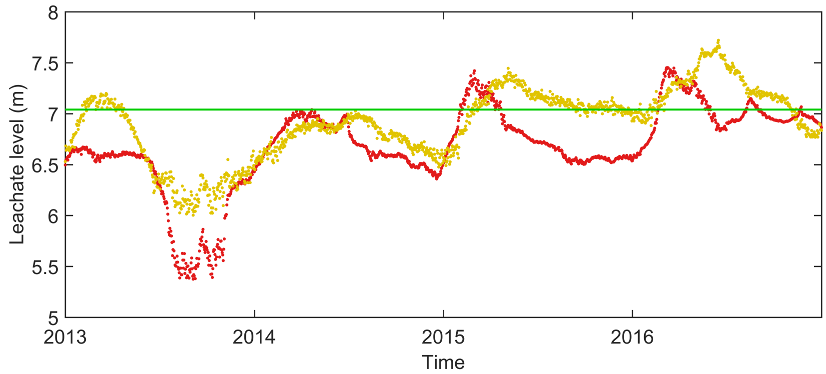

Figure 5.6: The leachate levels of compartment 3 (red) and 4 (yellow) and the dike level (green).

5.3. Model parameters

Input values for the model are the dry density, landfill area and landfill height. The dry density of the waste at De Kragge II is estimated to be 1.3 ton/m^3 (Oonk, 2014). The area of compartments 3 and 4 are respectively 57593 m^2 and 61012 m^2. The landfill height is estimated to be 16 meters for both compartments. An overview of the parameters optimized within the model is given in Table 5.1.

Table 5.1: An overview of the parameters optimized by the model

Parameter	unit	Parameter	unit	Parameter	unit
Recultivation layer					
Δz_{root}	[m]	f_{crop}	[-]	$\theta_{res,rec}$	[-]
c	[-]	K_{sat}^{inf}	[m^2/d]	m_{inf}	[-]
Waste layer					
μ_{slow}	[d]	σ_{slow}	[d]	μ_{fast}	[d]
σ_{fast}	[d]	β	[-]	K_{sat}^{base}	[m/d]
m_{base}	[-]	$\theta_{res,im}$	[-]	f_{water}^{ini}	$[\frac{kgwater}{kgdryweight}]$
n	[-]				
Drainage layer					
ϕ_{drain}	[-]	k_{side}	[m/d]		

6 Water balance check

After the modelling approaches are implemented, the water balance is checked for errors. The balances of all three layers and the total water balance are calculated for each day.

6.1. Recultivation layer

In the recultivation layer the storage is the difference between rainfall, evaporation and infiltration into the waste layer for the total area, shown in Equation 6.1. The storage can also be calculated by the difference in water content, multiplied with the area and the thickness, shown in Equation 6.2. The difference between these two storage calculations gives the water balance error of the cover layer.

$$A_{lf} \cdot \Big((q_{inf} + q_{rain} - q_{evap} \cdot f_{crop})_{t+1} - (q_{inf} + q_{rain} - q_{evap} \cdot f_{crop})_t \Big) - dS_{rec} = 0 \tag{6.1}$$

$$dS_{rec} = (\theta_{t+1} - \theta_t) \cdot \Delta z_{root} \cdot A_{lf} \tag{6.2}$$

6.2. Waste layer

The storage in the waste layer is calculated by the difference between inflow and outflow, shown in Equation 6.3. The second way to calculate the storage is by taking the sum of water volumes in all mobile cells and the bulk volume (Equation 6.4). The difference between these two storage terms gives the water balance error of the waste layer.

$$(A_{lf} \cdot q_{inf} - Q_{drain})_{t+1} - (A_{lf} \cdot q_{inf} - Q_{drain})_t - dS_{waste} = 0 \tag{6.3}$$

$$dS_{waste} = V_{im,t+1} - V_{im,t} + V_{mob,t+1} - V_{mob,t} \tag{6.4}$$

6.3. Drainage layer

Balancing the inflow and outflow fluxes in the drainage layer gives the first storage term (Equation 6.5). The storage can also be calculated by the difference in water level multiplied with the landfill area and porosity, shown in Equation 6.6. The water balance error of the drainage layer is the difference between the two storage terms.

$$(Q_{drain} + Q_{sides} - Q_{out})_{t+1} - (Q_{drain} + Q_{sides} - Q_{out})_t - dS_{drain} = 0 \tag{6.5}$$

$$dS_{drain} = (L_{t+1} - L_t) \cdot A_{lf} \cdot \phi_{drain} \tag{6.6}$$

6.4. Total error

The total error is the balance between rainfall, evaporation and outflow, calculated according to Equation 6.7. The errors for scenario 2.1 are visualised in Figure 6.1. Since the errors are so small (10^{-11}), the error can be neglected.

$$(A_{lf} \cdot (q_{rain} - q_{evap}) - Q_{out})_{t+1} - (A_{lf} \cdot (q_{rain} - q_{evap}) - Q_{out})_t - dS_{tot} = 0 \tag{6.7}$$

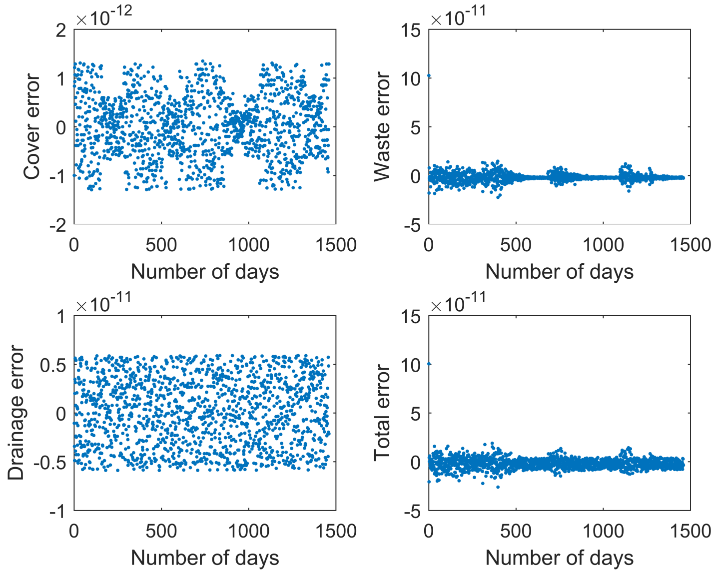

Figure 6.1: The water balance error of the three layers and the total error for scenario 2.1

7 Results and discussion

In this chapter the modelling results will be presented and discussed. The results of each scenario are given in order of approaches. To approximate model uncertainty the analysis is based on a visual check and quantitative criteria.

The visual analysis is based on the fits of the modelled data on measured data. It is a first check to see if the model output shows similar characteristics as the measured data. Because a visual analysis of the data can be very subjective, the results will be analysed in more detail using objective criteria (Bennett et al., 2013). This check on model errors starts with analysing residual plots. The difference between measured and modelled data is plotted over time. The points should be distributed randomly. Systematic changes in error over time indicate missing mechanisms in the model structure.

The model uncertainty can be determined from the parameter optimization results of the model scenarios. In this research there are two criteria used to give an idea of the model uncertainty. During parameter optimization, the distribution of each parameter value goes to a converged probability distribution. The smaller the distribution, the more certain a parameter can be determined. This can be visualised with plotting the histograms of each parameter or by presenting the 5% and 95% quantiles. Comparing the information increase per parameter for the different model scenarios can be done using the Kullbakc-Leibler divergence (D_{KL}) given in Equation 7.1 (Kullback and Leibler, 1951). Given the fact that each scenario starts with the same prior range, the ratio between posterior ($p(H_i|\tilde{y})$) and prior ($p(H_i)$) distribution indicates how much information is gained from parameter i. The higher the D_{KL}, the more information is gained about a parameter resulting in a smaller model uncertainty.

$$D_{KL} = \int p(H_i|\tilde{y}) \cdot ln\left(\frac{p(H_i|\tilde{y})}{p(H_i)}\right) \cdot dH_i \tag{7.1}$$

Model uncertainty is also influenced by the model complexity. A fundamental complexer model, might represent reality at its best but also has more unknown parameters, therefore increasing the model uncertainty. The optimal model is the one that best balances between complexity and information content. A good way to approximate the model complexity is by calculating the harmonic mean of likelihoods (Equation 7.2) (Newton and Raftery, 1994). The model scenario with the highest marginal likelihood has the best balance between information content and model complexity.

$$L^m = \left(\frac{1}{N}\sum_{i=1}^{N} L(H|\tilde{y})^{-1}\right)^{-1} \tag{7.2}$$

Where $L(H|\tilde{y})$ is likelihood of the parameter set H given the model and N is the length of the likelihood vector.

7.1. Approach 1

This section describes the results from modelling approach 1. In this approach, both the outflow and leachate level were modelled and fitted with measured data. The approach has been implemented on the 4 scenarios described in Chapter 4. In scenario 1.1 and 1.2, made for compartment 3 and 4 respectively, the leachate level and outflow of the modelled compartments were used for calibration, while the leachate level of the adjacent compartment was given as input. In scenario 1.3 and 1.4, both compartments were coupled, so the outflow and leachate levels of both compartments were used for calibration. In scenario 1.3 the waste of both compartments were similar, while in scenario 1.4 the parameters for the travel time distribution may differ. From the parameter estimation it followed that scenarios 1.1 and 1.2, differed in waste layer parameter values, therefore scenario 1.4 was implemented. An overview of the four scenarios for approach 1 are given in Table 7.1

Table 7.1: An overview of the different modelling scenarios for approach 1

Scenario	Compartment	Modelling waste layer		Leachate level information of adjacent compartment		Outflow information of modelled compartment(s)	
		Discretized travel time	Circular convolution function	Input	Calculated	Calculated	Input
1.1	3	x		x		x	
1.2	4	x		x		x	
1.3	3&4	x			x	x	
1.4	3&4	x			x	x	

7.1.1. Visual evaluation

Figure 7.1 shows the cumulative leachate outflow of scenarios 1.1 to 1.4. All scenarios show similar results. The outflow of compartment 3 is fitted better than compartment 4. The leachate level fits are shown in Figure 7.2. Scenarios 1.1 and 1.2 show reasonable fits, but scenarios 1.3 and 1.4 are fitted less good. A consequence of the leachate level not well described, is that the storage behaviour is modelled with large error. This leads to a misinterpretation of the storage dynamics, influencing for instance sideflow.

7.1.2. Quantitative evaluation

The outflow residuals are shown in Figure 7.3. For all scenarios the data points are uniformly spread, so this indicates that there is no structural model error. However the residuals are very large. On average the leachate production of the landfill is around 60 m^3 per day, while the outflow residuals can reach values of 100 m^3. The outflow error is large compared to the average outflow. With such a large error it is impossible to get reliable information about the storage dynamics of the landfill.

Another way to get insight in the error is by analysing the standard deviation (σ) values from the likelihood function (Equation 4.17 in Chapter 4). The likelihood function searches for a minimum value, therefore the last term of the function needs to be minimized. The model tries to reduce the error between measured and modelled data, but if this is not possible it will increase the σ value. A large value for σ indicates that the model has problems fitting the data. It also means that most information about comparing the measurements and the model is lost. In Table 7.2 the σ values of outflow and level are shown. The σ values of the outflow are very large, indicating that the model has trouble fitting the results.

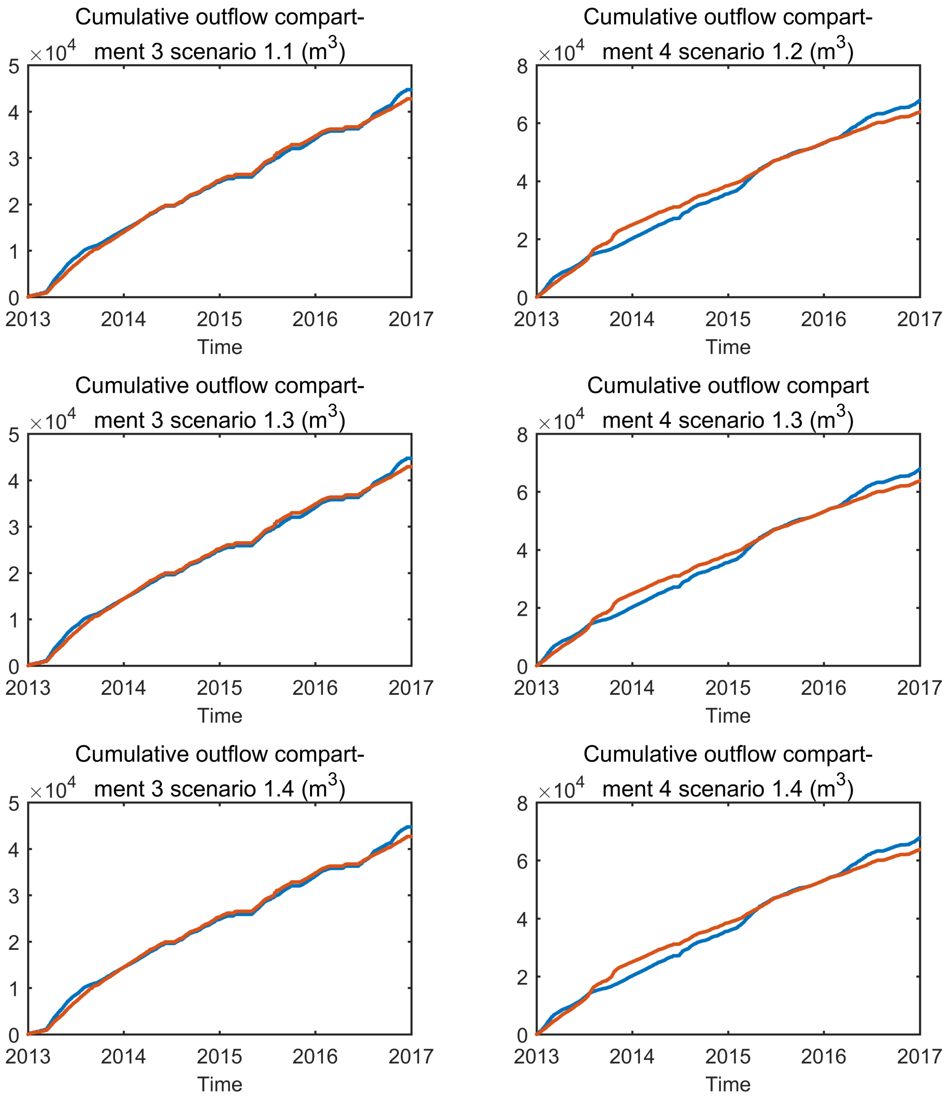

Figure 7.1: The cumulative outflow of measured data (blue) and modelled data (red) for approach 1.

Table 7.2: The σ values from the likelihood functions of approach 1

Scenario	Compartment	σ_{out} (m^3)	σ_{level} (m)
1.1	3	740	0.16
1.2	4	2691	0.15
1.3	3	711	0.27
	4	2526	0.20
1.4	3	807	0.36
	4	2884	0.17

There are two explanations for the large errors in the modelled outflow. The first one being the correlation between leachate level and outflow. Data of the outflow regulation, such as the opening area of the valve, are unknown. This makes it difficult to estimate the correlation. The error in the model shows, that indeed, the correlation is implemented too simplistic. The other explanation comes from the error in the water balance discussed in Chapter 5. In this chapter it was discussed that there is a water balance error of around 4000 m^3. Summing the outflow errors of each scenario individually gives values ranging from 1826 to 3955 m^3. Because the modelled errors are in the same order of

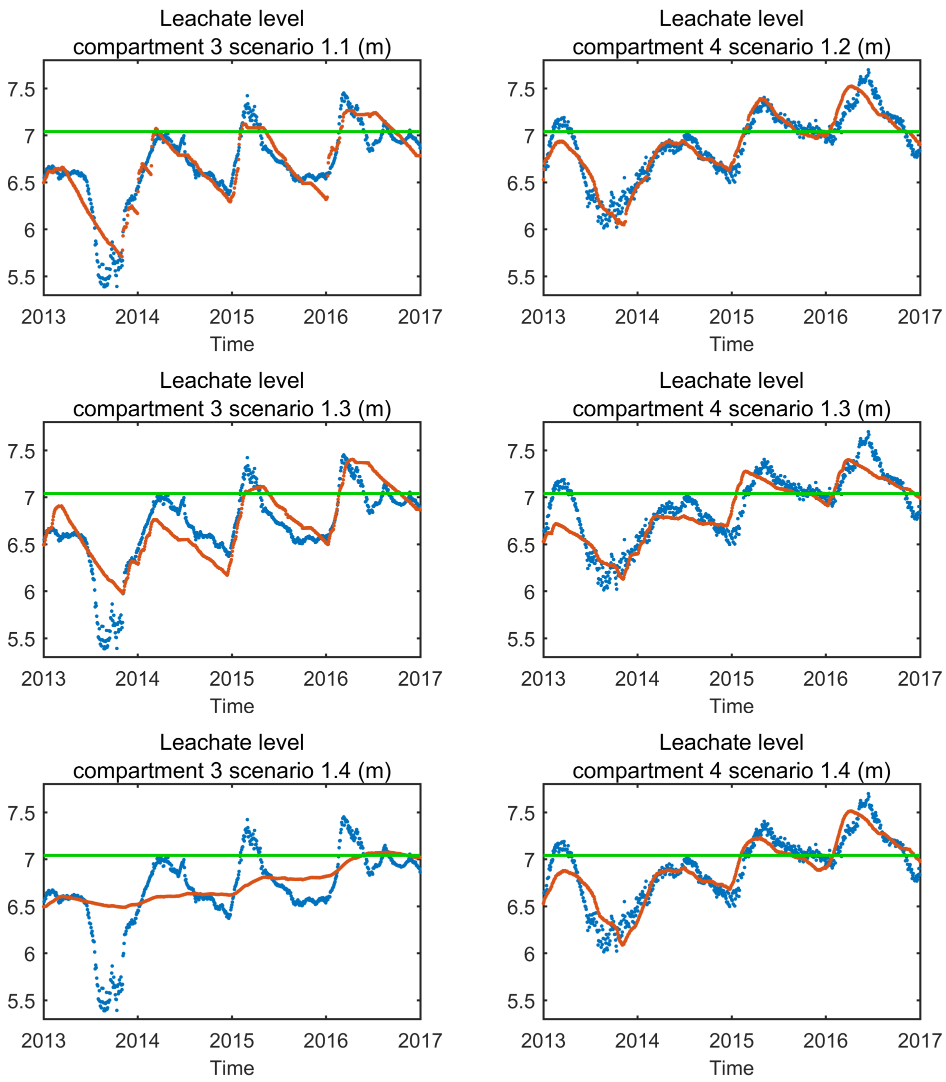

Figure 7.2: The leachate level of measured data (blue) and modelled data (red) for approach 1 and the dike level (green).

magnitude, the main reason for the error must be the water balance error.

The level residuals, shown in Figure 7.4, are not spread uniformly. This indicates structural error. The structural error is likely caused by the incorrect correlation between level and outflow. In an attempt to remove the structural error, a second approach, where the correlation was taken out, was implemented.

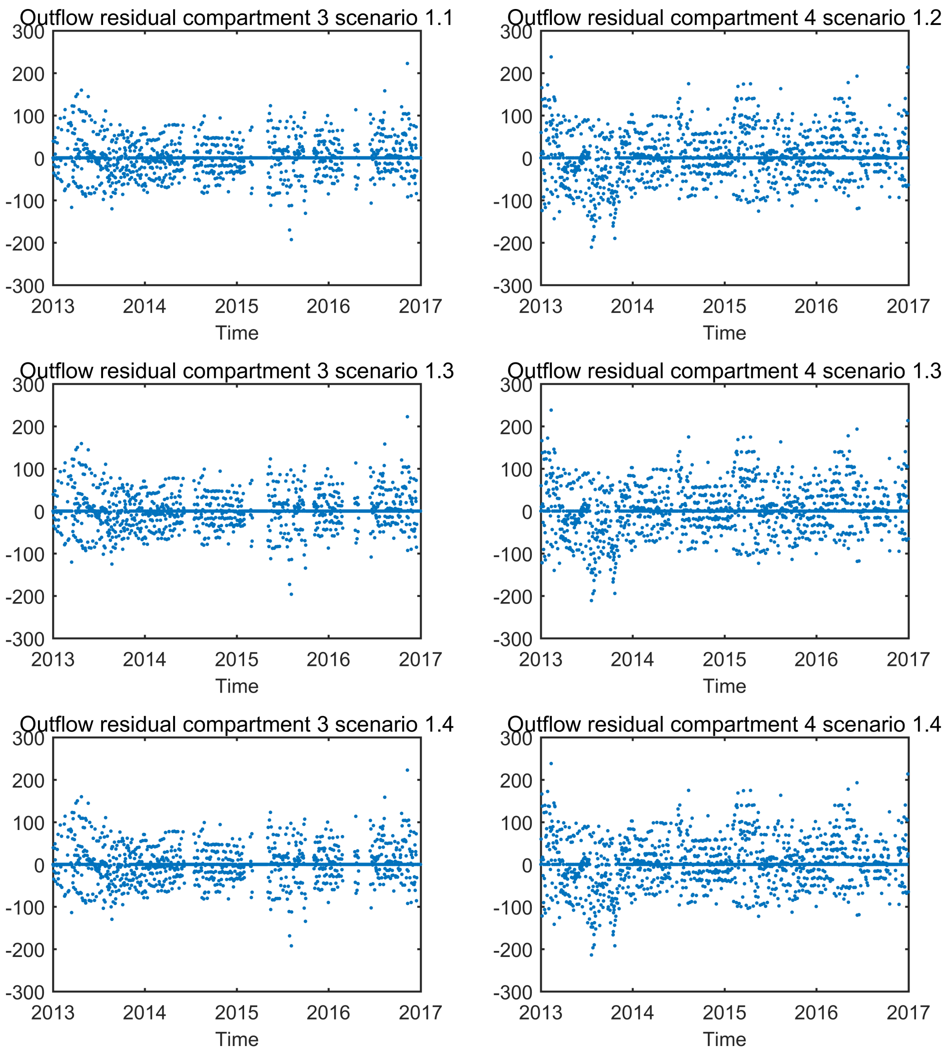

Figure 7.3: The Outflow residual plot for approach 1.

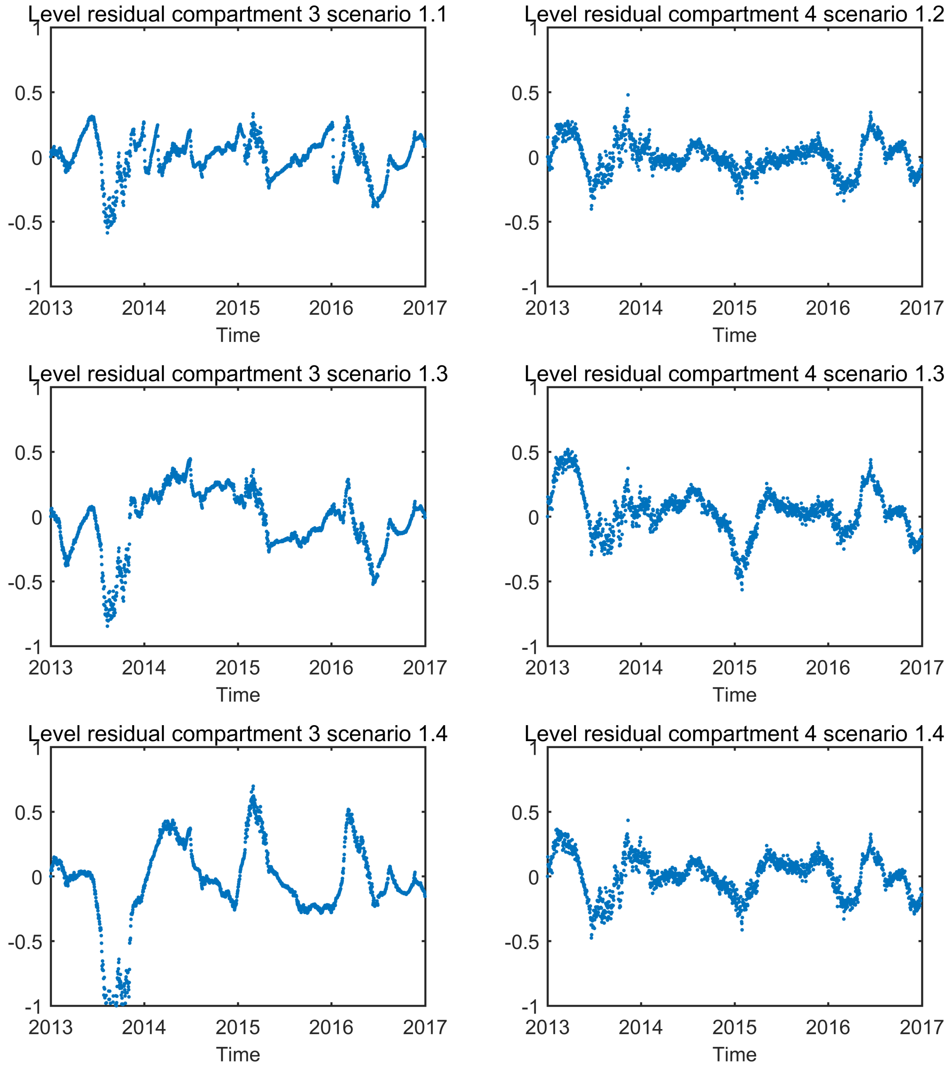

Figure 7.4: The level residual plot for approach 1.

7.2. Approach 2

This section describes the analysis of the results of approach 2. Compared to the first modelling approach, in this case the leachate outflow was given as input. In scenario 2.1, compartment 3 was modelled, where the leachate level of compartment 3 was used for calibration and the outflow of compartment 3 and the leachate level of compartment 4 were given as input. Scenario 2.4 is the same model, but then made for compartment 4. In scenario 2.3, both compartments were coupled. In this case the leachate levels of both compartments were used for calibration and the outflow of both compartments was given as input. The same input and calibration data was used for scenario 2.4. The difference between scenario 2.3 and 2.4 is the waste layer calculation. In scenario 2.3, the waste layer parameters are the same and therefore this model uses only one travel time distribution. However, the results of scenario 2.1 and 2.2 showed a difference in the waste layer parameters for the compartments. Therefore, in scenario 2.4 the waste layers were assumed different and two travel time distributions were calculated. An overview of the modelled scenarios for approach 2 is given in Table 7.3.

Table 7.3: An overview of the different modelling scenarios for approach 2

Scenario	Compartment	Modelling waste layer		Leachate level information of adjacent compartment		Outflow information of modelled compartment(s)	
		Discretized travel time	Circular convolution function	Input	Calculated	Calculated	Input
2.1	3	x		x			x
2.2	4	x		x			x
2.3	3&4	x			x		x
2.4	3&4	x			x		x

7.2.1. Visual evaluation

Figure 7.5 shows the fits of scenarios 2.1 to 2.4. The leachate levels for scenario 2.1 and 2.2 are modelled well, being the modelled data following the same pattern as the measured data. The modelled level for compartment 4 of scenario 2.3 and 2.4 is averaging over the measured data and does not capture the peak values.

7.2.2. Quantitative evaluation

The standard deviations of the leachate levels of each scenario are given in Table 7.4. The results are a bit lower than the results for scenario 1.1 to 1.4 (Table 7.2). Because both approaches show similar fits it can be concluded that the incorrect correlation between leachate level and outflow did not have a large impact on the leachate level fits in approach 1. Although, using the leachate outflow as input data did not reduce the structural error, it is still better to use the outflow data as input, because of the large σ_{out} values in approach 1.

The level residuals are shown in Figure 7.6. The results for compartment 3 show similar errors. The error for compartment 4 of scenarios 2.3 and 2.4 are larger than the errors of scenario 2.2 for compartment 4. This was also seen in the fits. Compared to model approach 1, the residuals of scenario 2.3 and 2.4 have been reduced. Not all errors show white noise, indicating a structural error remains in all the models. Analysing the dynamics in the different layers in the model should give more information on where the structural error comes from.

Table 7.4: The σ values from the likelihood functions of approach 2

Scenario	Compartment	σ_{level} (m)
2.1	3	0.17
2.2	4	0.11
2.3	3	0.17
	4	0.25
2.4	3	0.24
	4	0.22

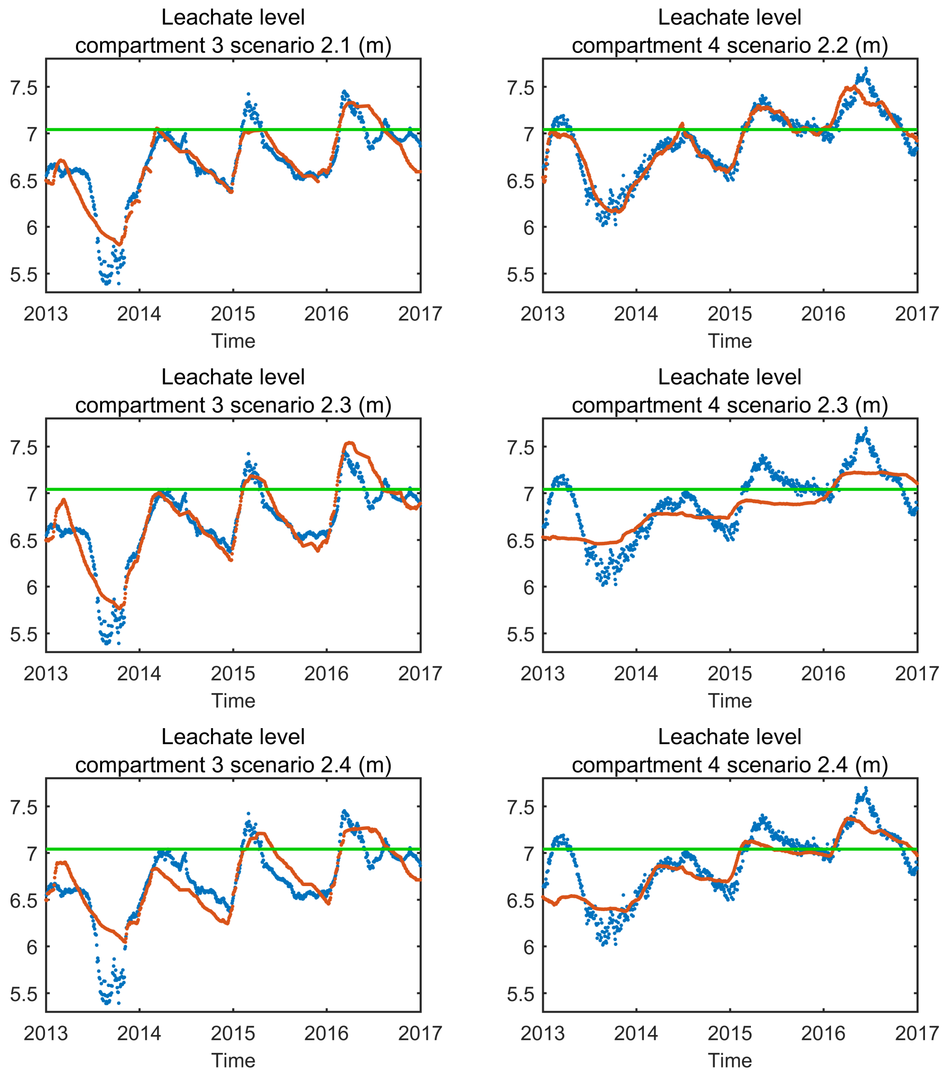

Figure 7.5: The leachate level of measured data (blue) and modelled data (red) for approach 2 and the dike level (green).

Recultivation layer

From the results of the recultivation layer, shown in Figure 7.7, it can be concluded that there are two ways to calibrate the system. In the first system, the recultivation layer is dry most of the time and water infiltrates into the waste layer when the effective saturation is higher than zero (Scenario 2.1 to 2.3). In this case the infiltration flux is the result of water flowing through the layer and is mainly depended on the saturated hydraulic conductivity (K_{sat}^{inf}) and the empirical shape parameter (m_{inf}). In the second system the layer is completely saturated all days. In the model a restriction was implemented that, when the water content is estimated higher than the saturated water content, excess rainfall can directly infiltrate in the waste layer (Equation 4.6 in Chapter 4). So in this scenario the infiltration flux is determined by the result of balancing evaporation and rainfall. Water flow through the layer is so small that it can be neglected.

The two different systems can be seen clearly in Figure 7.7. Where in scenario 2.1, 2.2 and 2.3, infiltration is dominated by water flow and in scenario 2.4, infiltration is determined by the results of rainfall minus evaporation. For all scenarios it also shows that infiltration into the waste layer is only occurring in winter periods, when evaporation is small. So the evaporation flux has a large impact on the infiltration.

The parameter values determined for each scenario are shown in Table 7.5. The value for the saturated hydraulic conductivity for scenario 2.4 is much lower than for scenario 2.1, 2.2 and 2.3. This

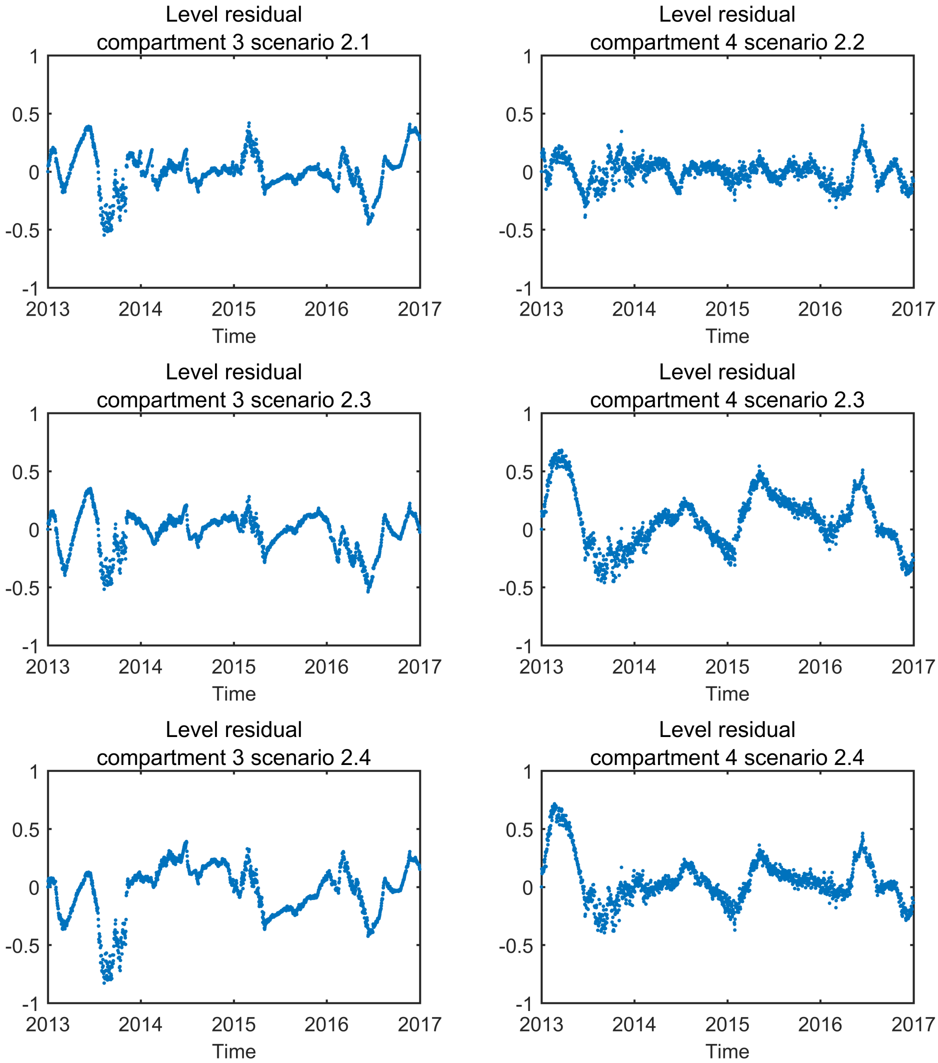

Figure 7.6: The leachate level residual plot for approach 2.

is logical since water flow does not influence q_{inf} at all in this scenario. Comparing the D_{KL} values of the recultivation layer, shows that the parameters of the uncoupled models are better identified, so more information is gained. In all models the f_{crop} factor is determined higher than would be expected based on the recultivation layer structure. This large crop factor can be caused by the gap in the measured water balance discussed in Chapter 5. In order to compensate for the water balance error the evaporation is increased.

In scenario 2.2, a problem with the initial conditions was detected. The first value of the infiltration flux is very large (0.14 m). The rest of the calibration period the infiltration flux is significantly lower than values form the other scenarios. For this approach, the initial water content value resulting from scenario 3.1, which was already converged, was implemented. The reason for this was to increase calculation speed. However, it seems to be a too rough assumption. For further analysis of the model it is advised to start the calculation time a bit earlier than the calibration time.

In scenario 2.4 the recultivation layer is completely saturated for the whole calibration period. This is caused by how the effective saturation calculation is implemented in MATLAB. The effective saturation is calculated according to Equation 4.2 from Chapter 4. Where $\theta_{res,rec}$ and $\theta_{sat,rec}$ are optimized by the model and θ_{in} is calculated according to Equation 4.4 from Chapter 4. The values of all three parameters are somewhere between zero and one. Physically θ_{in} can not be smaller than $\theta_{res,rec}$ and $\theta_{res,rec}$ can not be larger than $\theta_{sat,rec}$. However, when optimizing these parameters the model

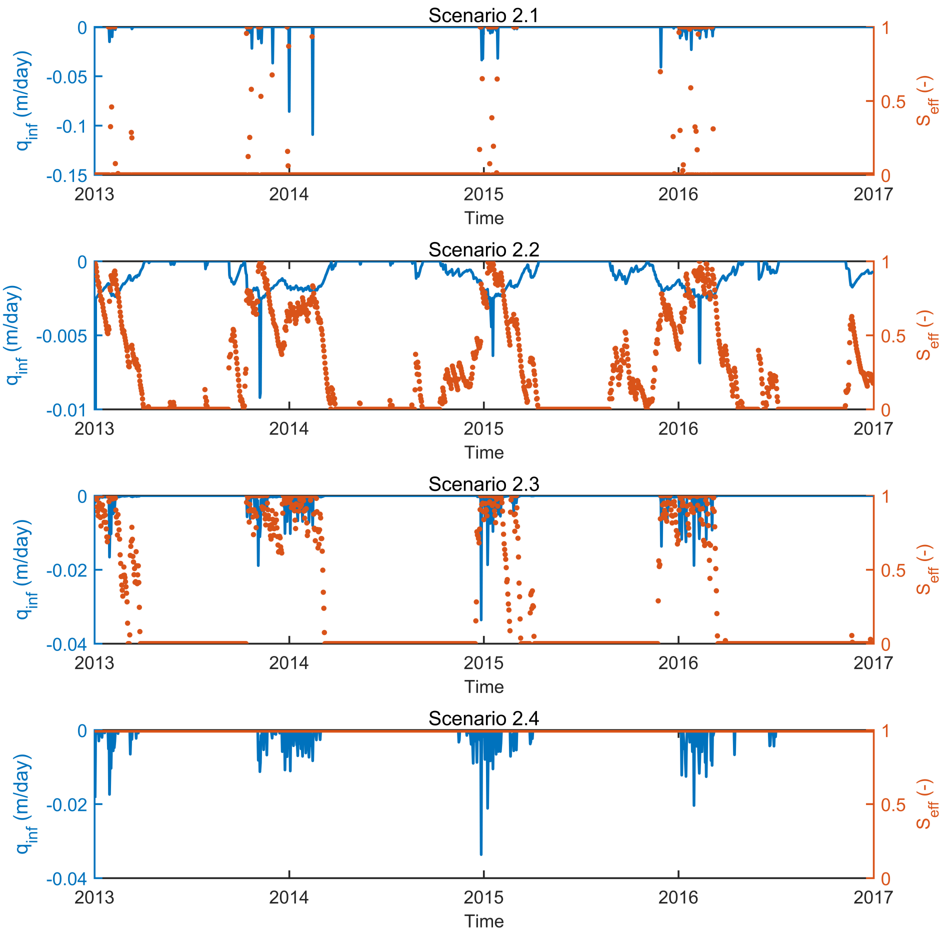

Figure 7.7: Infiltration into the waste layer and the effective saturation of the recultivation layer over time for approach 2. The first value of the infiltration flux for scenario 2.2 was -0.14 m, but was omitted for improved visualisation.

can indeed calculate a value for $\theta_{res,rec}$ larger than $\theta_{sat,rec}$ and θ_{in} smaller than $\theta_{res,rec}$. When this happens, the effective saturation will be larger than 1. A restriction is implemented that this is not possible ($\theta_{sat,rec}$ is forced to be 1). If $\theta_{sat,rec}$ is calculated according to Equation 7.4, this correction is not necessary any more.

$$\theta_{sat,rec} = c \cdot (1 - \theta_{res,rec}) \tag{7.3}$$

$$\theta_{sat,rec} = \theta_{res,rec} + c \cdot (1 - \theta_{res,rec}) \tag{7.4}$$

Although the model scenarios show different mechanisms in the cover layer, they show similar results for q_{inf}. In Figure 7.8, the cumulative infiltration flux is given for each scenario. Except for scenario 2.2, where a problem with the initial condition was discovered, the results are the same. Therefore it is concluded that the complex calculation of the cover layer mechanism is not necessary to determine the infiltration flux. The aim of this research is to get insight in the water dynamics inside the waste layer and with this in mind it would be better to simplify the cover layer. So the system as calibrated in scenario 2.4 is preferred.

Calculating the infiltration flux, according to Equation 7.5, would reduce the cover layer parameters from 6 to 2. This reduction in parameters reduces the models uncertainty. So simplifying the cover layer would reduce the model uncertainty, while the result stays the same. Therefore simplification according to Equation 7.5 is advised.

$$q_{inf} = q_{rain} - E_{pot} \cdot f_{crop} \tag{7.5}$$

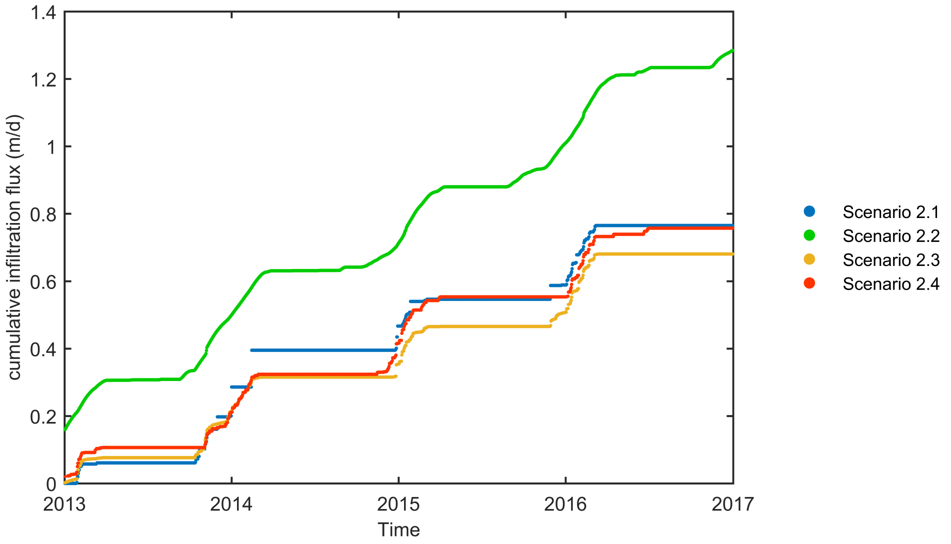

Figure 7.8: The cumulative infiltration into the waste layer for approach 2.

Table 7.5: Quantiles 0.05 - 0.95 and D_{KL} values for each parameter of approach 2

	Δz_{root} [m]		f_{crop} [-]		$\theta_{r,cover}$ [-]		c [-]	
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}
prior	0.10 - 1.50		0.10 - 1.50		0.00 - 0.40		0.0 - 1.00	
Scenario 2.1 c3	0.3517 - 0.3638	4.16	1.4696 - 1.4995	3.55	0.2790 - 0.2838	3.78	0.3932 - 0.4046	3.84
Scenario 2.2 c4	1.0346 - 1.0551	3.61	1.1122 - 1.1222	3.14	0.0313 - 0.0360	4.19	0.1095 - 0.1226	4.54
Scenario 2.3 c3&4	0.3757 - 0.4187	1.09	1.4860 - 1.4908	2.37	0.1887 - 0.2395	0.83	0.3093 - 0.3268	1.03
Scenario 2.4	0.5580 - 1.1894	0.39	0.9183 - 1.0787	1.13	0.0940 - 0.3494	0.52	0.3613 - 0.3856	0.69

	K_{sat}^{inf} [m/d]		m^{inf} [-]		μ_{fast} [d]		σ_{fast} [d]	
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}
prior	$10^{-15.00}$ - $10^{0.00}$		0.00 - 5.00		1 - 148		1 - 20	
Scenario 2.1 c3	$10^{-0.86}$ - $10^{-0.31}$	2.81	3.3591 - 3.3808	4.81	1.1 - 1.3	1.32	1.9 - 2.8	0.67
Scenario 2.2 c4	$10^{-2.59}$ - $10^{-2.53}$	5.52	0.6290 - 0.8920	3.02	14.2 - 14.8	3.17	1.6 - 1.7	2.59
Scenario 2.3 c3&4	$10^{-5.06}$ - $10^{-4.69}$	1.65	1.1866 - 1.3859	1.11	3.1 - 4.2	1.14	5.0 - 5.1	1.49
Scenario 2.4 c3&4	$10^{-9.40}$ - $10^{-5.91}$	0.39	0.2066 - 3.2515	0.61	c3: 4.4- 20.0	0.82	c3: 1.1 - 19.2	0.20
					c4: 2.3 - 15.9	0.49	c4: 1.2 - 5.0	0.36

	μ_{slow} [d]		σ_{slow} [d]		β [-]		K_{sat}^{base} [m/d]	
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}
prior	2 - 22026		1 - 20		0.01 - 0.99		-4.00 - 0.00	
Scenario 2.1 c3	4.4 - 26.3	0.87	1.2 - 2.1	1.44	0.1537 - 0.6446	0.68	$10^{-3.14}$ - $10^{-0.13}$	0.08
Scenario 2.2 c4	480.4 - 520.4	3.20	1.05 - 1.06	5.21	0.6438 - 0.6456	4.17	$10^{-2.54}$ - $10^{-2.23}$	1.79
Scenario 2.3 c3&4	21.3 - 38.7	1.27	1.0 - 1.8	1.29	0.7575 - 0.8118	1.08	c3: $10^{-0.96}$ - $10^{-0.93}$	1.16
							c4: $10^{-1.45}$ - $10^{-1.41}$	0.94
Scenario 2.4 c3	5.8 - 1125	0.11	3.5 - 10.6	0.79	0.1692 - 0.8611	0.48	$10^{-3.12}$ - $10^{-0.01}$	0.13
Scenario 2.4 c4	2.8 - 80.5	0.40	2.0 - 6.6	0.45	0.1337 - 0.7186	0.38	$10^{-1.67}$ - $10^{-0.67}$	0.40

	m_{base} [-]		$\theta_{res,im}$ [-]		n [-]		f_{water}^{ini} [$\frac{kgwater}{kgdryweight}$]	
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}
prior	0.10 - 4.00		0.01 - 0.99		1 - 1461		0.1 - 0.99	
Scenario 2.1 c3	0.3979 - 3.5508	0.08	0.3369 - 0.7283	0.08	764 - 2992	0.12	0.0104 - 0.0284	3.91
Scenario 2.2 c4	1.5690 - 2.7266	1.09	0.0241 - 0.0264	4.84	798 - 811	4.34	0.0271 - 0.0291	5.24
Scenario 2.3 c3&4	c3: 1.5064 - 3.2137	0.18	c3: 0.4635 - 0.5379	0.34	1398 - 1474	1.82	c3: 0.0766 - 0.0912	1.72
	c4: 1.9617 - 3.1010	0.31	c4: 0.3929 - 0.4613	1.05			c4: 0.7011 - 0.7406	1.61
Scenario 2.4 c3	1.1674 - 2.0166	0.25	0.3203 - 0.6545	0.50	523 - 907	0.47	0.0360 - 0.1323	1.84
Scenario 2.4 c4	0.8019 - 2.2728	0.18	0.7109 - 0.7442	0.58	1044 - 1268	1.12	0.5109 -0.6513	0.56

	ϕ_{drain} [-]		k_{side} [m^2/d]		σ_{level} [m]		$L(H\|\tilde{y})$ [-]
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}	quantiles
prior	0.10 - 1.00		1.0 - 100		0.02 - 2.0		
Scenario 2.1 c3	0.1985 - 0.2082	3.74	1.3688 - 7.9991	2.56	0.1702 - 0.1747	3.33	482.31 - 0.509.10
Scenario 2.2 c4	0.1309 - 0.1362	4.74	42.16 - 48.21	1.78	0.1067 - 0.1089	4.95	1189 - 1193
Scenario 2.3 c3&4	c3: 0.1282 - 0.1387	1.56	99.5844 - 99.9788	1.45	c3: 0.1618 - 0.1789	2.00	472.4783 - 478.6082
	c4: 0.6660 - 0.6822	1.69			c4: 0.2346 - 0.2568	2.04	
Scenario 2.4 c3&4	c3: 0.2156 - 0.2735	0.78	31.1375 - 78.8879	0.44	c3: 0.2296 - 0.2823	2.13	-445.9578 - 151.3495
	c4: 0.4028 - 0.8654	0.32			c4: 0.2212 - 0.3816	2.15	

Waste layer
Water in the waste layer is divided in mobile and immobile water. Figure 7.9 shows the mobile and immobile water volumes for each scenario over time. The mobile and immobile water volumes follow the same peaks as the infiltration flux. The mobile water volume in compartment 4 is much larger than in compartment 3. This is mainly caused by the area difference, which leads to more water infiltration.

In most scenarios the mobile water decreases over time, so water is flushed out to the drainage layer. It indicates a quick response of rainfall to water being drained. The low values for μ_{fast} shown in Table 7.5 confirm this. The amount of days it takes for water to flow through the preferential flow paths is low for scenario 2.1 and 2.2. For scenario 2.1, 2.3 and 2.4 also the parameters for μ_{slow} are quite low. Clearly scenario 2.2 gains most information from the model parameters, since the D_{KL} values are high compared to the other scenarios.

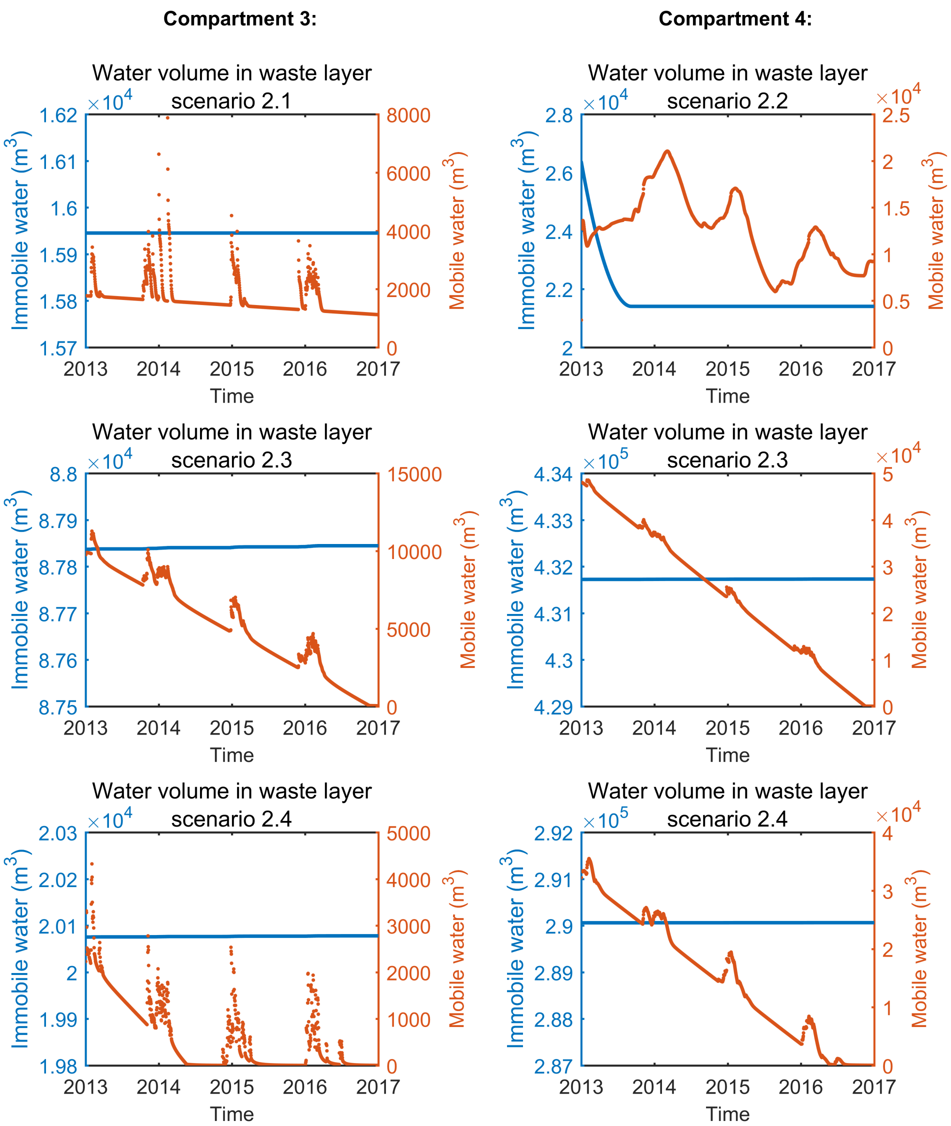

Figure 7.9: Mobile water (red) and total water (blue) stored in the drainage layer for approach 2.

Figure 7.9 shows that only in scenario 2.2 water is flowing from the immobile to the mobile zone. In all other scenarios the baseflow is zero. This can also be seen in the parameter distributions. The model scenarios 2.1, 2.3 and 2.4 find small values for K_{sat}^{base} and have no preferred values for the parameters m_{inf} and $\theta_{r,im}$. The D_{KL} values are low. This indicates that the parameters are not optimized, because all combinations lead to zero baseflow. For scenario 2.2 where there is baseflow, these three parameters are determined with much more certainty.

The lacking baseflow in scenarios 2.1, 2.3 and 2.4 is caused by the large values estimated for the travel time. Figure 7.10 shows the probability density function of scenarios 2.1 to 2.4. The amount of water corresponding to large travel times is very low. Therefore, it would be advised to adjust the estimated travel time just after the pdf was estimated. This can be done by reducing the value of n, the second-last value of the travel time, indicating the transition from the mobile to the immobile water phase. A large value of n, also means that the baseflow does not have impact on Q_{out} at all, because baseflow only affects the largest value of the travel time.

To reduce n a cut-off value could be set, that removes all travel times receiving less water than the cut-off value. All the water left in the water balance is then added to the immobile water volume. For example the value of n for scenario 2.1 could be reduced to around 50. The sum of volume with a travel time between 50 to 4000 days can then be added to the immobile water volume. This would also allow to improve the optimization of the baseflow parameters. Because for large travel times the baseflow parameters can not be optimized.

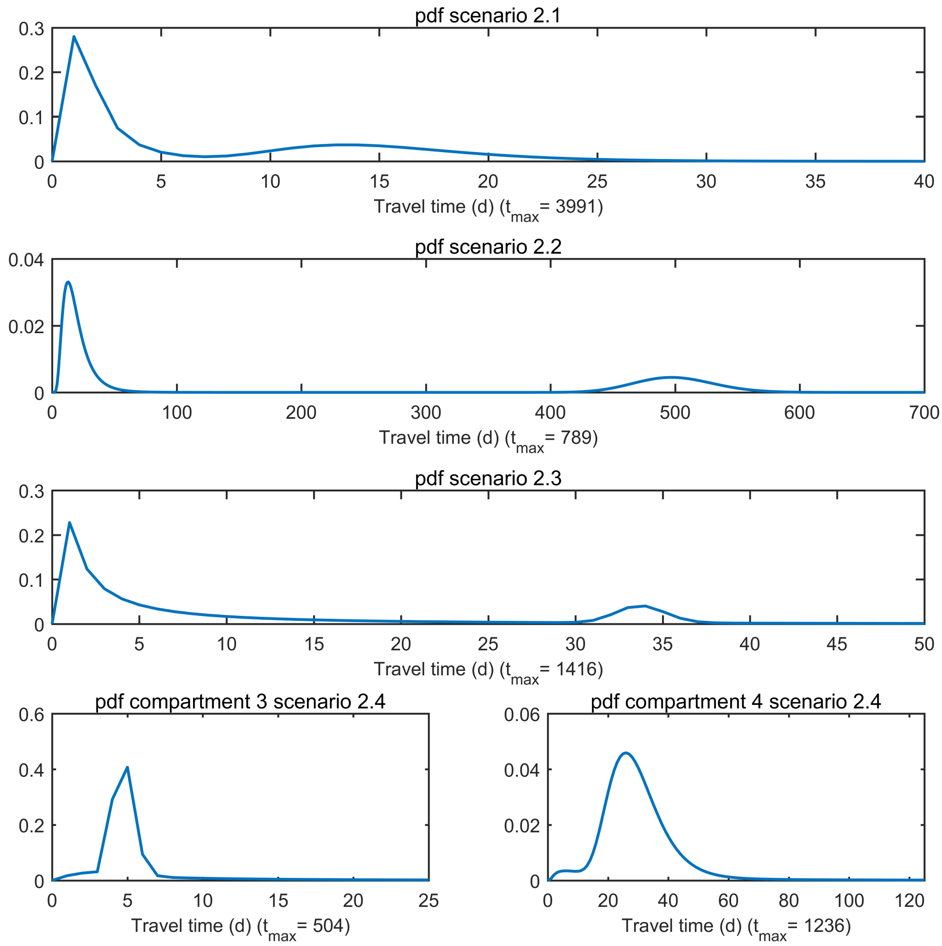

Figure 7.10: The travel time distributions for approach 2. The horizontal axes have been cut-off for improved visualisation.

Drainage layer

In the drainage layer, water can flow from one compartment to another. In Figure 7.11 this water flow is shown for each scenario of approach 2, where positive flow indicates water moving into compartment 3. The differences between the scenarios can be explained in two ways. The water flow between compartments depends on the leachate level in the landfill. So an error in the leachate level estimation directly influences the sideflow. Another reason could be the gap in the water balance determined in Chapter 5. In the uncoupled models (scenario 2.1 and 2.2) the sideflow can compensate for this gap. In these cases the sideflow is a combination of the actual sideflow and a sink term. This sink term is the difference between the measured leachate outflow and the actual outflow. When the leachate levels are correctly estimated this sink term could be estimated by taking the difference in sideflow between scenario 2.1 and 2.2. The difference between water volume flowing sideways for scenario 2.1 and 2.2 is 4913.7 m^3. This value is very close to the estimated leachate outflow error of 4200 m^3. The water flow for scenario 2.2 from compartment 4 into compartment 3 is larger than for scenario 2.1. From this the conclusion can be drawn, that the moments that the flowmeter was bypassed and the tanker truck collected the leachate directly from the collection pit, it must have taken most of the leachate from the collection pit of compartment 4.

For scenario 2.3 and 2.4 there is no sink term, therefore the outflow error can not be compensated. As a result these scenarios show much larger values for sideflow than scenarios 2.1 and 2.2. Because in this case the model is unable to compensate for the water balance leak these scenarios show worse fits for the leachate level compared to the uncoupled models. Without compensation for the water balance error a coupled model is therefore not preferred.

The sideflow influences the water balance of compartment 3 when the levels are higher than the dike. The sideflow calculated in scenarios 2.3 and 2.4 are not reliable, because of the poor fits of the leachate level. The sideflows are lilkely overestimated due to the error in the measured water balance. These results show that in order to accurately model the water dynamics in compartment 3, the error in measured water balance must be minimized and the water level in both compartments should never exceed the dike level.

The first two years of the calibration period the measured leachate levels of both compartments do not rise above the dike. Reducing the calibration period to 2013 and 2014 would reduce uncertainty in the model, since sideflow can than be excluded from the model. Another advantage of reducing the calibration period is the error in the water balance. The errors are the largest in 2015 and 2016, so this will also increase model certainty. A disadvantage of reducing the calibration period is that it will reduce the amount of data used. Using less data for calibration increases the probability of missing periodic patterns.

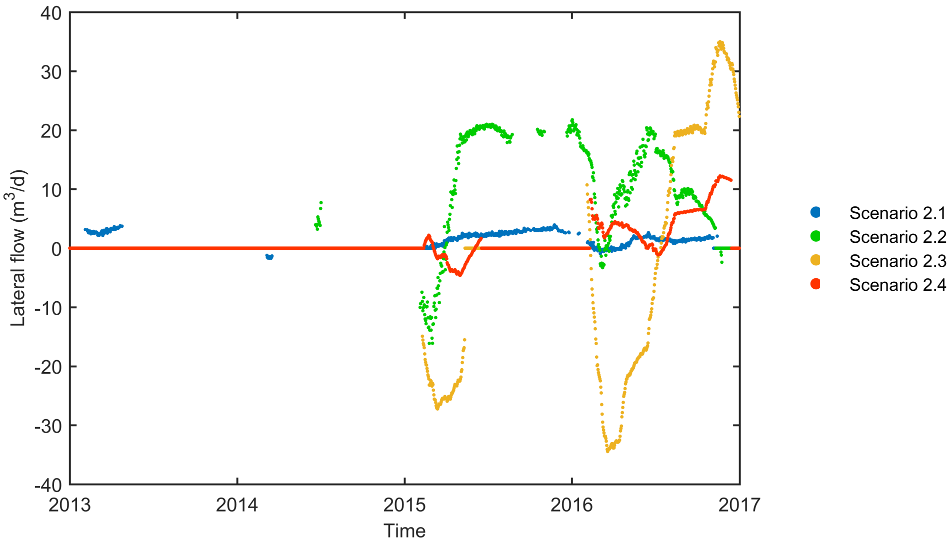

Figure 7.11: Water flow between compartments 3 and 4 for approach 2. Where positive flow is water flowing into compartment 3.

Total Storage

The cumulative total storage in the landfill is shown in Figure 7.12. Only in scenario 2.1 an increase in water storage, comparable with the increase in leachate level in the drainage layer over time, is noticed. As was shown earlier, the mobile water volume in the waste layer decreases over time. However in the total storage, this decrease is not noticed. So the decrease in mobile water volume does not mean that more water is flowing out of the landfill. It shows that the distribution of water in the landfill is shifted from the waste layer to the drainage layer, indicating a quick response between rainfall events and level drainage. This shows the presence of very fast preferential flow paths. The difference between upward or downward trend can be caused by the magnitude of the evaporation fluxes.

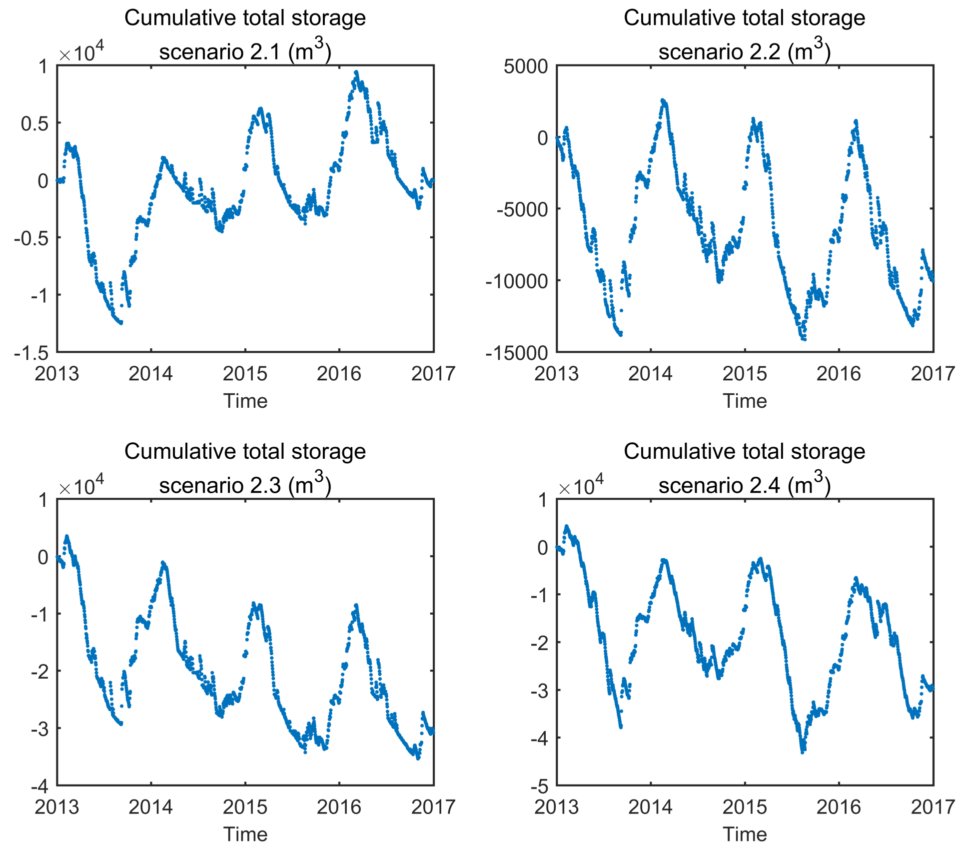

Figure 7.12: The cumulative total storage in the landfill for approach 2.

7.3. Approach 3

The results of approach 3 will be discussed in this section. In this approach the drainage flux from the waste layer is calculated by using the circular convolution function of MATLAB. Approach 2 did not show converged parameters fast enough, therefore approach 3, which has a much faster calculation speed, was implemented. Gaining information of the influence of simplifying the waste layer on the leachate level fits was the second reason for implementing approach 3.

The third approach has been applied on three scenarios. Scenario 3.1 and 3.2 are the models for compartment 3 and 4 respectively. In scenario 3.1 the leachate level of compartment 3 was used for calibration and the leachate level of compartment 4 and the outflow of compartment 3 were given as input. In scenario 3.4 both compartments were modelled. The leachate levels were used for calibration and the outflow of both compartments was given as input. In this scenario water flow through the waste layer was assumed to be different for both compartments. An overview of the implemented scenarios is given in Table 7.6

Table 7.6: An overview of the different modelling scenarios for approach 3

Scenario	Compartment	Modelling waste layer		Leachate level information of adjacent compartment		Outflow information of modelled compartment(s)	
		Discretized travel time	Circular convolution function	Input	Calculated	Calculated	Input
3.1	3		x	x			x
3.2	4		x	x			x
3.4	3&4		x		x		x

7.3.1. Visual evaluation

In approach 3, the measured leachate levels were used to fit the modelled data. In Figure 7.13 the fitting results are shown. Scenario 3.1 and 3.2 show good results. Scenario 3.4 has trouble fitting both leachate levels at the same time. The leachate level in compartment 3 is sometimes overestimated, while the leachate level in compartment 4 has trouble with the extreme values. The coupled model seems to be able to fit both levels reasonably, compared to the other approaches.

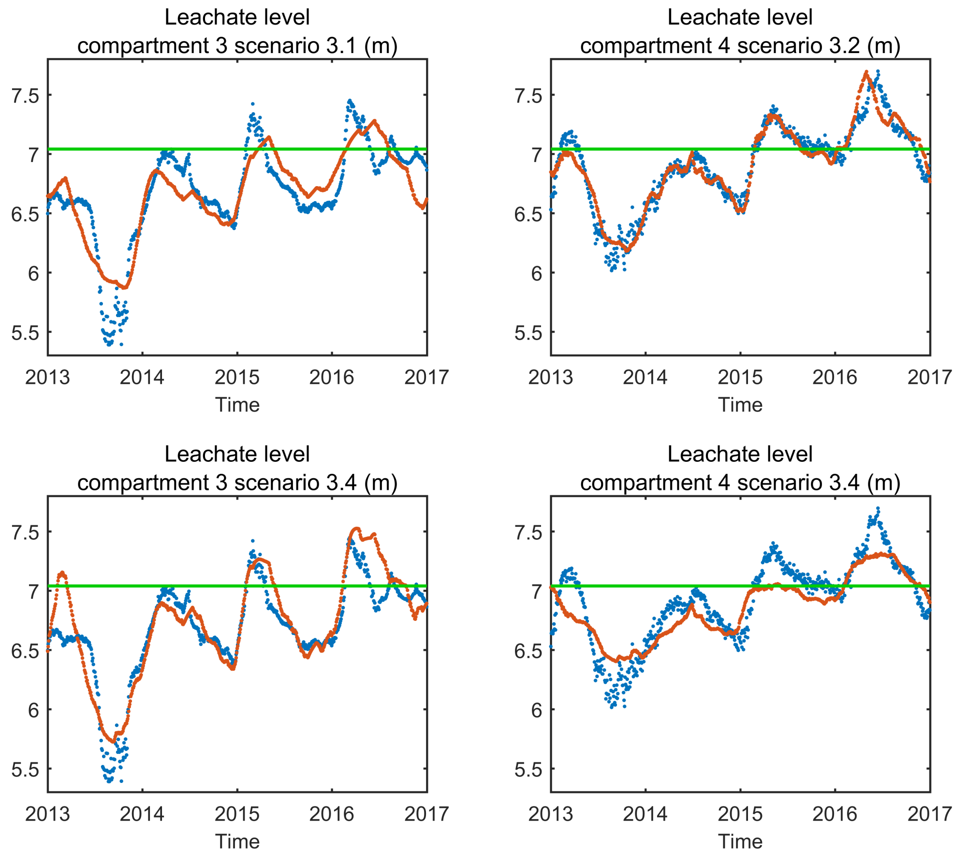

Figure 7.13: The leachate level of measured data (blue) and modelled data (red) for approach 3 and the dike level (green).

7.3.2. Quantitative evaluation

The standard deviations of the three scenarios for approach 3 are given in Table 7.7. Only the standard deviation of scenario 3.1 is higher than for scenario 2.1. The biggest difference is between scenario 3.4 and 2.4. This was also confirmed by the improved leachate level fits.

The model errors are visualised in the residual plots, shown in Figure 7.14. It does not show a uniform spread of the residuals. Although the other graphs are much better, there is still not a uniform distribution of the points, which indicate structural model errors. Comparing these results with approach 2, the residuals did not decrease. The structural error is not solved with approach 3, but the fits did improve.

Table 7.7: The σ values from the likelihood functions of approach 3

Scenario	Compartment	σ_{level} (m)
3.1	3	0.21
3.2	4	0.10
3.4	3	0.19
	4	0.18

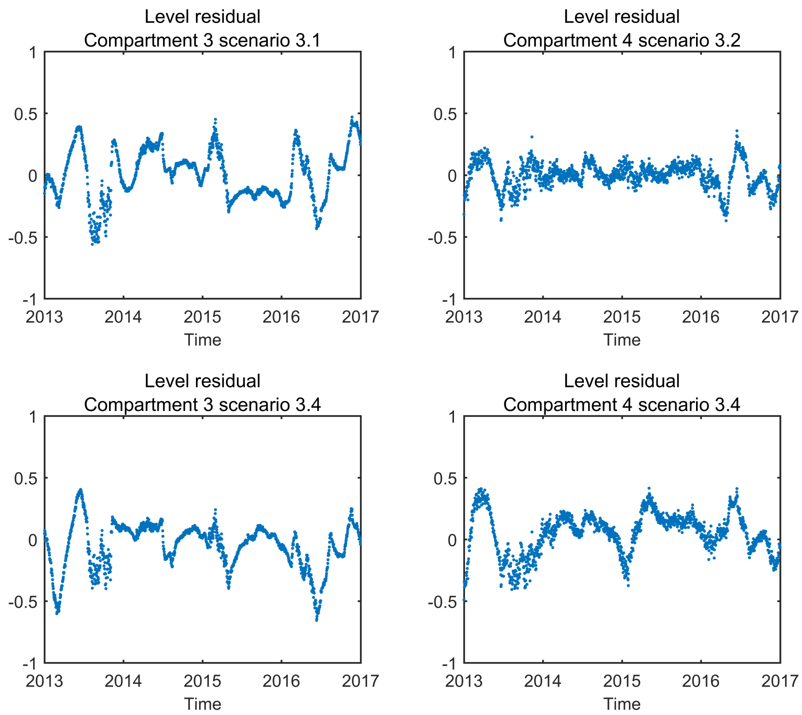

Figure 7.14: The leachate level residual plot for approach 3.

Table 7.8: Quantiles 0.05 - 0.95 and D_{KL} values for each parameter of approach 3

	Δz_{root} [m]		f_{crop} [-]		$\theta_{r,cover}$ [-]		c [-]	
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}
prior	0.10 - 1.50		0.10 - 1.50		0.00 - 0.40		0.40 - 1.00	
Scenario 3.1 c3	0.2979 - 0.4493	1.25	1.0356 - 1.0426	4.90	$3.11 \cdot 10^{-5}$ - 0.0014	5.29	0.6268 - 0.9477	0.44
Scenario 3.2 c4	0.3789 - 0.3792	8.00	1.0326 - 1.0326	10.77	0.2315 - 0.2317	7.27	0.6087 - 0.6124	5.51
Scenario 3.4	0.2398 - 0.2471	4.33	1.4351 - 1.4712	3.02	0.0094 - 0.0101	5.83	0.1990 - 0.2015	5.19

	K_{sat}^{inf} [m/d]		m^{inf} [-]		μ_{fast} [d]		σ_{fast} [d]	
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}
prior	$10^{-15.00}$ - $10^{0.00}$		0.00 - 4.00		1 - 148		1 - 20	
Scenario 3.1 c3	$10^{-3.6061}$ - $10^{-3.5785}$	4.80	0.0012 - 0.0465	5.08	1.6 - 49.7	0.23	1.2 - 14.8	0.07
Scenario 3.2 c4	$10^{-0.5978}$ - $10^{-0.5976}$	10.17	0.1488 - 0.1489	10.39	50.6 - 52.0	4.72	1.4 - 1.5	3.77
Scenario 3.4 c3&4	$10^{-13.0315}$ - $10^{-6.0090}$	0.38	3.0482 - 3.7070	0.21	c3: 13.7 - 16.1	3.16	c3: 3.6 - 4.1	1.67
					c4: 3.1 - 3.3	4.19	c4: 11.0 - 17.1	1.12

	μ_{slow} [d]		σ_{slow} [d]		β [-]		ϕ_{drain} [-]	
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}	quantiles	D_{KL}
prior	2 - 22026		1 - 20		0.01 - 0.99		0.10 - 1.00	
Scenario 3.1 c3	11.7 - $1.0175 \cdot 10^4$	0.77	1.05 - 1.07	4.80	0.0101 - 0.0198	4.31	0.1126 - 0.1239	4.36
Scenario 3.2 c4	1617.1 - 1704.8	5.45	1.04 - 1.04	6.27	0.5417 - 0.5596	3.31	0.0908 - 0.0932	5.32
Scenario 3.4 c3	1241.2 - 1879.21	2.74	11.8 - 13.7	1.95	0.5969 - 0.6281	3.00	0.0840 - 0.0877	4.59
Scenario 3.4 c4	1508.7 - 1670.4	4.86	1.04 - 1.05	6.15	0.3506 - 0.3713	2.93	0.1572 - 0.1730	3.72

	k_{side} [m^2/d]		σ_{level} [m]		$L(H\|\tilde{y})$ [-]
	quantiles	D_{KL}	quantiles	D_{KL}	quantiles
prior	1.00 - 120.00		0.02 - 2.00		
Scenario 3.1 c3	8.7766 - 11.5917	2.63	0.2038 - 0.2146	4.84	214.8208 - 227.9798
Scenario 3.2 c4	55.1656 - 57.8921	2.52	0.1029 - 0.1087	5.49	1188.40 - 1196.90
Scenario 3.3 c3&c4	117.8941 - 119.9231	3.74	c3: 0.1835 - 0.2007	3.09	766.0636 - 774.9022
			c4: 0.1748- 0.1853	3.06	

Recultivation layer
The corrected calculation of the saturated water content discussed in Section 7.2.2, has been implemented for this case. The results of approach 3 are shown in Figure 7.15. In all three cases the effective saturation is changing over time. This indicates that the error with the effective saturation being 1 all the time has been solved. The parameter quantiles and D_{KL} values are shown in Table 7.8. The D_{KL} values for the cover layer are higher than the values in approach 2. This means that the model gains more information from the parameter values, resulting in more certainty.

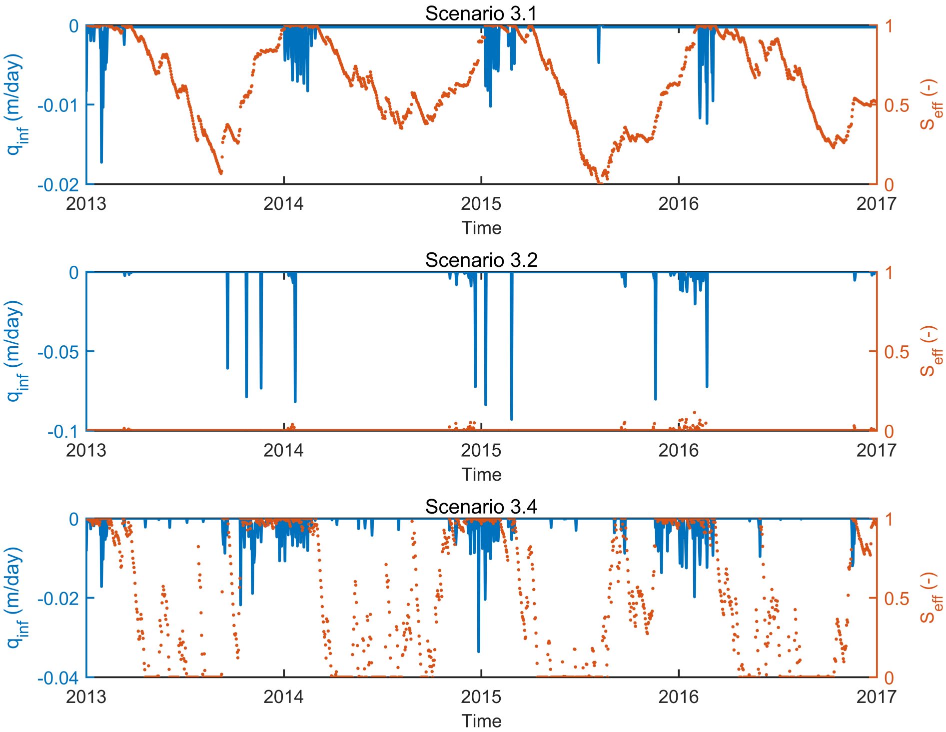

Figure 7.15: Infiltration into the waste layer and effective saturation of the recultivation layer over time for approach 3.

Waste layer
The water storage in the waste layer is shown in Figure 7.16. The storage in scenario 3.1, 3.2 and compartment 4 of scenario 3.4 follows the infiltration pattern. In summer periods, when the infiltration flux is low, the waste drains, while in winter periods, water is stored.

From comparing the waste layer parameters with approach 2 a few differences can be found. Both approaches give similar values for fast moving water, but the slow moving water has much larger travel times for approach 3 than approach 2. Almost all D_{KL} values for scenario 3.1 are smaller than the values for scenario 2.1. Almost all D_{KL} values for scenario 3.2 are larger than for scenario 2.2. The D_{KL} values for scenario 3.4 are much larger than for scenario 2.4. These values indicate that from the parameters of scenario 3.1 less information is gained compared to scenario 2.1, while for scenario 3.2 and 3.4 more information is gained from the parameters compared to the same scenarios of approach 2.

Drainage layer
The water flow between compartments 3 and 4 is shown in Figure 7.17. This figure shows similar results as approach 2. The sideflow for scenario 3.1 is the smallest and the sideflow for scenario 3.4 is the largest. This is mainly caused by the determination of the parameter k_{side}. The smallest value for k_{side}, shown in Table 7.8, corresponds with scenario 3.1, while the largest value corresponds with scenario 3.4. Due to the poor fit of the leachate level the sideflow estimated in scenario 3.4 remains unreliable.

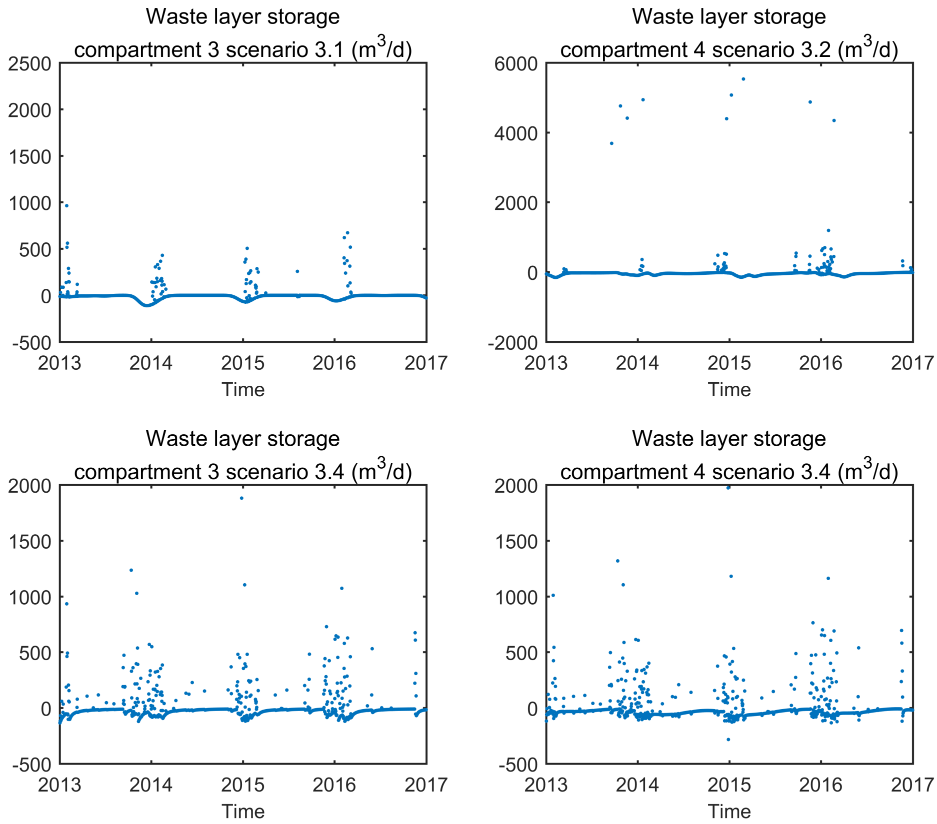

Figure 7.16: Water storage in the waste layer for approach 3.

Total Storage

The cumulative total storage for approach 3 is shown in Figure 7.18. All scenarios show the same storage pattern. Although in scenario 3.1 a slight decrease in water storage can be seen. Compared to approach 2 there is no upward or downward trend, which intuitively seems more correct. Overestimation of the crop factor is most likely balancing the gap in the water balance, resulting in a stable storage pattern.

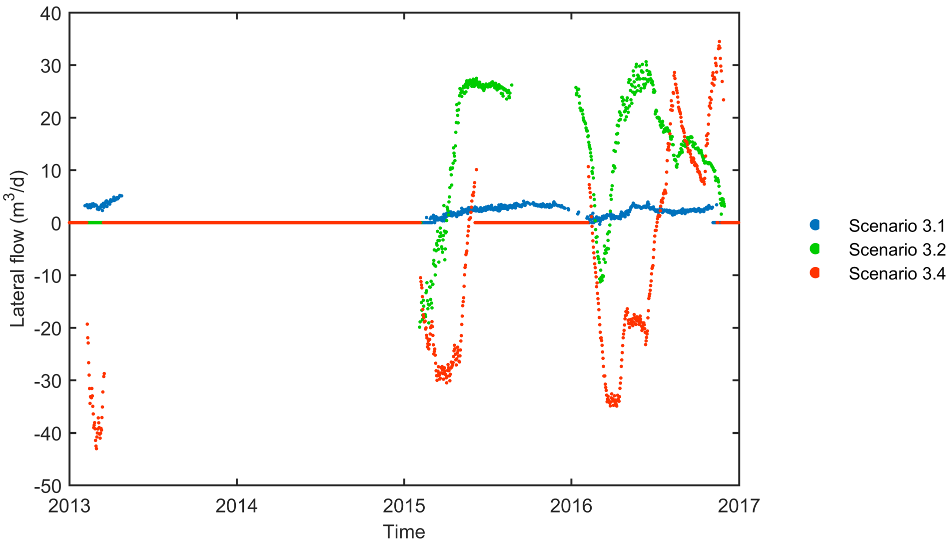

Figure 7.17: Water flow between compartments 3 and 4 for approach 3. Where positive flow is water flowing into compartment 3.

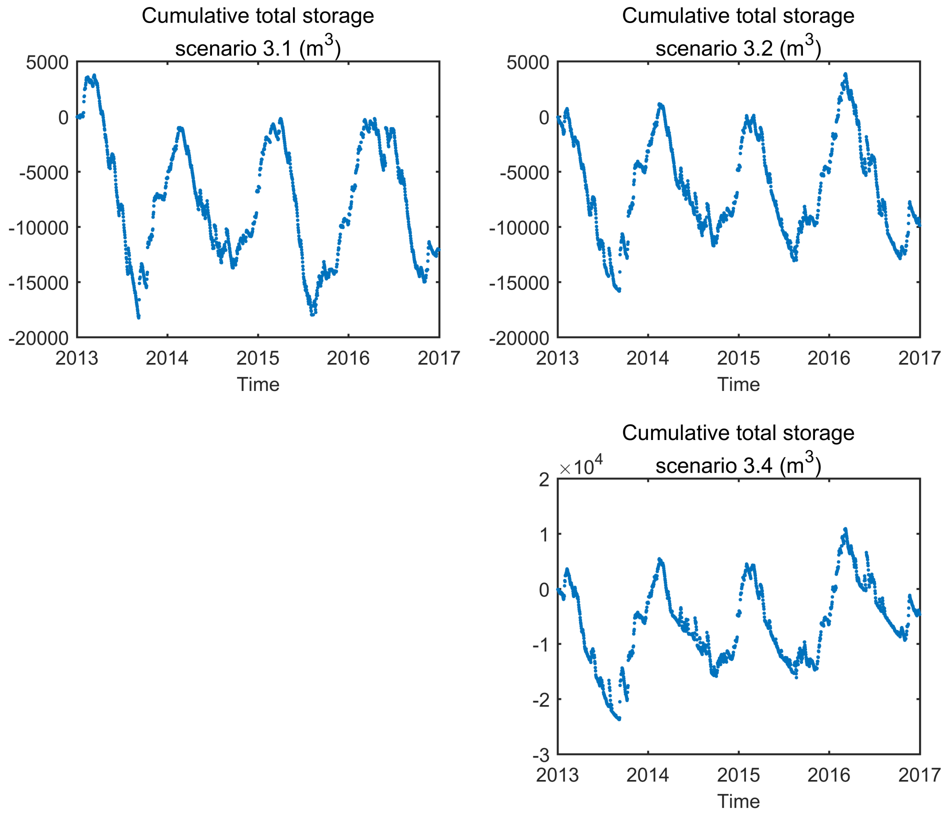

Figure 7.18: Cumulative total storage in the landfill for approach 3.

7.4. The optimal model

The log marginalized likelihood values for all scenarios are given in Table 7.9. Scenario 2.2 and 3.2 have the best balance between complexity and reality. All scenarios of Approach 1 give bad values. This confirms the idea that approach 1 is not sufficient enough again. the best scenarios are scenarios 2.1, 2.2 and 3.4.

Table 7.9: The log marginalized likelihood for al scenarios

Scenario	L^m
1.1	-1,1135.58
1.2	-1,2796.01
1.3	-2,5091.13
1.4	-2,5385.01
2.1	494.54
2.2	1191.20
2.3	513.70
2.4	-220.99
3.1	224.52
3.2	1184.37
3.4	702.21

From analysing the different models it can be concluded that approach 3 gives the best fits. The recultivation layer is also best implemented in approach 3. The largest D_{KL} values are obtained with approach 3. The largest marginalized likelihood values are obtained with the uncoupled models of approach 2 and the coupled scenario of approach 3. For modelling the water balance a combination between approach 2 and 3 is the best option.

8 Conclusion and Recommendations

The aim of this research was to adapt the existing model, created for two demonstration projects, to describe the water balance for the third demonstration field. The question to be answered in this research is:

Which modelling adaptation allows insight in the water dynamics of compartment 3 of De Kragge II, with minimal uncertainty?

In order to find a model that describes the water dynamics with minimal uncertainty, three different model implementations were evaluated. To evaluate the model uncertainty, visual and quantative criteria were used. The fits of modelled on measured data were used as a visual check. The quantitative analysis consists of evaluating the information content per parameter with the Kullback-Leibler divergence (D_{KL}) and the information content versus complexity with the marginalized likelihood value.

For approach 1, the outflow fits of the modelling results on measured data gave large errors. This was indicated by large standard deviations of the total error with respect to leachate outflow measurements. The error in the outflow estimation is likely caused by: 1) a gap in the water balance of the measured data 2) the implemented correlation between leachate level and outflow and 3) the fact that many factors influencing the flow rate, such as the operator's actions, were unknown. Because of the large errors, approach 1 would not provide sufficient information to analyse the water dynamics in the landfill. Therefore, approach 1 was rejected and a second approach was implemented. In the second approach only the leachate levels were used for calibration with measured data and the outflow was given as input.

For approach 2, the fits of the modelled leachate levels on the measured data, showed better results. The leachate levels were fitted with reasonable error. However, still errors in leachate level fit were present, because of the water balance error in the measured data. Approach 3, where the waste layer was simplified to increase calculation speed and reduce model complexity, showed the best fits of the modelled leachate levels and also more information was gained about the parameters, since the D_{KL} values for approach 3 were the highest.

At this point approach 2 and 3 both have advantages and disadvantages. Approach 2 gave the best insight in the water dynamics given its complexity, shown by the higher values for the marginalized likelihood. Approach 3 gave the best fits, the highest D_{KL} values and is the fastest model. From these results it would be advised to use approach 3 to improve the model. An improvement for approach 3, would be a distinction between mobile and immobile water.

In addition, each approach was evaluated with different model scenarios in which the compartments where either coupled or uncoupled. The coupled models for approach 2 and 3 showed larger errors in the leachate level fits than the uncoupled models. The D_{KL} values were also higher for the uncoupled models.

Given the results of the different scenarios, it would be advised to use the uncoupled models for the analysis of water dynamics inside the landfill, since these models showed the best fits, highest D_{KL} and marginalized likelihood values. However, correcting for the water balance gap in the measured data, might improve the results of the models. A coupled model is preferred above an uncoupled model, since uncoupled models do not have a closed water balance.

From analysing the results of the modelled water dynamics a few conclusions could be drawn about the model. The sideflow between the two compartments is about 5 to 25 m^3/day. The model showed that water in the landfill, flows fast from the cover layer to the drainage layer. The infiltration flux of the recultivation layer model seemed to be dominated by rainfall and evaporation. Therefore this model could be simplified by omitting water storage and flow through the layer.

8.1. Recommendations for model improvement

After analysing the results of the approaches three possible model improvements were discovered.

In the modelling approaches, no corrections are made for a gap in the measured water balance error. This leachate was extracted directly from the collection pits, in this way bypassing the flowmeters. The water balances indicated that this leachate was mainly extracted from compartment 4. To correct for the measured water balance gap the outflow data of compartment 4 should be corrected. Since, it is unknown on which days the trucks collected leachate form the landfill there are two options to correct for the error. The first option is dividing the monthly difference in leachate collection over each day of the month. This probably reduces the overall error, but might increase daily errors. Another option would be analysing on which days the leachate outflow is low. The leachate level data of these days could indicate that leachate was actually extracted. This method might reduce the overall error but increases uncertainty in outflow because of interpretation mistakes. However it is expected that correcting for the water balance error will improve the model fits, reduce the overall error, give better insight in water flow between compartments and reduce the modelled crop factor.

The results of the recultivation layer showed that different storage dynamics in the recultivation layer have the same impact on the infiltration dynamics into the waste layer. Therefore, the simplest method for the recultivation layer could be used. Simplification of the recultivation layer could be implemented by balancing rainfall and evaporation instead of calculating water flow and storage inside the layer. This will reduce the amount of model parameters and therefore increases the model certainty. If it is preferred to keep the recultivation layer calculation in the model two changes are necessary:

1. To prevent errors with the intial value it is advised to start the calculation period a bit earlier than the calibration period. A month earlier should be sufficient.
2. The calculation of $\theta_{sat,rec}$ should be corrected.

For approach 1 and 2, the water infiltrating the waste layer is calculated by discretizing the travel time over given retention times. The value corresponding to the second-last value of the retention time (n), indicates the transition from the mobile to the immobile water phase. The value n can become very large, so that baseflow, water flow from the immobile to the mobile phase, has no impact any more. Restricting n by analysing the pdf will improve the division of water over the mobile and the immobile parts and improve baseflow calculation. n could be reduced by setting a cut-off value with respect to a minimal probability value in the tail of the pdf. All water that has travel times larger than the cut-off value can then be added to the immobile water part.

8.2. Recommendations for the operator

If more was known about the operating procedure, the model results could be improved significantly. For instance, the leachate transported by truck is stored monthly instead of daily. Therefore, correcting for the water balance error can not be done without errors. Data on when the flowmeters were bypassed, how many trucks were filled and which compartment was drained are of great importance for improving the model. The operators are advised to improve there data storage, by reporting this data on a daily basis and keep track of everything that went differently in a logbook.

Bibliography

T.M. Alslaibi, I. Abustan, Y.K. Mgheir, and S. Afifi. Quantification of leachate discharged to groundwater using the water balance method and the Hydrologic Evaluation of Landfill Performance (HELP) model. *Waste Management & Research*, 31:50–59, 2013. doi: 10.1177/0734242X12465462.

A.H.M. Faisal Anwar and L.C. Thien. Investigating Leachate Transport at Landfill Site Using HYDRUS-1D. *International Journal of Environmental Science and Development*, 6(10):741–745, October 2015. doi: 10.7763/ijesd.2015.v6.691.

N.D. Bennett, B.F.W. Croke, G. Guariso, J.H.A. Guillaume, S.H. Hamilton, A.J. Jakeman, S. Marsili-Libelli, L.T.H. Newham, J.P. Norton, C. Perrin, S.A. Pierce, B. Robson, R. Seppelt, A.A. Voinov, B.D. Fath, and V. Andreassian. Characterising performance of environmental models. *Environmental Modelling & Software*, 40:1–20, 2013. doi: 10.1016/j.envsoft.2012.09.011.

K.U. Berger. On the current state of the Hydrologic Evaluation of Landfill Performance (HELP) model. *Waste Management*, 38:201–209, 2015. doi: 10.1016/j.wasman.2015.01.013.

G. Botter, E. Bertuzzo, and A. Rinaldo. Catchment residence and travel time distributions: The master equation. *Geophysical Research Letters*, 38:1–6, 2011. doi: 10.1029/2011GL047666.

C. Brandstätter, D. Laner, and J. Fellner. Carbon pools and flows during lab-scale degradation of old landfilled waste under different oxygen and water regimes. *Waste Management*, 40:100–111, 2015. doi: 10.1016/j.wasman.2015.03.011.

J. Fellner and P.H. Brunner. Modeling of leachate generation from MSW landfills by a 2-dimensional 2-domain approach. *Waste Management*, 30:2084–2095, 2010. doi: 10.1016/j.wasman.2010.03.020.

Google Maps, n.d. URL https://www.google.com/maps/@51.5100554,4.3418981,2257m/data=!3m1!1e3.

Heidemij Adviesbureau. Richtlijn onderafdichtingsconstructies voor stort- en opslagplaatsen, 1993a.

Heidemij Adviesbureau. Richtlijn drainagesystemen en controlesystemen grondwater voor stort- en opslagplaatsen, 1993b.

E.C. Hernández, W. Strycharski, and B. Varannai. Database structure for baseline monitoring of the Kragge II landfill. Technical report, Delft University of Technology, 2016.

M. Hrachowitz, P. Benettin, B.M. van Breukelen, O. Fovet, N.J.K. Howden, L. Ruiz, Y. van der Velde, and A.J. Wade. Transit times - the link between hydrology and water quality at the catchment scale. *WIREs Water*, 3:629–657, 2016. doi: 10.1002/wat2.1155.

Introductie Duurzaam Stortbeheer, 2017. URL http://duurzaamstortbeheer.nl/.

IWACO B.V. Richtlijn geohydrologische isolatie van bestaande stortplaatsen, 1997.

S. Kullback and R.A. Leibler. On information and sufficiency. *The Annals of Mathematical Statistics*, 22(1):79–86, 1951.

Ministerie van VROM. Richtlijn voor dichte eindafwerking op afval- en reststofbergingen, 1991.

M.A. Newton and A.E. Raftery. Approximate bayesian inference with the weighted likelihood bootstrap. *Journal of the Royal Statistical Society*, 56(1):3–48, 1994.

H. Oonk. Voortgangsresultaten nulonderzoek ids de kragge 2, 2014.

Rijksoverheid. Green deal duurzaam stortbeheer. 2011.

N.H. Rosqvist, L.H. Dollar, and A.B. Fourie. Preferential flow in municipal solid waste and implications for long-term leachate quality: valuation of laboratory-scale experiments. *Waste Management & Research*, 23:367–380, 2005. doi: 10.1177/0734242x05056995.

P.R. Schroeder, C.M. Lloyd, P.A. Zappi, and N.M. Aziz. *The Hydrologic Evaluation of Landfill Performance (HELP) Model*, 4526.

J. Šimůnek, N.J. Jarvis, M.Th. van Genuchten, and A. Gärdenäs. Review and comparison of models for describing non-equilibrium and preferential flow and transport in the vadose zone. *Journal of Hydrology*, 272:14–35, 2003. doi: 10.1016/S0022-1694(02)00252-4.

A-J. Tinet, L. Oxarango, R. Bayard, H. Benbelkacem, G. Stoltz, M.J. Staub, and J.-P. Gourc. Experimental and theoretical assessment of the multi-domain flow behaviour in a waste body during leachate infiltration. *Waste Management*, 31:1797–1806, 2011. doi: 10.1016/j.wasman.2011.03.003.

R. Valencia, W. van der Zon, H. Woelders, H.J. Lubberding, and H.J. Gijzen. Anammox: An option for ammonium removal in bioreactor landfills. *Waste Management*, 31:2287–2293, 2011. doi: 10.1016/j.wasman.2011.06.012.

A.G. van Turnhout. *Characterizing Dominant Processes in Landfills to Quantify the Emission*. PhD thesis, Delft University of Technology, 2017.

Verengiging van Afvalbedrijven. Integraal plan van aanpak 'introductie duurzaam stortbeheer op praktijkschaal'. 2014.

Vereniging Afvalbedrijven. Deelplan van Aanpak verduurzamingspilot op stortplaats de kragge 2. techreport, 2015.

J.A. Vrugt. Markov chain Monte Carlo simulation using the DREAM software package: Theory, concepts, and MATLAB implementation. *Environmental Modelling & Software*, 75:273–316, 2016. doi: 10.1016/j.envsoft.2015.08.013.

Werkgroep Afvalregistratie. Afvalverwerking in nederland, gegevens 2016. Technical report, 2016.

Wet MB 2017, August 2017. URL `http://wetten.overheid.nl/BWBR0003245/2017-08-30`.

A.I. Zacharof and A.P. Butler. Stochastic modelling of landfill leachate and biogas production incorporating waste heterogeneity. Model formulation and uncertainty analysis. *Waste Management*, 24: 453–462, 2004. doi: 10.1016/j.wasman.2003.09.010.

A

Drawing of the drainage system of De Kragge II

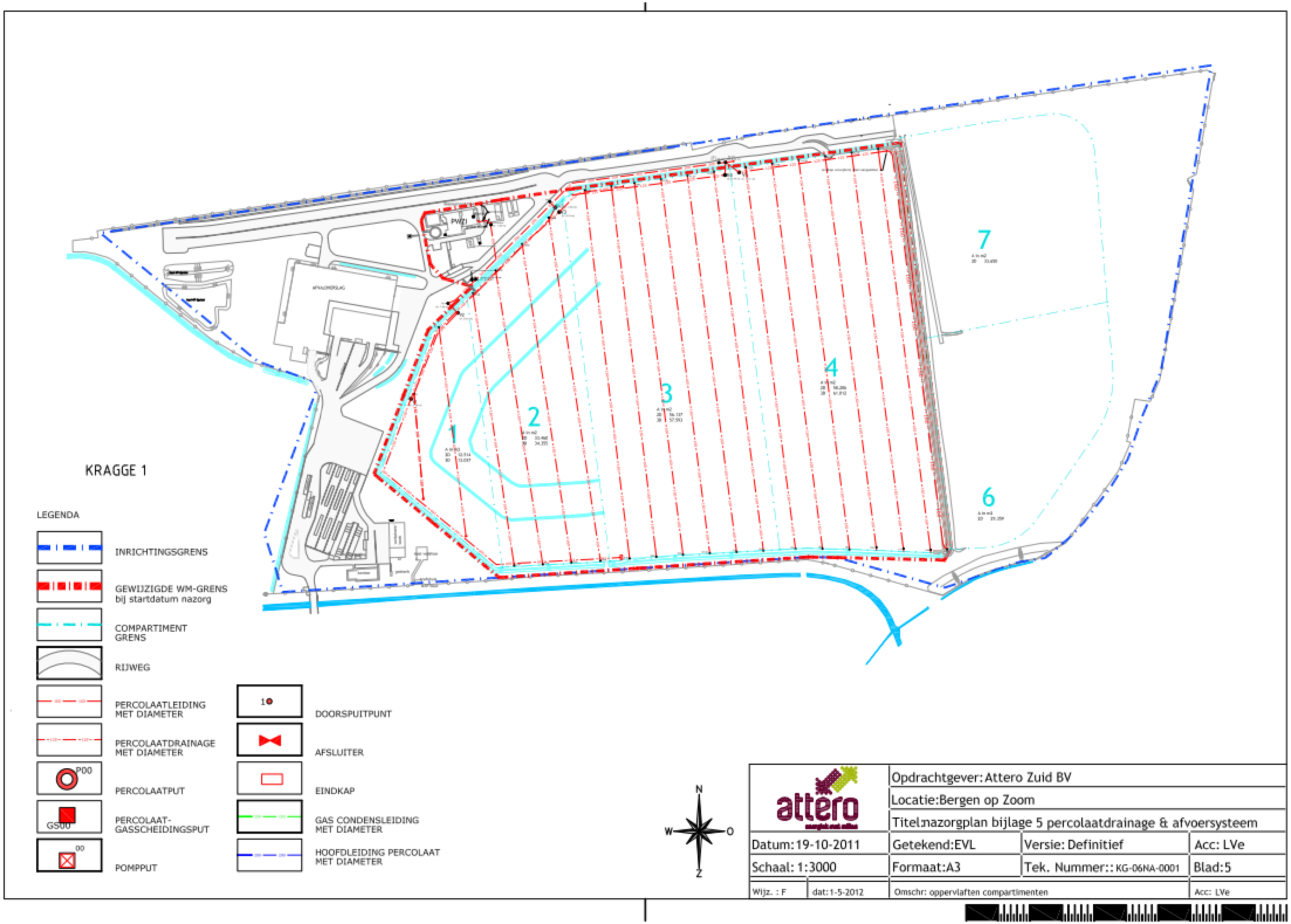

Figure A.1: Drainage system of Landfill De Kragge II.

B

Drawings of the collection and leachate pit

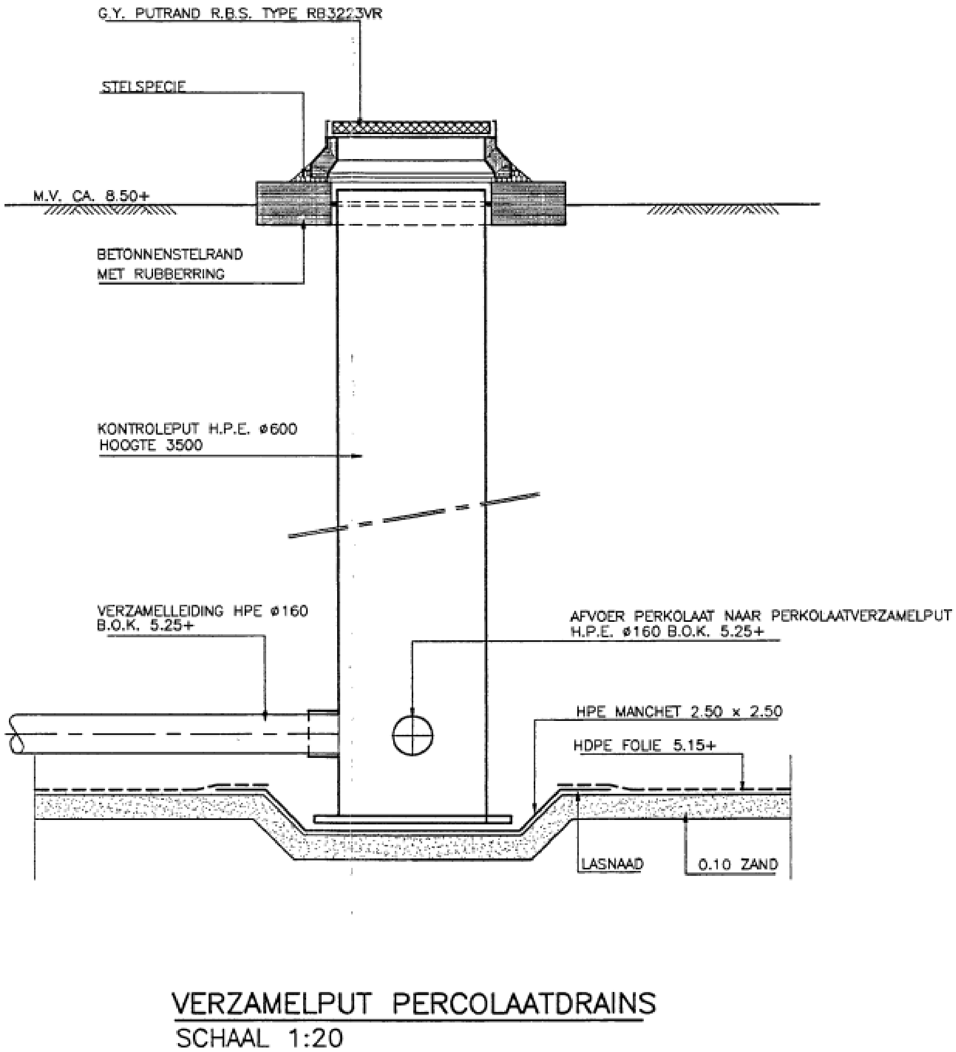

Figure B.1: Section drawing of the collection pit of compartment 3.

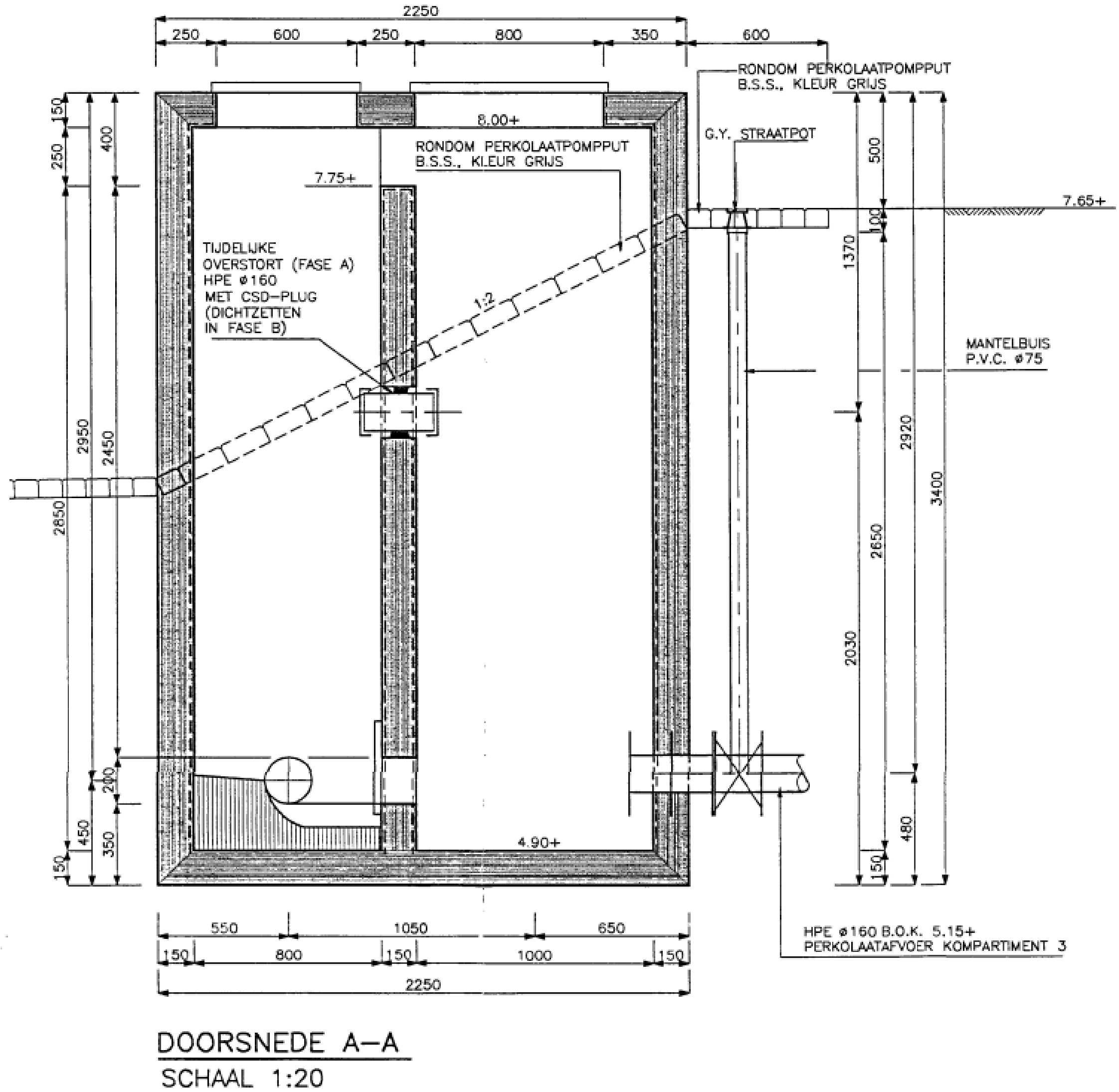

Figure B.2: Section drawing of the leachate pit of compartment 3 and 4.

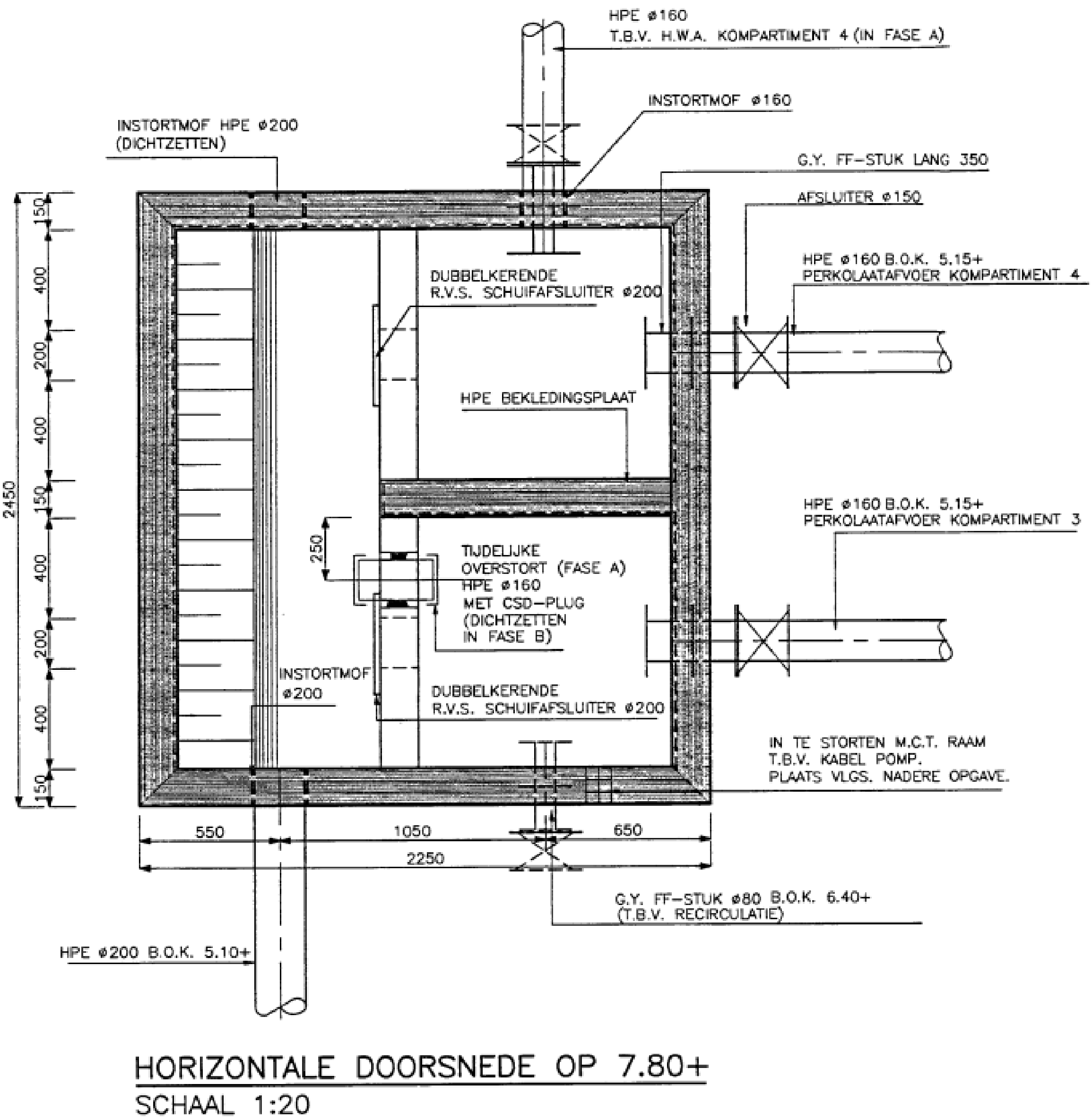

Figure B.3: Horizontal section drawing of the leachate pit of compartment 3 and 4.