MODELING MSW LANDFILLS WITH KNMI RADAR PRECIPITATION DATA

BACHELOR THESIS

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PREFACE

Before you lies my bachelor thesis *Modeling MSW landfills with KNMI radar precipitation data.* It has ben written to fulfil the graduation requirements of the bachelor study program *Applied Earth Sciences* at the faculty of Civil Engineering and Geosciences at the University of Technology of Delft. The thesis is written in the direction of the master track *Environmental engineering.*

This research connects the curriculum of the bachelor program Applied Earth Sciences and my bachelor thesis. Main courses that overlap are; Mathematics, Remote sensing and geostatistics, Instrumentation & signals with Matlab®, Mechanics and transport by flow in porous media. The acquired skills while working on this project can be found in the reflection in appendix B.

ABSTRACT

The goal of this bachelor thesis is to compare different datasets of precipitation from the Royal Netherlands Meteorological Institute for the purpose of modelling municipal solid waste landfills. It is essential to develop after-care methods for landfills so the future generations do not have to cope with the burden of the emission potential of the contaminants. Due to the complex and inhomogeneous nature of the landfill systems modelling is an essential part of understanding the process and predicting the behaviour of the emissions in the future. To model the mass balance an estimate of the precipitation is needed which can be retrieved from two datasets; rain gauges and the precipitation radar. The precipitation radar dataset has a higher resolution and might provide another, and maybe better, estimate for the modelling of the landfills. To see whether this is the case first a comparison for the daily scale is made, second a statistical analysis is performed to determine the difference in distributions between the datasets and third the datasets are compared as a result of the model of the landfills. The results of these comparisons and test show that the radar precipitation data gives a more accurate estimation on a daily basis but the trend in rainfall between the radar precipitation and the automatic rain gauge system is similar. The thesis concludes that the input of the radar dataset in the model creates a better model of the landfill on both a daily basis as on the long-term.

CONTENTS

1. INTRODUCTION

1.1 Landfills in the Netherlands

In the Netherlands over 60Mtons of waste is produced every year of which approximately 80% is recycled. Around 40% of the non-recycable waste is incinerated and 12,5% is landfilled. The past decades the amount of waste that is landfilled has decreased by 80% but the amount in 2017 was still 2,7 Mtons. (Rijkswaterstaat, 2018). The waste is stored on one of the nineteen operational municipal solid waste (MSW) landfills in the Netherlands. (CBS, PBL, RIVM, & WUR, 2017). This is because some waste streams can not be processed otherwise and landfilling is the only viable final option to safely remove it from the economical cycle. The protection of the health and environment is high on the agenda of (local) governments. Proof of this in the Netherlands is the *soil quality decree* (besluit bodemkwaliteit) from the ministries in 2008. This decree strives for a better balance in soil quality for human health and environment and socio-economic developments. (Ministry of Housing, Spatial Planning and the Environment (VROM), 2007).

Landfills are a threat to the environment via gasses and leachate. Potent greenhouse gasses, such as methane, are produced during biochemical mineralization of the organic waste and eventually enter the atmosphere. Leachate is produced after precipitation infiltrates the waste-body which then gets polluted by the waste. If this contaminated leachate would not get collected, it would flow into the underlying soil and eventually the groundwater and surface water The production of leachate can be prevented as a whole by covering the waste body with an impermeable liner but this would require eternal aftercare. Up till now the covering of the waste body has been the most common solution. (Turnhout v., 2017).

When the threat of the landfills to the health and environment is within the regulations of the authorities aftercare of landfills can be brought to an end. This implies that no harmfull effects can occur in the post-aftercare period. (Laner, Crest, Scharff, Morris, & Barlaz, 2012). However the monitoring and controlling of the waste has been passed to future generations in the Netherlands. To prevent this from happening further it is necessary to revise regulations on aftercare and create incentives to actively stabilise landfills. (Scharff, 2014).

The authorities and landfill operators have started experiments to investigate if so called sustainable after-care approaches can cause a substantial decrease in the emissionpotential. This requires that after the deposition of the waste, no longer a water thight cover has to be installed on top of the landfill. This allows for recirculation of leachate and aeration in order to achieve a condition where the health and environment is no longer under threat. The produced leachate is collected by a drainage system for treatment (Rijksoverheid, 2011).

1.2 Research questions

The mechanisms underlying the emissions need to be modelled and understood to predict and demonstrate the impact of the sustainable approaches on the long term emission potential. The amount of leachate generated from landfills over multiple years can be predicted using mass balance models. The leachate discharge can be calculated since it is equal to the difference in precipitation and the sum of actual evapotranspiration, runoff and water storage within the waste body. (Fellner & Brunner, 2010).

This research of this bachelor thesis is focussed on the leading actor in the water balance model; precipitation. The Royal Netherlands Meteorological Institute (KNMI) maintains two measurement systems for precipitation; rain gauges and weather radar. From both datasets an estimate for the rainfall of the landfill can be created. The rain gauges Question is however:

1. What are the differences in measured precipitation accumulations between radar and the nearest KNMI station?

And with that comes the second question:

2. How does the choice of the precipitation input (radar versus nearest KNMI station) affect the mass balance model of the landfill?

Due to the geographical distance between the landfill and the nearest knmi weather station the hypothesis is that the mass balance model for the landfill will become more accurate when using radar precipitation data as input.

1.3 Thesis structure

In chapter 2 the basic layout is given of how the water balance of flows and the corresponding equations to this process. This is used in how the model is build and all the different flow fluxes are calculated. In chapter 3 a description is given of all the datasets and how the precipitation accumulations are measured The limitations and benefits of these datasets are also described.

Chapter 4 reports all the acquired results in three parts. First a daily comparison between the datasets, second a statistical analysis of the datasets and third the effects of the implementation in the model of the different datasets. The daily comparison describes the differences for the year 2016 and also what might cause differences on a daily scale. The statistical analysis investigates if the datasets have similar distributions and are equal in trend. The model implementation describes how the modelled data differs form the measured outcome and how come and what choice of input is eventually the most accurate.

2. BASIC MODEL OF A LANDFILL

To model the landfills the landfill is split up in three sections. The cover layer, the waste body and the drainage layer. Each layer has its own mass flow of water as can schematically be seen in figure 1. The model and equations are recovered from (Turnhout v., 2017) and some personal documents.

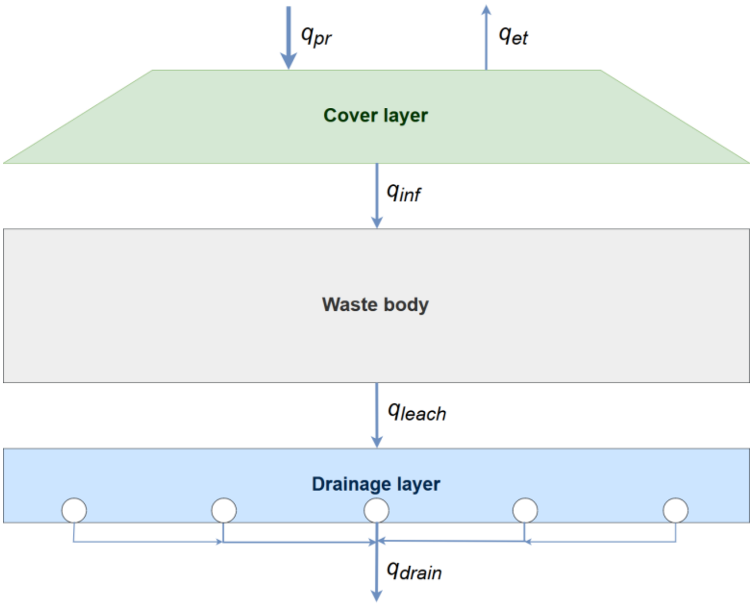

Figure 1- Schematic overview of the landfill and the flow paths.

2.1 Cover layer

The cover layer is the layer on top of the entire waste body. This is layer of a certain thickness is the layer in which crops grow where their roots are present. From this layer evapotranspiration can take place. This gives the water balance of the cover layer the following equation:

$$\frac{\Delta S_{cl}}{\Delta t} = q_{pr} - q_{et} - q_{inf} \tag{1}$$

where S_{cl} is the storage in the cover layer $[m]$, Δt is the time $[day]$, q_{pr} is the precipitation $[m/day]$, q_{et} is the evapotranspiration $[m/day]$ and q_{inf} is the infiltration flux to the waste body $[m/day]$. Downward flow is positive and upwards flow (q_{et}) is negative.

$$q_{inf} = -K_{cl}\left(\frac{S_{cl} - S_{cl_{min}}}{S_{cl_{max}} - S_{cl_{min}}}\right)^{m} \tag{2}$$

where K_{cl} is the hydraulic conductivity of the cover layer $[m/day]$. $S_{cl_{max}}$ is the maximum achievable storage in the cover layer and $S_{cl_{min}}$ is the minimum storage in the cover layer where water will still freely drain. m is a dimensionless empirical shape parameter. The evaporation term is given by:

$$\mathrm{q_{ev}} = \mathrm{E_{pot}}\,\mathrm{C}_f \tag{3}$$

where E_{pot} is the potential evaporation flux $[m/day]$ taken from the KNMI and C_f is the crop factor $[-]$ to adjust the evaporation for the vegetation growing on the landfill.

2.3 Waste body

Due to the complex nature of water flow in the heterogeneous waste body it is chosen to model the flow with a stochastic stream tube model. The flow of the produced leachate q_{leach} is calculated from the probability distribution of retention times of the water inside the waste-body:

$$q_{leach}(t) = \int_0^t q_{inf}(t-\tau) \cdot f(\tau)\, d\tau \qquad (4)$$

where t is the time at a given moment and τ is the retention time of the water in the waste body. The bimodal lognormal distribution $f(\tau)$ of the retention times describes how water is retained in preferential fast and slow flow paths within the waste body:

$$f(\tau; \mu_{fast}, \sigma_{fast}, \mu_{slow}, \sigma_{slow}, \beta) = \frac{\beta}{\tau\sigma_{fast\sqrt{2\pi}}}\, exp\frac{-(\ln\tau - \mu_{fast})^2}{2\sigma_{fast}^2} + \frac{1-\beta}{\tau\sigma_{slow\sqrt{2\pi}}}\, exp\frac{-(\ln\tau - \mu_{slow})^2}{2\sigma_{slow}^2} \qquad (5)$$

where β is the fr action between fast and slow moving water and μ and σ are the mean and standard deviation of the fast moving or slow moving water residence times.

2.4 Drainage layer

Water levels in the drainage layer are kept at a nearly constant water level. Therefore it is assumed that the flux from the drainage system is identical to the flux entering the drainage system.

$$q_{drain} = q_{leach} \qquad (6)$$

3. KNMI PRECIPITATION DATASETS

3.1 Description

To obtain a value of the precipitation on top the landfill different datasets can be used. For instance the Royal Netherlands Meteorological Institute (KNMI) maintains two rain gauge networks: an automatic network and a manual network of rain gauges. The automatic rain gauge network consists of over thirty weatherstations ($\approx 1\ station\ per\ 1000km^2$) that every ten minutes measure air temperature, atmospheric pressure, winddirection & -speed, relative hummidity, solar radiation, visibility and precipitation. The manual network of rain gauges consists of over threehundred rainfall stations ($\approx 1\ station\ per\ 100km^2$) with daily precipitation accumulations measured at 0800 UTC. (Overeem, Holleman, & Buishand, 2009); (Koninklijk Nederlands Meteorologisch Instituut, 2019).

The distribution of precipitation in the Netherlands is also monitored by radar which produces an indirect estimate of the precipitation intensity. Based on series of radar images an estimate of the fallen precipitation can be made. The radar emits short pulses which are reflected by precipitation. Since 1997 the KNMI measured the precipitation depths for durations of 15 minutes to 24 hours for the Netherlands ($3{,}55 \times 10^4 km^2$). The pixels are 2,4 km grids ($\approx 6km^2$). Since 2008 the resolution increased for both the duration and the pixel resolution. The measurements intervals decreased to every 5 minutes and the spatial resolution increased to 1km. Both radar datasets are validated and bias adjusted by using both KNMI rain gauge networks. The radars that measure the precipitation are installed in Den Helder and De Bilt. The radar in De Bilt was replaced by a new radar in Herwijnen ($\approx 30km\ south\ of\ De\ Bilt$). (Overeem et al., 2009); (Overeem, 2019).

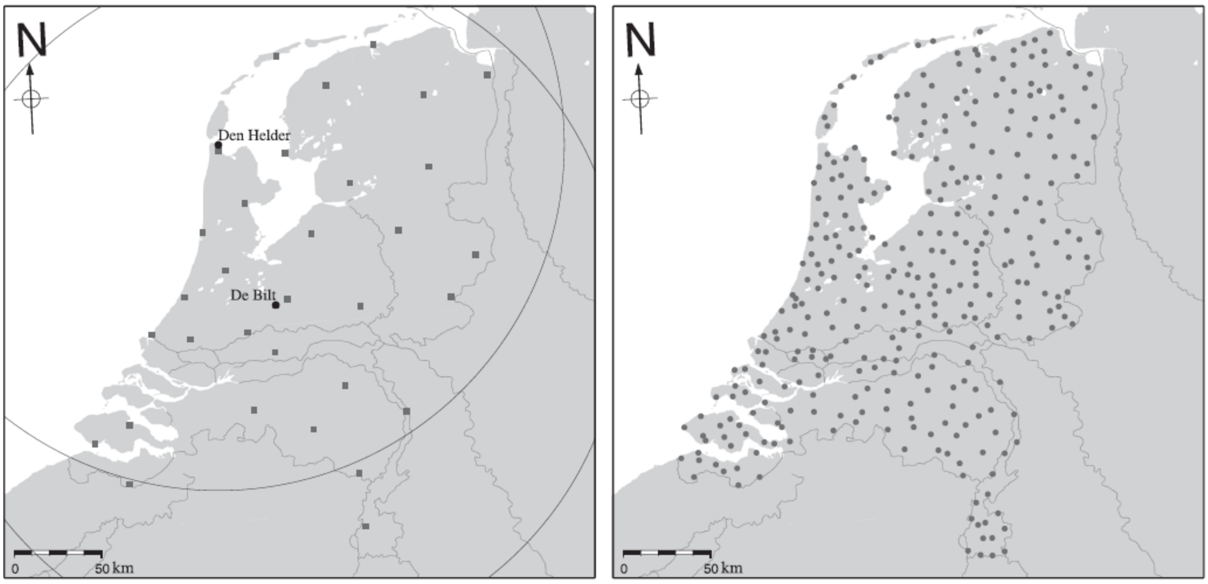

Figure 2 Map of the Netherlands with on the left the locations of the automatic rain gauges and the radar locations in De Bilt and Den Helder (and their ~200km range circles). On the right are the locations of the manual rain gauges. Figure is not entirely up to date. (Overeem et al., 2009).

3.2 Measurement differences

The KNMI states on its website: "*Radar images are not as accurate as the rain gauge measurements but they are a valuable asset to the monitoring network, especially for rain that falls in-between the rain gauges."* (KNMI, 2019). To test this the landfill at the Wieringermeerpolder used. The nearest automatic rain gauge system is at Berkhout at ~15km distance and the nearest manual rain gauge is at Medemblik at ~2km distance. The resolution of the Berkhout automatic rain gauge is higher since the precipitation is measured every ten minutes while the precipitation at Medemblik is only measured daily at 0800h. The weather station at Berkhout also gives daily information about the potential evapotranspiration which the rain station at Medemblik does not.

The radar data is used by the KNMI as an addition to the rain gauge network, mainly for rainfall that drops in between rain gauges. Also the radar data is used for climatological probability of extreme precipitation events. (KNMI, 2019). The radar scans clouds above 1500meter while light precipitation, such as drizzle or light snow, can precipitate from a cloud ceiling of 500 meter. This means that sometimes drizzle or light snow is not visible on the radar images. Mist is also not observed by the radar but this is officially not a type of precipitation. Snow with a low saturation range is also less visible than snow with a high saturation grade due to the reflectivity of the water in the ice-crystals. The sometimes low fallrate of the snowflakes can create a difference in horizontal movement of the flakes due to the wind. (KNMI, 2019).

4. RESULTS

4.1 Daily comparison for the year 2016

For this thesis the main focus was on the 24 hour precipitation depth radar data from the KNMI. This follows due to the fact that the evaporation data is only available on a daily basis of 2400h to 2400h.

The test case is based on the landfill at Wieringermeer. Nearest precipitation from an automatic rain gauge is received from the Berkhout weather station 15 kilometres away from the landfill. To get a clear overview of the difference in precipitation the year 2016 is taken.

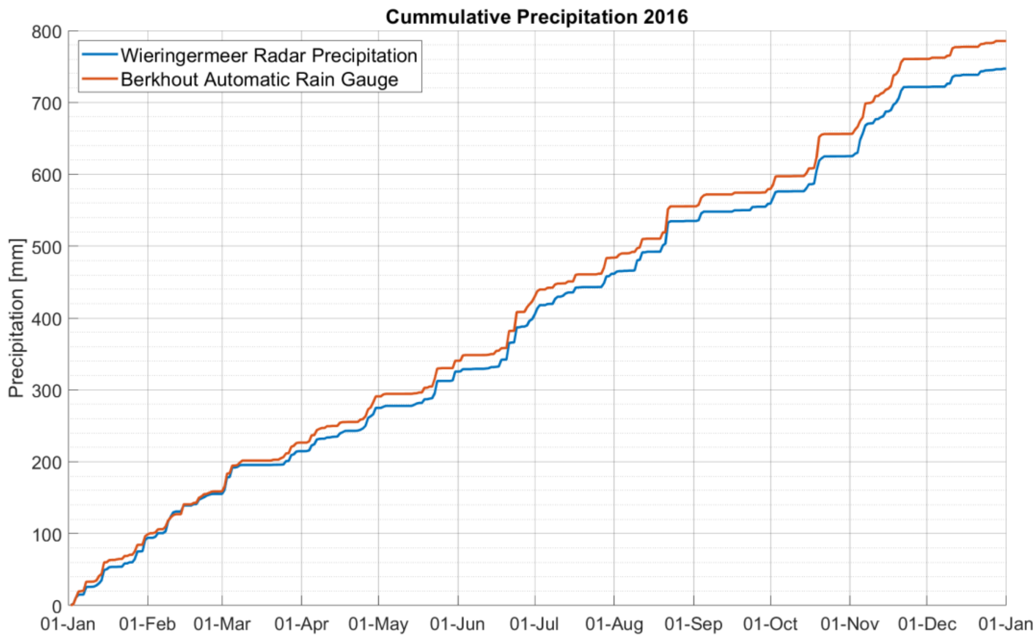

Figure 3 – Cumulative precipitation for the year 2016

In the year 2016 is clearly visible that the there is a difference in the accumulated precipitation. In summer and autumn, when there are more heavy precipitation events a larger difference is developed than in other times of the year.. To survey this the difference between the precipitation is looked at between Wieringermeer radar and Berkhout (visualized in figure 4). From this it can be seen that for most days at which there is no precipitation at Wieringermeer, there is no difference in precipitation at Berkhout either. So for nearly all dry days; no difference in precipitation is observed. However on the days where there is precipitation, differences start to occur. To see what happens on one of these days the radar image for the eighth of February is recovered from the KNMI which can be seen in figure 4. Here it is visible that there is a raincloud that travels over Wieringermeer landfill but not over the Berkhout Weather station.

These differences in daily precipitation might originate from three different sources. The most important one is the difference in location since the distance between the two places is over 15 kilometres. Another reason is the different measuring techniques of the radar and the rain gauges. Also random errors could occur in the datasets which might result in inaccuracies and differences.

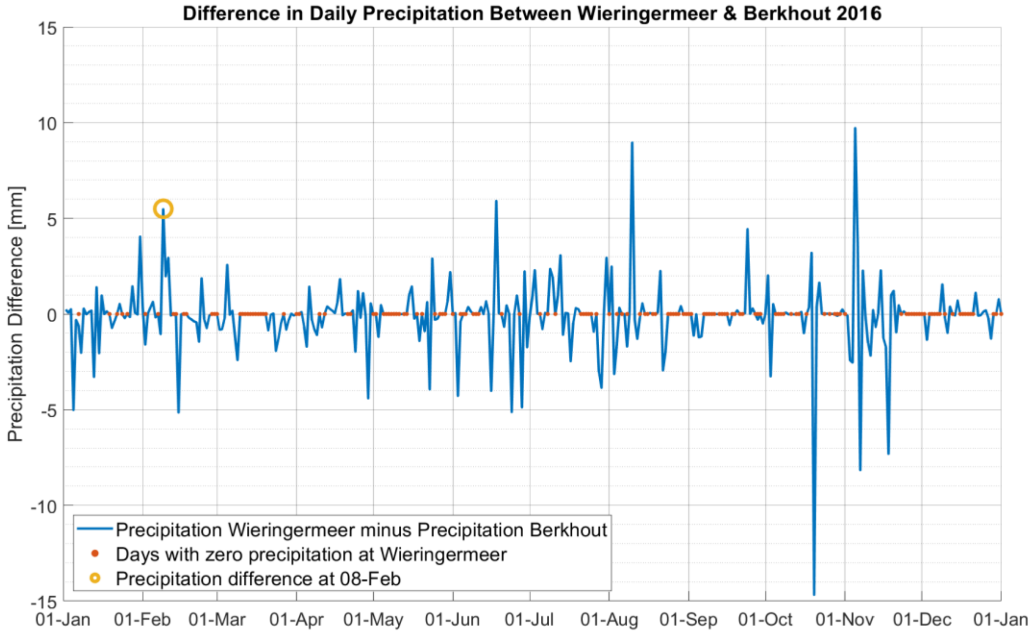

Figure 4 – Difference in the daily precipitation between the Wieringermeer landfill radar pixel and the Berkhout automatic rain gauge weather station. Difference is calculated by substracting the precipitation in Berkhout from the precipitation in Wieringermeer. In red are the days indicated where there is no precipitation accumulation measured in Wieringermeer. In yellow is a testcase indicated to compare the radar image from the 8th of february.

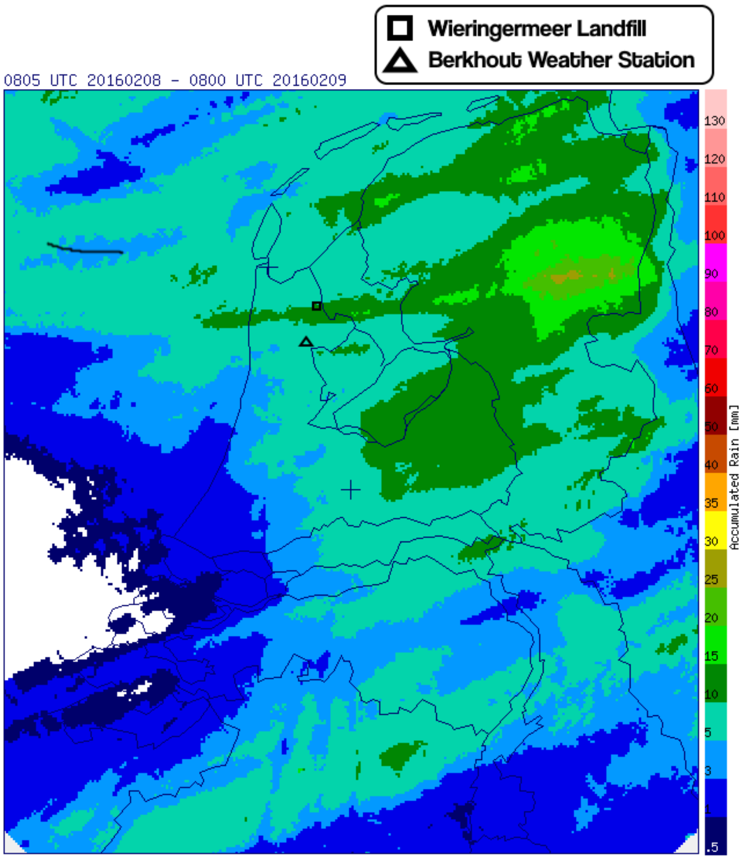

Figure 5 – Corrected daily radar image from 08:05h 08-02-2016 till 08:00h 09-02-2016 with indications of the location of the Wieringermeer landfill and the Berkhout Weather Station. Source: (Koninklijk Nederlands Meteorologisch Instituut, 2019)

4.2 Statistical analysis

The differences on a day-to-day basis are visible but to obtain a better understanding of the datasets as a whole a statistical analysis is required. The daily precipitation data is used over eleven years (01 January 2008 until 31 December 2018). A quick overview of the datasets, their origin and measurement times are given in table 1. Part of the Berkhout Weather Station and Wieringermeer Radar 24 is also used for the 2016 comparison.

Table 1 – Short description of all the used datasets for the statistical analysis

Name dataset	**Measurement type**	**Abbreviation**	**Measurement time**
Berkhout Weather Station	Automatic Rain Gauge	BH24	24:00 – 24:00
Berkhout Radar	Radar Dataset	BH24R	24:00 – 24:00
Medemblik Rain Station	Manual Rain Gauge	MB08	08:00 – 08:00
Wieringermeer Radar 24	Radar Dataset	WM24R	24:00 – 24:00
Wieringermeer Radar 08	Radar Dataset	WM08R	08:00 – 08:00

For all these datasets (from 2008 until 2019) some basic statistics as the mean, median, standard deviation and variance are calculated which can be seen in table 2. Since the median is 0,15 mm and the mean is 2,30 mm, all datasets are very skewed and not normally distributed. A probability plot for these datasets is added in appendix A, figure 8.

Table 2 – Basic statistics for the use datasets

Precipitation source	**Mean (mm)**	**Median (mm)**	**Standard Deviation (mm)**	**Variance (mm^2)**
Berkhout Weather Station	2,29	0,10	4,66	21,75
Berkhout Radar	2,45	0,17	4,90	23,97
Medemblik Rain Station	2,30	0,20	4,45	19,80
Wieringermeer Radar 24	2,23	0,15	4,39	19,29
Wieringermeer Radar 08	2,23	0,15	4,31	18,54

The daily difference is partially looked at for 2016 in section 4.1 However it is also of importance to statistically analyse the daily differences between the datasets as a whole. The daily differences between datasets that are most important for the research are; (1) the difference in precipitation between the radar pixel above the Berkhout weather station and the station itself, (2) the difference between the radar above the landfill at Wieringermeer and the weather station at Berkhout and (3) the difference between the radar above the landfill at Wieringermeer and the rain station at Medemblik. In table 3 these differences are analysed with the same statistics as table 2. Here it is visible that the radar datasets above Wieringermeer produce a lower estimate of precipitation on the long-term. The pixel of the Berkhout radar however produces a much higher estimate than the automatic rain gauge at the Berkhout Weather station. Interesting to see that the distribution of the daily difference between Wieringermeer Radar and Berkhout Weather station has larger spread. There are more large (>10mm) differences in accumulated precipitation than the other datasets when compared. This has probably mainly to do with the larger distance between the geographical locations. The other compared differences between the radar and rain gauges do not show any days where the precipitation difference is higher than 12 mm.

Table 3 – Basic statistics for the differences in daily precipitation between some comparable datasets

Daily difference in accumulated precipitation	**Mean (mm)**	**Median (mm)**	**Standard Deviation (mm)**	**Variance (mm^2)**
BH24R minus BH24	0,16	0,00	1,03	1,06
WM24R minus BH24	-0,06	0,00	2,10	4,41
WM08R minus MB08	-0,08	0,00	0,98	0,96

Since the datasets are not normally distributed we plot the histograms of the log10 values of the precipitation. We exclude all values below 0,05 mm of precipitation due to the measurement range of the rain gauges. Looking at the histograms in figure 6 it is seen that that the datasets are not lognormally distributed. An Anderson-Darling test to see if the logarithmic datasets are normally distributed has a negative outcome for all logarithmic datasets. No specific distribution type can be fitted onto the original distributions of the datasets either.

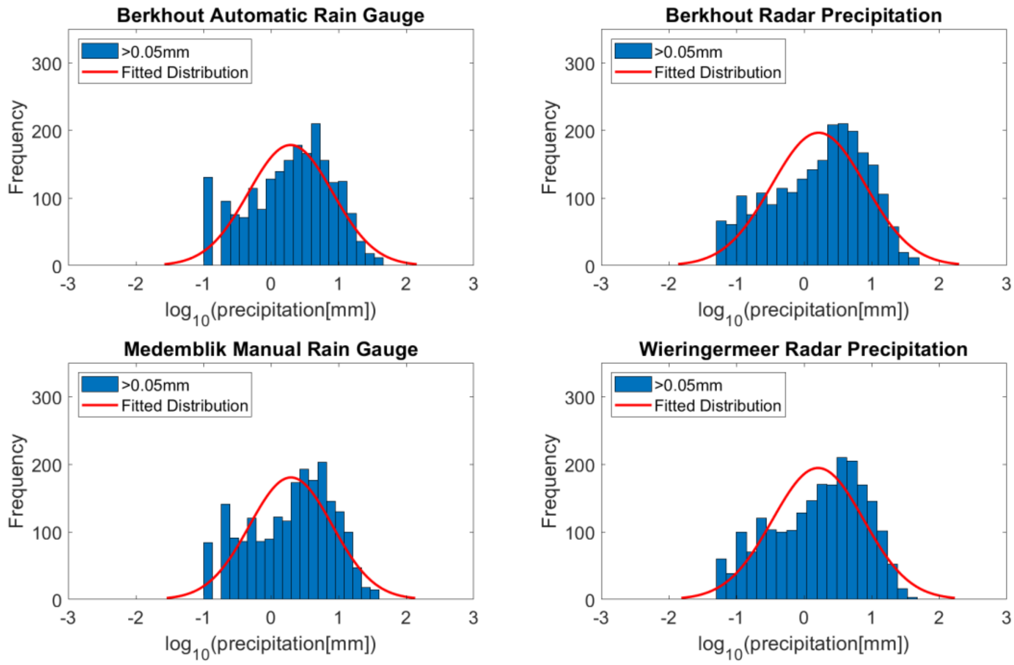

Figure 6 – Histograms for the logarithmic precipitation values (>0,05mm) of four of the datasets.

To test if the distributions of the datasets are similar, a non-parametric test has to be performed. Therefore the Mann-Whitney U test is performed to compare all the datasets the original daily accumulated precipitation values from the automatic & manual rain gauge and the radar dataset. The null hypothesis for the Mann-Whitney U test is that the data in the different datasets are samples from continuous distributions with equal medians, against the alternative that they are not. The tests return a *p*-value which indicates the probability of the result assuming that the null hypothesis is true. The second value 'h' is if the null hypothesis conditions are met at the 5% significance level where 0 is true and 1 is false, indicated in green and red respectively in table 4 (The MathWorks Inc., 2019).

Table 4 – Results for the Mann-Whitney U test where all datasets are compared. Given are the *p-value* for all the test and whether the null hypothesis is true (0) of false (1).

***p* / h**	Berkhout Weather Station (24H)	Berkhout Radar (24H)	Medemblik Rain Station (08H)	Wieringer-meer Radar (24H)	Wieringer-meer Radar (08H)
Berkhout Weather Station (24H)		**0,02 / 1**	**0,01 / 1**	**0,56 / 0**	**0,43 / 0**
Berkhout Radar (24H)			**0,00 / 1**	**0,09 / 0**	**0,13 / 0**
Medemblik Rain Station (08H)				**0,00 / 1**	**0,00 / 1**
Wieringermeer Radar (24H)	Mann-Whitney U Test				**0,86 / 0**
Wieringermeer Radar (08H)					

Not all tests return with a positive confirmation of the null-hypothesis. As the medians from the datasets tend to differ and the distributions are not all the same. While the radardataset is bias corrected for the weather stations the radar pixel above the Berkhout weather station do not seem to compare in any test. On the other hand the radardata from Wieringermeer does have a comparable continuous distribution with equal medians to the Berkhout Weather Station. The dataset from the manual rain gauge in Medemblik is not comparable to all radar datasets. Probably due to the disability to measure low precipitation values since the measurements are done manually. This could also be a explanation for the relatively high median compared to the other datasets.

The model for the mass balance of the landfill at Wieringermeer uses the data from the Berkhout Weather Station as input. The question now is with what precipitation data the input is best replaced. The Medemblik Rain Station is difficult data to implement in the model. It has no comparable distribution to any other dataset and it is measured from 0800h to 0800h. These measurement times do not match the ones of the evaporation dataset, which is measured from 2400h to 2400h. The radar 24H dataset from the radar pixel above the Wieringermeer landfill therefore fits better within the timeslot. Also the Mann-Whitney U test showed that the distribution is similar to the Berkhout Weather station radar dataset. However the daily differences are large due to the large geographical distance between the datasets so therefore they are significantly different in a good way.

4.3 Model implementation

Given the complex nature of the landfill systems the 'classic' modelling of giving some input and receiving some output would become analytically intractable. Also the fact that leachate flux, one of the output factors, is measured on-site results in the possibility to optimize the model for input and output datasets. This is done with Markov chain Monte Carlo simulation using the DREAM software package for Matlab®. This model requires three kinds of input data; the forcing data (precipitation & evaporation), the initial states (prognostic variables e.g. $C_f, S_{cl_{max}}$ $etc.$) and system invariants (parameters). The model outputs diagnostic variables where the prognostic variables are optimized and calibrated against the observations. Also a quality of the fit is calculated where to quantify how accurate the model is. (Vrugt, 2016).

The model analyses the landfill from the year 2000 until 2019. The first model uses the precipitation from the automatic rain gauge at Berkhout weather station for the entire period. The second model uses the precipitation data from Berkhout till 2007 and the radar data from Wieringermeer from 2008 onward. This is due to the fact that there is no 1x1km grid radar data available prior to 2007. This is not a problem for the model because before period of 2012 there is no information of the outflow before July 2012. The period before July 2012 is used as a burn-in period where the water balance gets going and becomes less artificial than some arbitrary starting conditions.

Of course there will be differences between the model and the measurements since the measurements are more punctual than the mode. From figure 7 it can be seen that the daily difference from model 1can be large with values over 100 m^3 per day. Keep in mind that the average flow per year is around 9000m^3. The measurement and model difference for model 2 is lower as a whole with no differences higher than 90m^3. Some statistics from these differences were, just as the differences in precipitation in table 3, put next to each other in table 5.

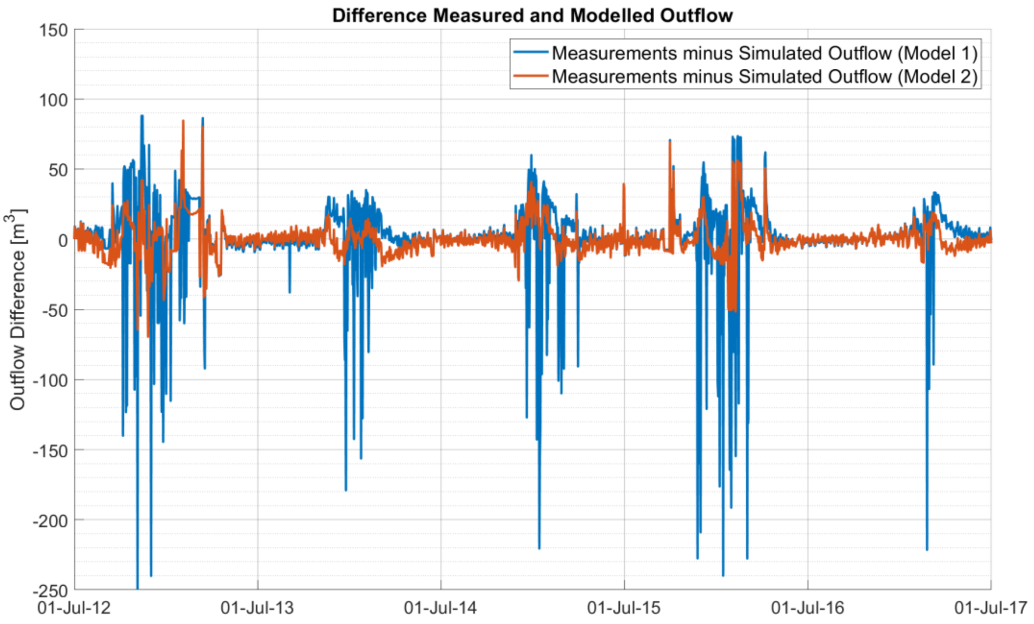

Figure 7 – Difference in the measured and modelled outflow for both models calculated by substracting the modelled outflow from the measured outflow.

Table 5 - Basic statistics for the daily differences in measured and modelled outflow between the two models

Difference	Mean (m^3)	Median (m^3)	Standard Deviation (m^3)	Variance (m^6)
Difference measurements and model 1(Berkhout)	0,33	0,90	30,11	906,91
Difference measurements and model 2 (Wieringermeer)	0,02	-0,81	12,21	148,96

Table 5 shows that the spread in the distribution of the difference in outflow is much larger for the first model with the precipitation data from berkhout than the second model with the data from Wieringermeer. This confirms what was seen as a result of table 3 where the daily difference in the precipitation had a large spread as well. Here on a daily basis the model from with the precipitation from Wieringermeer underestimates the measured outflow with 0,02 m^3 which is equal to 20 liters.

The model itself calculates a likelihood function that summarizes the distance between the model simulations and the corresponding observations. Therefore this function can be used to determine the error. The exact equation and derivation of this function can be found in Vrugt, 2016. In table 6 the outcome of this likelihood can be found as a number where the smaller the number the better the fit and thus the more accurate the model is as a whole.

Table 6 – Log-likelihood value for both models

Model	*Log-likelihood*
Model 1 (Berkhout precipitation)	-8.27e+06
Model 2 (Wieringermeer precipitation)	-7.66e+06

The model calculates a lot of parameters and other figures of the different flow fluxes which could be of interest. Extra tables and figures are added in appendix A.

5. CONCLUSIONS

The long-term emissions of municipal solid waste landfills pose a threat to the health and environment. To understand the processes in these landfills that produce the emissions landfills are investigated with models and experiments. However to model the water balance in the landfills the source for the inflow due to precipitation came from data from automatic rain gauges tens of kilometres away from the landfills. Therefore the radar precipitation data from the KNMI was researched for this thesis to verify if this dataset is a viable option for modelling MSW landfills. Two research questions were formulated: **1. What are the differences in measured precipitation accumulations between radar and the nearest KNMI station?** and **2. How does the choice of the precipitation input (radar versus nearest KNMI station) affect the mass balance model of the landfill?**

Three types of datasets could be used as input for the precipitation for the modelling of landfills. The first is the, up to now used, automatic rain gauge dataset with information every ten minutes. These datasets are placed at over thirty locations across the Netherlands along with a lot of other information. Also over 300 manual rain gauges are located in the Netherlands which measure the daily accumulated precipitation. The second is the radar dataset which has a spatial resolution of 1x1km and measures the precipitation intensity every five minutes. These datasets each have their own advantages and disadvantages according to the collected data, measurement type and geographical location. The third one that could be used is the manual rain gauge network which has as an advantage that the distance to the landfills is generally closer than the automatic rain gauges due to the over three hundred present manual rain gauges. However the precipitation is only measured every 24 hours at 0800h. The automatic rain gauge gives a frequent and accurate estimate for the precipitation. Also these weather station give a lot of other meteorological information that is essential for the model such as the potential evaporation. Both rain gauge networks have the disadvantage that they can’t measure low amounts of precipitation accurately (<0,05mm for the automatic rain gauges) and the networks are limited by location. The radar has less difficulty with measuring low amounts of precipitation and is has a higher spatial resolution of 1x1km. However the radar has more difficulty with light precipitation and snow and is not as accurate as the rain gauges in converting the measurement in an accurate precipitation estimate.

These differences in measurement type affect the choice of input precipitation. When compared it is visible that due to the distance in geographical location more large daily differences (>10mm) in daily accumulated precipitation start to occur. This is due to a difference in the geographical location and the travel paths of rainclouds. However the Mann-Whitney U test proved that when comparing the datasets, for some of them the distributions and their medians are similar. This concluded that for the choice of input precipitation the 24H Wieringermeer radar dataset was most promising as alternative to the Berkhout automatic rain gauge dataset. The daily difference between these two datasets was significant, however the distributions of the datasets were still similar. When both datasets were used as an input choice for the modelling of the landfill, the model still used the Berkhout weather station evaporation data for the daily potential evapotranspiration.

The model outcome with the radar dataset had a better fit than the model with the dataset from Berkhout. Also on a daily basis the difference in the measured and modelled outflow was lower. So to conclude the hypothesis stated is true. The model does increase in accuracy for both the long term and the short term the model for the Wieringermeer landfill when using the KNMI radar dataset as input. The biggest gain is on the daily scale where the differences in daily outflow are much lower. The trend however is still similar to the old model but the quality of the fit is better which makes the KNMI radar data more viable for modelling on the long term. Whether the KNMI radar dataset provides the other landfills than the one in Wieringermeer with a more accurate outcome is not yet known. However the results form this case study are promising that the quality of the models for other landfills might increase as well while these landfills also have a large geographical distance to the nearest weather station.

The error of the model is still not zero but models will always have some error. After this research the model can still be optimized further to diminish the error. This leaves the following three questions for further research:

- The model now still uses the evaporation dataset from Berkhout which is 12 kilometres away. Can this dataset be replaced by another more accurate dataset?
- The precipitation accumulation is also measured on site at the landfill. How accurate are radar rainfall estimates with respect to on-site precipitation measurements?
- There are at the moment two more landfills that are investigated for sustainable after care. Does the quality of the models for these landfills increase as well after changing the input for the precipitation to the radar dataset? The landfill at Kragge is nine kilometres apart from the nearest weather station, the landfill at Braambergen is over 22 kilometres apart.

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A. FIGURES AND TABLES

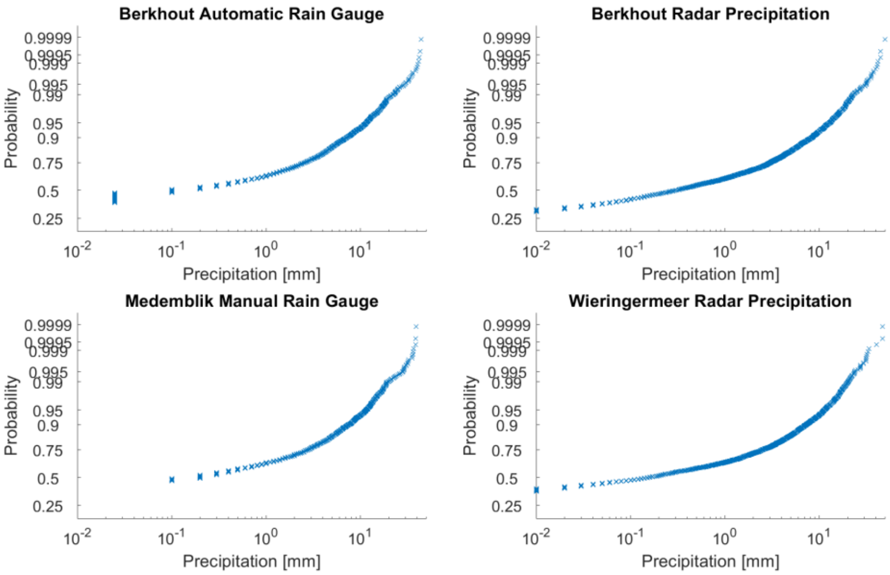

Figure 8 – Probability plot for the precipitation accumulation of the different datasets

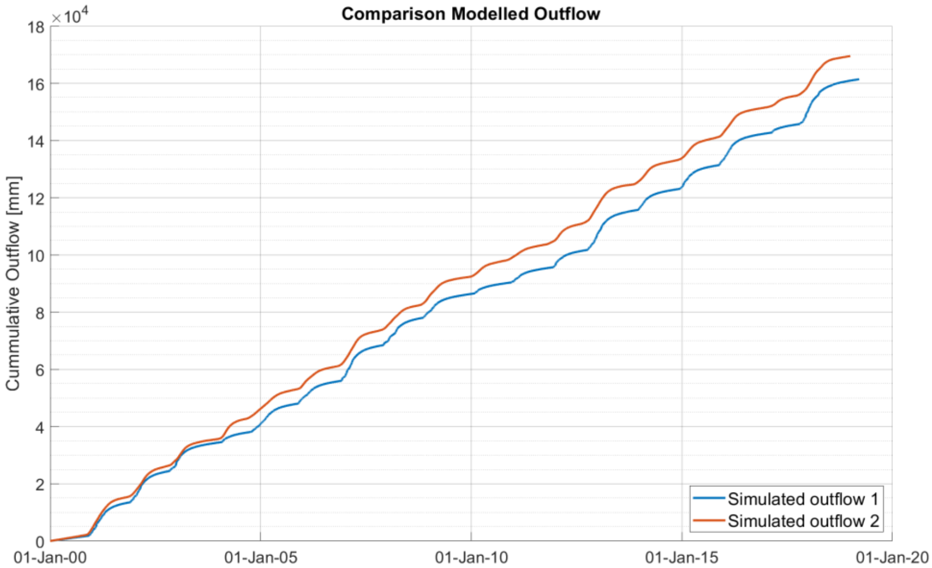

Figure 9 – Cumulative outflow for both models

Table 7 – Optimized parameters for both models without units

Model 1	dR	cF	thR	thS	cLKsat	cLmval
	5,4E-01	1,0E+00	1,0E-03	5,8E-01	-3,8E+00	4,4E-06
	Tau1	Sig1	Tau2	Sig2	Ffrac	LFarea
	3,4E-01	4,4E-02	3,8E+00	8,9E-01	4,3E-01	4,6E+00
Model 2	dR	cF	thR	thS	cLKsat	cLmval
	3,1E-01	8,2E-01	1,0E-03	5,0E-01	-3,5E+00	1,1E-01
	Tau1	Sig1	Tau2	Sig2	Ffrac	LFarea
	1,3E-02	3,9E+00	3,9E+00	7,0E-01	1,0E-02	4,4E+00

Table 8 – Correlation coefficient matrix for all the parameters for both models. In red are the correlation coefficients for model 1, in blue all the correlation coefficients for model 2. The vale for the correlation coefficients can vary between -1 and 1. 1 means that the parameters behave in the same way. -1 means that the paramaters behave in the opposite way. 0 means that the parameters have no influence on each other whatsoever.

Corr coef	dR	cF	thR	thS	cL Ksat	cL mval	Tau1	Sig1	Tau2	Sig2	Ffrac	LF area
dR	1	-0,23	0,06	-0,10	0,23	-0,11	0,26	0,14	-0,29	0,27	-0,35	-0,24
cF	0,58	1	0,40	0,29	-0,25	0,51	-0,13	0,14	0,25	-0,35	-0,01	0,28
thR	0,36	0,58	1	0,38	-0,04	0,63	-0,04	0,33	0,15	-0,38	0,00	0,05
thS	0,27	0,55	0,31	1	-0,60	0,26	-0,49	0,29	0,60	-0,12	0,46	0,81
cL Ksat	-0,45	-0,88	-0,56	-0,43	1	-0,03	0,41	-0,06	-0,58	0,11	-0,61	-0,83
cL mval	0,53	0,89	0,57	0,53	-0,85	1	-0,05	0,24	0,19	-0,45	0,01	0,03
Tau1	0,31	0,35	0,14	-0,24	-0,15	0,15	1	0,13	-0,96	0,08	-0,38	-0,52
Sig1	-0,46	-0,83	-0,70	-0,46	0,76	-0,78	-0,22	1	-0,06	-0,07	-0,04	0,11
Tau2	0,19	0,48	0,50	0,41	-0,60	0,58	-0,46	-0,61	1	-0,20	0,50	0,62
Sig2	0,18	0,64	0,26	0,25	-0,74	0,66	0,00	-0,44	0,45	1	-0,31	0,06
Ffrac	0,61	0,32	0,22	-0,13	-0,08	0,14	0,75	-0,25	-0,27	-0,30	1	0,48
LF area	0,67	0,84	0,42	0,19	-0,69	0,69	0,66	-0,61	0,12	0,52	0,63	1

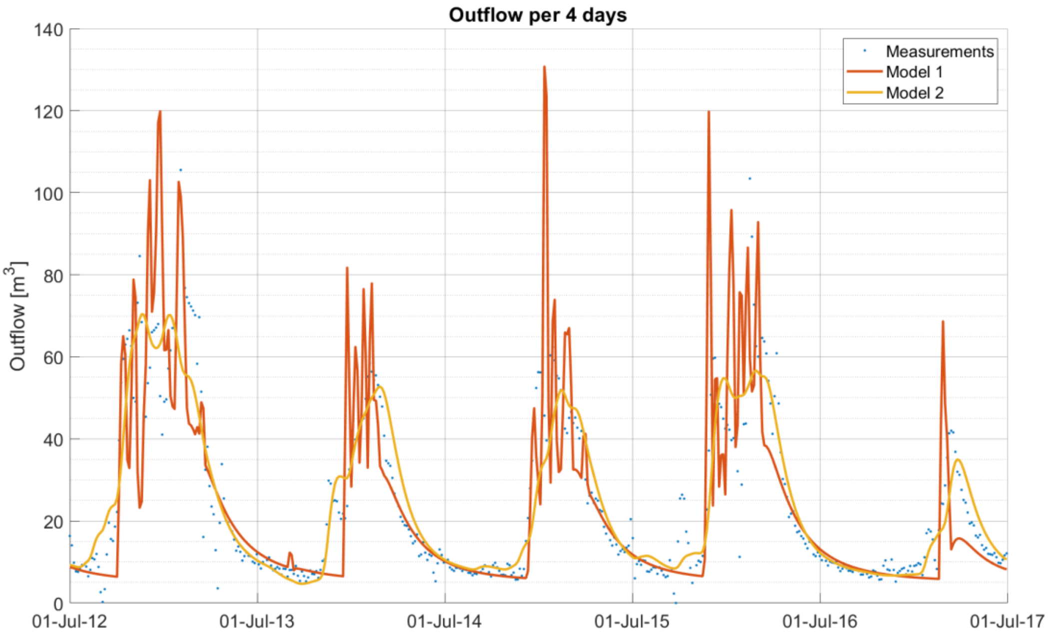

Figure 10 – Measurements of outflow compared to both model predictions for the outflow.