# On the rise of the groundwater table due to infiltration of surface water

A case study on wooden pile foundations in the neighbourhood Oud-Hillegersberg, Rotterdam


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May 7, 2019

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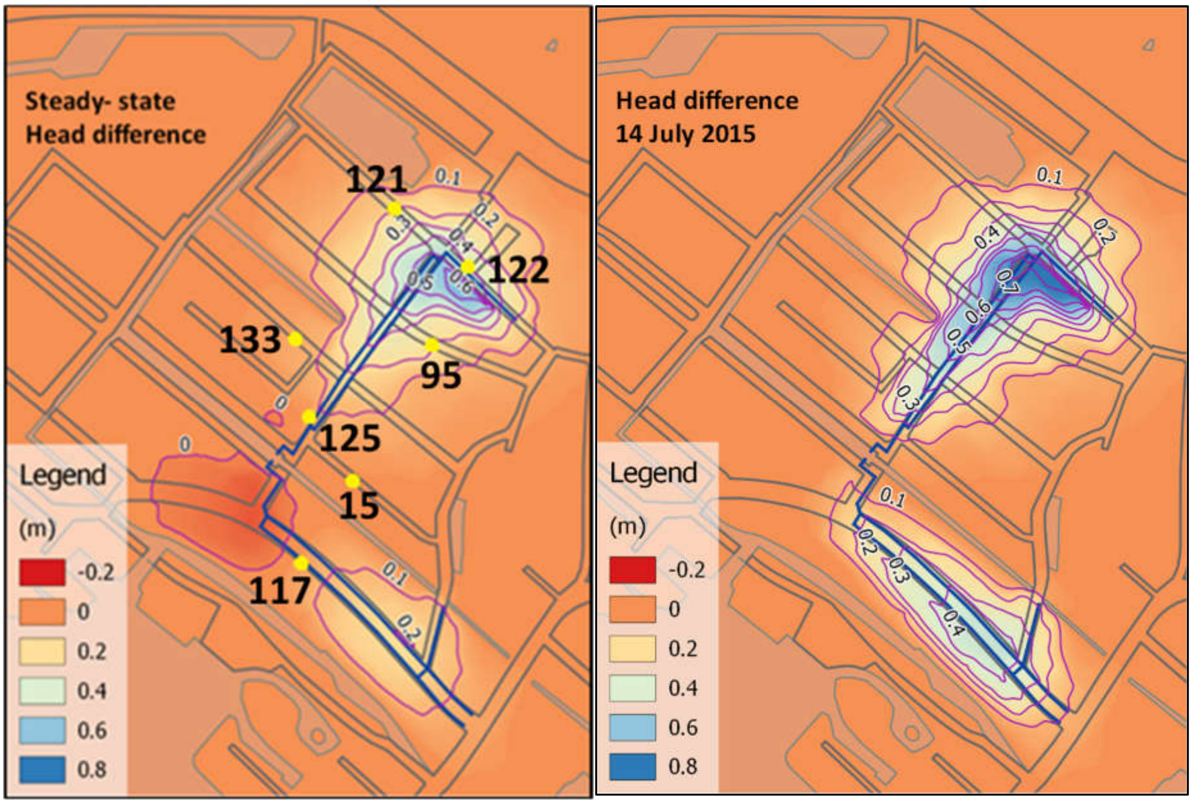
## Samenvatting

De Rotterdamse wijk Oud-Hillegersberg is een woonwijk gelegen in het noordelijk deel van Rotterdam. Het merendeel van de bebouwing is gebouwd in de jaren ’30 met een deels houten fundering (Commissie Grondwater Oud-Hillegersberg, 2014). Door grondwaterdaling zijn funderingspalen droog te komen staan met paalrot als gevolg. In 2010 en 2011 zijn infiltratieleidingen aangelegd in de Adriaen van der Doeslaan en de Berglustlaan om de grondwaterstand te verhogen (Commissie Grondwater Oud-Hillegersberg, 2014; Gemeente Rotterdam, 2013; Royal HaskoningDHV, 2016). De zomer van 2015 was droger dan de voorgaande zomers en gaf de gelegenheid om de effectiviteit van de infiltratieleidingen te evalueren voor droge periodes. De volgende 3 onderzoeksvragen leidden het onderzoek:

1. Hebben de infiltratieleidingen een merkbaar effect op de grondwaterstand in de zomer van 2015?
2. In hoeverre stijgt de grondwaterstand in de zijstraten van de Van der Doeslaan en de Berglustlaan gemiddeld genomen en voor de droge zomer van 2015?
3. Welk effect heeft klimaatverandering op de grondwaterstand?

Voor het beantwoorden van de vragen zijn vier freatisch grondwatermodellen opgezet: met infiltratieleiding en zonder; stationair en niet-stationair. Het verschil tussen de modellen met infiltratieleidingen en zonder infiltratieleidingen toont de effectiviteit. Het effect van klimaatverandering is benaderd door gebruik te maken van de Stresstest Light (Deltaprogramma Ruimtelijke Adaptatie, 2018). Hierbij is gekeken naar een huidige extreme (droogte van 2018 (KNMI, 2018)).




**Figuur 1 Verschil voor de stationaire situatie en 14 juli 2015 in de niet-stationaire situatie.**

Uit de resultaten blijkt dat de grondwaterstandstijging als gevolg van de infiltratieleiding het sterkst is langs de infiltratieleidingen in het noordelijk deel van de Van der Doeslaan en het oostelijk deel van de Berglustlaan. De grondwaterdynamiek wordt op veel punten vlakker (zie ook Figuur 2).


**Figuur 2 Tijdreeks voor locatie 130572-117. Gebaseerd op de locatie van de peilbuis aldaar.**

De resultaten voor de droogte van 2018 laten een sterke toename van het potentiële neerslagtekort zien. Dit tekort is niet in dezelfde mate terug te zien in de gemeten grondwaterreeksen voor grote delen van Oud-Hillegersberg. Alleen in het gebied gelegen op het rivierduin zijn grote verlagingen te zien. Een daling van de grondwaterstand in het Pleistocene pakket is hierin de sturende factor.

Door het vergelijken van de situatie met en zonder infiltratieleiding wordt inzichtelijk wat de verandering van de dynamiek is, zelfs als de waarden op zichzelf niet overeenkomen met metingen. Indien het model uitgebreid wordt, wordt geadviseerd om de onverzadigde zone mee te nemen in het model en om de doorlatendheid van bodem en duin verder te onderzoeken. In beide gevallen is meer velddata nodig.

Geconcludeerd kan worden dat de infiltratieleidingen een goede maatregel zijn om de grondwaterstand te stabiliseren. Het gebied op het rivierduin vraagt nog wel aandacht om ook hier de grondwaterstand te verhogen en te stabiliseren.

# 1 Introduction

This chapter introduces the topic of the study: groundwater flow in Oud-Hillegersberg, Rotterdam. The first paragraph will show the background of the study and the second paragraph follows up with the problem description. The next paragraph treats the aims and objectives of the study. The chapter ends with the reading guide for the thesis.

## 1.1 Background

The Dutch city of Rotterdam features several neighbourhoods with problems concerning groundwater. One of these neighbourhoods with groundwater problems is the neighbourhood of Oud-Hillegersberg, lying in the northern part of the city of Rotterdam. Most of the buildings in this neighbourhood were built in the Interbellum, between 1920 and 1940 (Commissie Grondwater Oud-Hillegersberg, 2014). The main groundwater related problem is rot of wooden pile foundations, this being the result of fall of the groundwater table (Commissie Grondwater Oud-Hillegersberg, 2014; Royal HaskoningDHV, 2016).

Between October 2010 and October 2011 the Rotterdam Municipality replaced the old sewerage system in the Adriaen van der Doeslaan and some of its side streets and the Berglustlaan and Bergluststraat (Gemeente Rotterdam, 2013). At the same time the infiltration pipe system was installed in the Adriaen van der Doeslaan, Oude Raadhuislaan, the Berglustlaan and the Bergluststraat. The Rotterdam Municipality published the evaluation report on the infiltration pipe system in June 2013. The presented changes to the groundwater table are the combined effects of the installation of the infiltration pipe system and the replacement of the leaky sewerage system.

They concluded that there is an evident increase in the mean groundwater table and the (mean) lowest measured values in the streets where the infiltration pipe system is present (Gemeente Rotterdam, 2013). Also a significant increase in the groundwater table was measured in the side streets of Adriaen van der Doeslaan, even in the streets where the sewerage system was not replaced. However it appears that no significant increase in the groundwater table was measured near the fluvial dune area in Adriaen van der Doeslaan and Oude Raadhuislaan.

In the time between the installation of the infiltration pipe system and the evaluation, there had been dry periods, but no dry summer. So it is not known yet what the effects of a long dry summer are on the groundwater tables, especially in the area near the fluvial dune.

In an article published in the periodical Riolering and written by Rob Heukels (Municipality of Hengelo) and Bertrick van den Dikkenberg (Wareco engineers) it is stated that the replacement of leaky sewerage pipes may increase the groundwater table in side streets up to 40 meters away from the replaced pipe (Heukels & Dikkenberg, 2013). It may be expected that something similar happens when an infiltration pipe system is introduced.

## 1.2 Problem description

The fall of the groundwater table has three causes (Commissie Grondwater Oud-Hillegersberg, 2014):

- Lowering of the surface water table of the polder Berg en Broek between 1944 and 1956. In this period the surface water table dropped by some 22 cm, due to a change of the surface water table regime in 1944, resulting in a fall of 11 cm and another change in the surface water table regime in 1955, dropping the level another 11 cm. These changes had a regional impact.

- Groundwater extraction by the industry. Industries extracted deep groundwater in large quantities between 1945 and 1980. Oud-Hillegersberg is partially situated on a fluvial dune, featuring a sandy subsoil and barely a water separating layer between the phreatic aquifer and the deeper aquifer. The groundwater extraction by the industry thus also had an effect on the groundwater table in the phreatic aquifer in some parts of Oud-Hillegersberg.
- Groundwater abstraction by the leaking sewerage system. The city of Rotterdam started installing a new sewerage system in Oud-Hillegersberg in the 1960’s. Contrary to the previously installed sewerage system, which discharged the sewage water unto the surface water by gravity, the new sewerage system was installed below the groundwater table. Eventually cracks appeared in the sewerage system due to settling of the soil, resulting in drainage of the groundwater by the sewerage system. The result was a lowering of the groundwater table on a local scale, with an increasing gradient near the leaky pipes.

A part of the sewerage system in Oud-Hillegersberg was replaced in 2011 (Commissie Grondwater Oud-Hillegersberg, 2014; Gemeente Rotterdam, 2013; Royal HaskoningDHV, 2016). At the same time several infiltration drains were installed. Figure 1 shows the locations of the infiltration drains. In Adriaen van der Doeslaan and in the central part and eastern part of Oude Raadhuislaan an infiltration drain system was installed. It is connected to Hoyledesingel in the south (see the left picture in Figure 1). The other infiltration drain system is installed in Berglustlaan and Bergluststraat. The infiltration pipe system is connected to Hoyledesingel to the northwest (see the right picture in Figure 1).

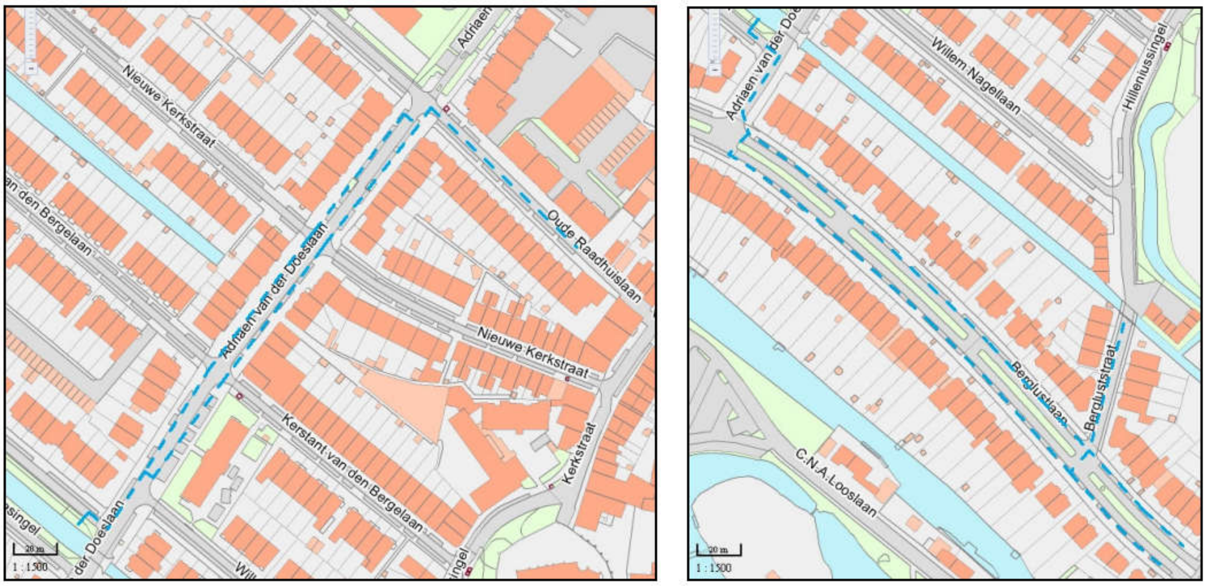



**Figure 1 Location of the installed infiltration pipes.** (Gemeente Rotterdam, 2013)

The Municipality of Rotterdam did an evaluation of the effect of the infiltration drains in July 2013. It was concluded that the system works, but an additional evaluation of the system is needed to see how the system works during dry summers (Gemeente Rotterdam, 2013).

Additionally the cgOH (groundwater committee of the residents association inHillegersberg) want to know more about the effects of the infiltration drains on the groundwater table in the side streets. They expect that the infiltration drains also raise the groundwater table in the side streets.

## 1.3 Research aim

Besides the 2013 evaluation report of the Rotterdam Municipality, the effects of the infiltration drains have not been studied extensively. The summer of 2015 proved to be dryer than other summers since the installation of the infiltration drains in autumn 2011. A study on the effects of the dry summer offers the opportunity to evaluate the effectiveness of the infiltration drains. The cgOH requested the study of the effectiveness of the infiltration drains during the 2015 summer, with special attention to the extent at which the infiltration drains still raise the groundwater in the side streets (the streets perpendicular to the 'main' streets with infiltration drains). This study of this dry period is also useful in the face of climate change, when periods of drought are going to reoccur more often.
The study is structured in three parts using these three research questions:

1. Do the infiltration drains have a noticeable effect on the Oud-Hillegersberg groundwater table during the summer of 2015?
2. To what extent is the groundwater table in the side streets raised by the infiltration drains in the main streets during the dry summer of 2015 and in the average scenario?
3. How will the Oud-Hillegersberg groundwater system be affected by climate change?

The aims of this thesis can be summed up as following: Evaluating the effectiveness of the infiltration drains in terms of the magnitude of groundwater table rise they induce and the extent at which their effect is measurable; and determining the effects of climate change on this groundwater system. The results of this study are to be used by the residents association inHillegersberg and the Rotterdam Municipality to discuss the Oud-Hillegersberg groundwater system and to evaluate the overall effectiveness of the infiltration drains. This study is part of a bigger puzzle to fix groundwater problems pertaining to Rotterdam and is also valuable as a case study for engineers, civilians and civil servants elsewhere, facing similar issues.

## 1.4 Reading guide

The first Chapter introduced the topic of the study: the Oud-Hillegersberg groundwater system, its problems and the effectiveness of the infiltration drain. The research questions are threefold and concern the dry summer of 2015, the reach of the infiltration drains and climate change. The outcome of the study will aid the residents association inHillegersberg and the Rotterdam Municipality in deciding what actions could be taken. Chapter 2 goes into more detail on the surroundings of Oud-Hillegersberg in terms of soil composition, ground water, surface water, precipitation and evaporation. The third Chapter concerns the methods and the theory applied to the study. The chapter will go into depth on the conceptual model and the related numerical models that are used to answer the research questions. The fourth Chapter describes the calibration and validation of the numerical models. Chapter 5 contains the results for the various topics studied, centring the results around the three research questions. In the sixth Chapter a synthesis of the discussions is described, followed up by a synthesis of the conclusions and the summary in the seventh Chapter.

# 2 Hydrological setting

This chapter aims at giving a concise overview of the hydrological background of this study. Phreatic groundwater does not exist in a vacuum, but is part of a larger system in which soil, deep groundwater, surface water, precipitation and evapotranspiration all have their role. All these parts can be translated to model parameters, which will be discussed in chapter 3.

## 2.1 Precipitation and evapotranspiration

Precipitation and evapotranspiration values for Rotterdam Airport are shown in figure 2, and are representative for Oud-Hillegersberg. The figure shows the series for recent years, 2010-2015. In this period the mean annual precipitation is around 900mm and the mean annual potential evapotranspiration is around 600mm. The precipitation shows large variabilities throughout the years, however the evapotranspiration has a steady recurrence throughout the years.

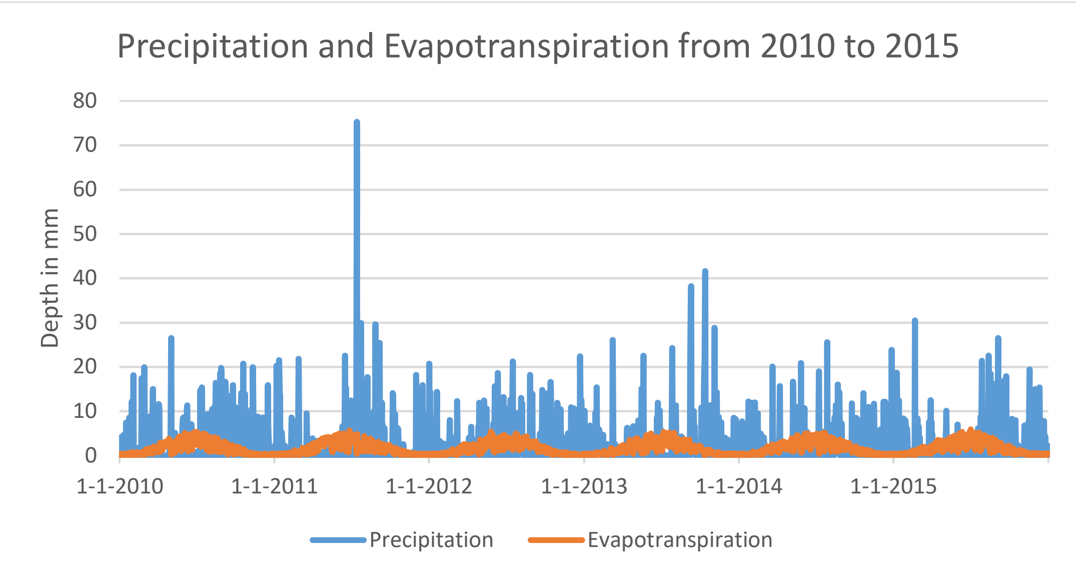



**Figure 2 Precipitation and potential evapotranspiration from 2010-2015. Source: Royal Netherlands Meteorological Institute (KNMI), time series from Rotterdam.**

Weather station Bergschenhoek also lies in the vicinity of Oud-Hillegersberg. Precipitation measurements are taken manually and evapotranspiration is not measured at all. The measured precipitation data for Bergschenhoek are actually for the day before since the weather station is measured manually each day at 8:00 in the morning, according to an employee of the Royal Dutch Meteorological Institute (KNMI). The datasets for Rotterdam Airport are used more commonly and are also the most practical to use in this study since both precipitation and evapotranspiration are measured.

**Data from weather station Rotterdam Airport is used in this study. The mean annual precipitation and evapotranspiration are 900mm and 600mm respectively between January 2010 and December 2015.**

## 2.2 Surface water

Oud-Hillegersberg is situated in the north-eastern part of the polder Berg en Broek. The other parts of Berg en Broek are the lakes Bergse Voorplas to the east, Bergse Achterplas to the southwest and Hillegersberg-Zuid to the south (Royal HaskoningDHV, 2016).

Oud-Hillegersberg features multiple canals which are all connected to each other and both lakes. Figure 3 shows a map of Oud-Hillegersberg, with a complete overview of the surface water.


Figure 3 Surface water in Oud-Hillegersberg. Source: http://www.gis.rotterdam.nl/gisweb2/default.aspx

The surface water stage in Berg en Broek is regulated and has a fixed level of -2.85m NAP as is decided in the surface water stage decree for Overschie and Schiebroek (HHSK, 2008). A small exception in Oud-Hillegersberg is the swimming pool Zwarte Plasje that has a variable surface water stage dependent on the seasons (HHSK, 2012). The Zwarte Plasje is mainly fed by rainwater. The culvert that connects the Zwarte Plasje to the Van den Hoonaardsingel can be closed off. Whenever the surface water stage reaches below -2.90m NAP, the culvert is opened and water flows into the Zwarte Plasje, until the surface water stage is at its initial state. The surface water stages in the surrounding polders of Oud-Hillegersberg are much lower, due to being on a lower elevation: The polder to the west has a fixed surface water gauge of -5.80m NAP, the polder to the north -6.20m NAP (HHSK, 2008).

**Oud-Hillegersberg features lots of surface water by means of canals, an outdoor swimming pool and two nearby lakes. The surface water stage is maintained at a constant level throughout the year at a stage of -2.85m NAP.**

## 2.3 Subsoil

The study entails a study on the phreatic groundwater. The groundwater stage in the Pleistocene aquifer has an effect on the phreatic groundwater and so the subsoil from the Anthropocene on top to the Holocene and Pleistocene below are relevant for the study. The layout of the lithography in Oud-Hillegersberg can be observed in figure 4. The image is based on cone penetration tests and the codes on top refer to addresses where the cone penetration tests took place. The cross section is taken roughly through the Adriaen van der Doeslaan, from southwest to northeast.

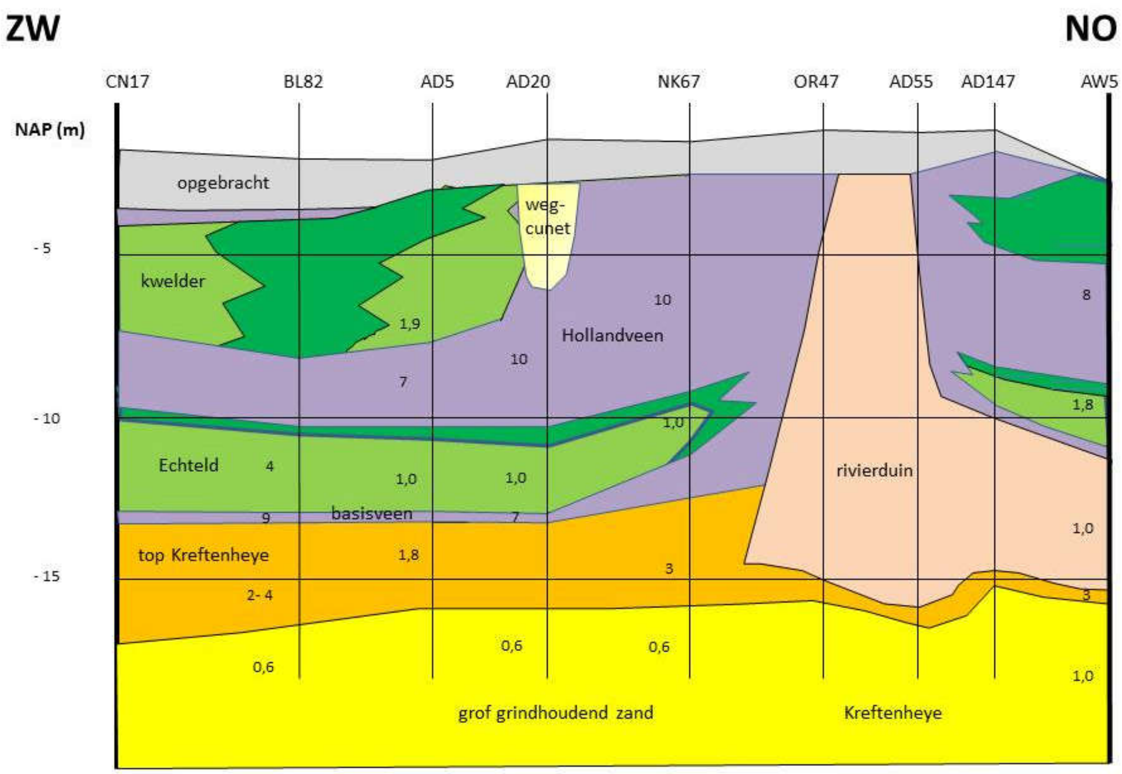



Figure 4 Cross section of the subsurface in Oud-Hillegersberg, in particular the street Adriaen van der Doeslaan. Source: cgOH

The first confined aquifer is situated in the Formation of Kreftenheye. The formation is mostly composed of sandy soil, with a grain sizes varying between moderate and coarse (210 -2000 µm) (Busschers & Weerts, 2003b). The top of this layer lies around -17.5 m NAP, with a slight variation throughout the neighbourhood, as can be observed from local cone penetration tests.

The Layer of Wijchen is situated on top of the Formation of Kreftenheye. According to DINOloket the Layer of Wijchen is composed of clay, ranging from silty clay to sandy clay (Busschers & Weerts, 2003b). This layer is about 1 to 2 meter in thickness, ranging from -15/-16 meter NAP to -16/-17 meter NAP (FUGRO, 2001). This layer effectively separates the fluvial dune on top of it with the confined aquifer.

The fluvial dune situated on top of the Layer of Wijchen is a peculiar part of the Oud-Hillegersberg subsoil. The fluvial dune reaches its highest elevation near the church Hillegondakerk in the old centre of Oud-Hillegersberg. Arcadis and Witteveen+Bos (2016) show that the fluvial dune starts already some 5.5 km to the east of Oud-Hillegersberg. According to the cgOH parts of the dune in Oud-Hillegersberg have been excavated in the past to the surrounding surface level. These parts are located on the intersection of the Adriaen van der Doeslaan and the Oude Raadhuislaan and the surrounding area nearby. The excavated parts of the dune are covered by a slim layer of mainly anthropogenic deposits. The dune arose from fluvial sand deposits. It is assumed that the dune is in its entirety made up of sand with a grain size ranging from fine to moderate. Arcadis and Witteveen+Bos (2016) assume a horizontal hydraulic conductivity of 5m/d and a vertical hydraulic conductivity of 0.5m/d, based on experience. These are typical values for fine sand.

The Holocene layers are varying layers composed of peaty and clayey soils. Some clayey layers are absent in the near vicinity of the outcropping fluvial dune, featuring an even more peaty lithography. In general the Layer of Wijchen is covered by a thin layer of peat with a varying thickness of 1 meter or less. The Formation of Echteld is situated on top of this peaty layer, ranging from about –9m NAP to –13m NAP. This layer is composed of fluvial sediments, featuring clayey sand (Busschers & Weerts, 2003a). The Formation of Echteld is covered by a 3m thick peat layer, from -7m NAP, at some places even -2m NAP, to -10m NAP to -11m NAP. This peat layer (Hollandveen) is thicker at locations near the fluvial dune where the fluvial sediments are absent, and might reach up to the anthropogenic layer. From -3m NAP to -4m NAP down to -8m NAP the soil is composed of *kwelder*[1] depositions, featuring clayey material. The top of this layer either coincides with the bottom of the anthropogenic layer at several places, in other places a thin peat layer of 0.5-1m separates the *kwelder* depositions from the anthropogenic layer.

The very top of the soil in Oud-Hillegersberg is composed of various anthropogenic deposits. The Anthropocene layer roughly starts at -3m NAP and then up to ground surface level, which is mostly around -1.5m NAP. The soil in this layer is highly heterogenous in composition; the soil may contain sand, clay, peat or other organic material and debris according to bores from Oude Raadhuislaan. The type of deposits is dependent on the location in the neighbourhood as well as the height of the surface ground level. In general three types of locations can be distinguished: streets, buildings, backyards.

- Streets have mostly been raised with sandy materials, which have a good permeability. The municipality of Rotterdam has executed several hand drillings in several streets in advance of sewerage replacement works. The bores show the sandy layout of the soil in the streets.
- The soil composition under buildings is not clear. It is expected to be a mixture of sand used to raise and level the area and peaty and clayey soils already deposited before. Houses in Oud-Hillegersberg feature semi-basements or cellars and crawl spaces. Inhabitants have encountered hollow areas below the floor of their house, where the ground has lowered due to subsidence.
- Backyards are usually less raised than the streets and houses, and slope down from the elevation at which the house is situated to the elevation at the back end of the backyard. This is especially visible in backyards with the back end near surface water. In several cases the surface level of the backyards nears the surface water level. Soil types in the backyards may differ and it is not exactly known what the composition of the soil is, since there are few

[1] A kwelder is similar to a salting or a mudflat, but is not necessarily located near the sea.

bores from the backyards. The bores from the aforementioned location in Oude Raadhuislaan show a mixture of peaty and clayey soils, as well as sand, coal ashes and debris. It is expected that the ground next to the houses has been raised more than other parts of the backyards. Due to the additional load on this part of the backyard it has experienced more subsidence than other parts of the backyards. In general it is expected that the peaty and clayey soils are disturbed, thus allowing a better hydraulic conductivity than confined peaty and clayey soils.

**The important parts of the subsoil in this study are the Anthropocene layer, the Holocene layer and the Pleistocene layer. On top of the Pleistocene layer a fluvial dune is located, which crops out near the centre of Oud-Hillegersberg. This fluvial dune features a high hydraulic conductivity, in contrast to the surrounding Holocene layer which features poor permeability. The permeability of the Anthropocene layer differs throughout the layer, with soils under roads featuring a high permeability, soils under building featuring moderate permeability and soils in gardens and yards featuring rather poor permeability.**

## 2.4 Groundwater in the Pleistocene

The first confined aquifer in the area is located in the Formation of Kreftenheye. The aquifer has a thickness of some 16 meters, from about -16m NAP to -32m NAP (FUGRO, 2001). The clayey Layer of Wijchen situated on top of the Formation of Kreftenheye prevents direct contact between the sandy fluvial dune and the sandy aquifer, and thus retards the infiltration of dune water to the aquifer.

The confined groundwater flows from the higher parts from the centre of Rotterdam to the low-lying north-eastern polders of Rotterdam (Royal HaskoningDHV, 2016). The surrounding polders northeast of Oud-Hillegersberg feature surface level heights down to -6m NAP, which explains the groundwater flow in the north-eastern direction. The hydraulic head in the aquifer is around -5m NAP in Oud-Hillegersberg (FUGRO, 2001; Royal HaskoningDHV, 2016).

Abstractions from industries like DSM Gist at Delft reduce the hydraulic head in the aquifer (ARCADIS Witteveen+Bos, 2016; Royal HaskoningDHV, 2016). DSM is allowed to abstract 13.5 million $m^3$/year, but has been abstracting less groundwater over the years, keeping up to their winter abstraction of 10.5 million $m^3$/year (ARCADIS Witteveen+Bos, 2016). The hydraulic head in Oud-Hillegersberg would increase by some 0.05m if the groundwater abstraction of DSM were to be stopped (ARCADIS Witteveen+Bos, 2016).

**The groundwater in the Pleistocene aquifer of the Formation of Kreftenheye is situated at a stage of about -5m NAP in Oud-Hillegersberg. The groundwater stage is affected by the extractions of DSM Gist at Delft. However the effects of these extractions are limited on the Oud-Hillegersberg groundwater stage, in case the extractions were to be stopped.**

## 2.5 Phreatic groundwater

The Municipality of Rotterdam maintains a number of phreatic groundwater monitoring wells. The locations of the wells and time series of the wells are accessible at their digital groundwater monitoring map. Figure 5 shows the locations of various monitoring wells in Oud-Hillegersberg. Measurements of the groundwater gauge are taken once a month. The area had lots of monitoring wells removed around the year 2011 and had new ones installed, often in the direct vicinity of the obsolete ones. A peculiar set of monitoring wells are on the sidewalk of the Adriaen van der

Doeslaan 56 to the Oude Raadhuislaan 41. At this location the fluvial dune nears the surface. This is reflected in the groundwater gauge data available for these monitoring wells, see Table 1.

Table 1 Monitoring wells intersection A v/d Doeslaan and Oude Raadhuislaan. Source: http://www.gis.rotterdam.nl/gisweb2/default.aspx

| Monitoring well | Length of the well (m) | Depth (m NAP) | Lowest measured value | Mean |
|---|---|---|---|---|
| **130572-3** | 3,06 | -4,52 | -3,93 | -3,26 |
| **130572-107** | 4,2 | -5,7 | -4,82 | -4,54 |
| **130572-109** | 2,5 | -4 | -3,83 | -3,40 |
| **130572-139** | 2,5 | -4,06 | -3,13 | -3,03 |

The time series for monitoring wells 107 and 109 also contain a lot of empty values, because no groundwater gauge could be measured, presumably because the wells were dry. The differences show the vicinity of the fluvial dune, especially visible for monitoring well 107, and seem to suggest that 139 is placed above some retardant type of soil, while the others are more likely to be placed in a sandy soil that easily infiltrates water to the fluvial dune below.

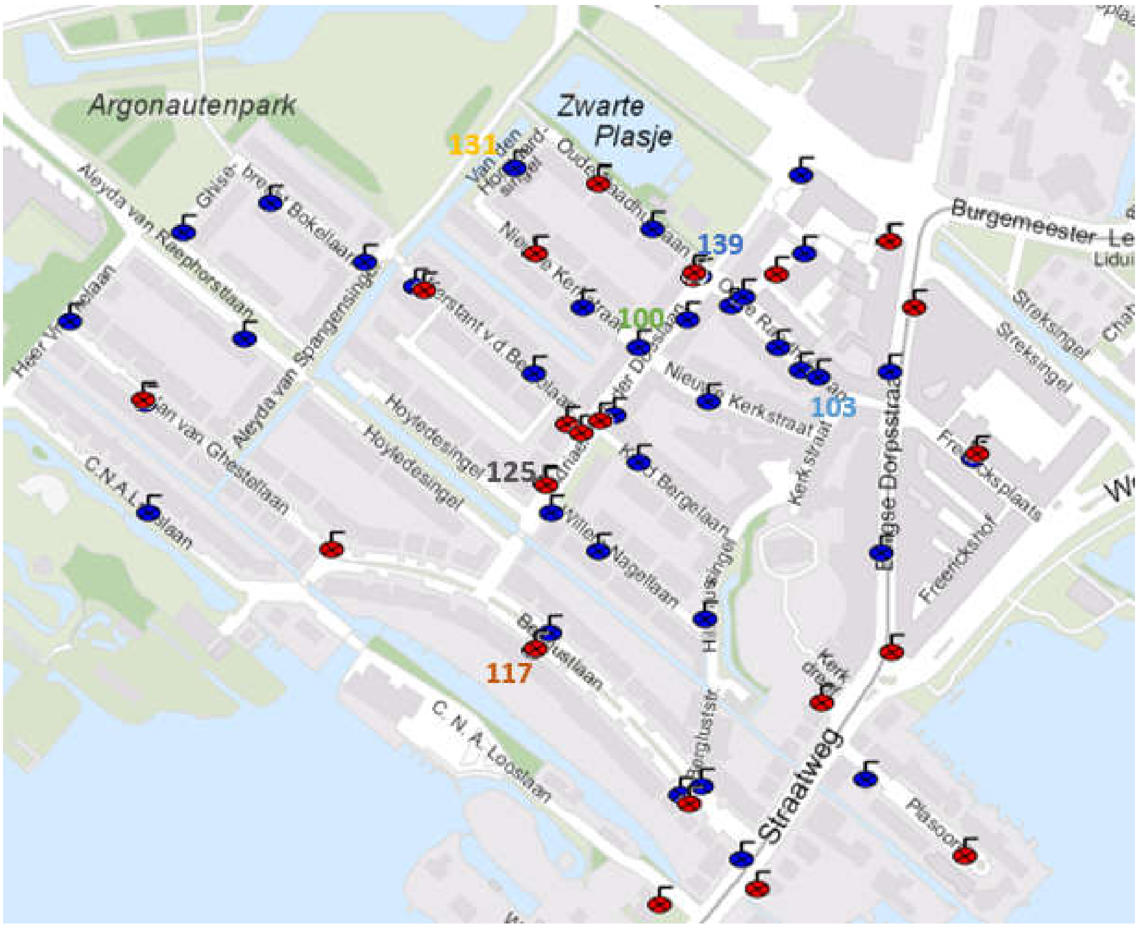



Figure 5 Groundwater monitoring network. Source: http://www.gis.rotterdam.nl/gisweb2/default.aspx

The time series for monitoring well 139 and several other monitoring wells are shown in Figure 6. Monitoring well 103 is placed in the Oude Raadhuislaan near the emerging part of the fluvial dune near the centre of Oud-Hillegersberg. The filter of the well reaches into the dune as can be observed from the graph. With the exception of monitoring well 125 all other wells feature groundwater table values of about or below the surface water level (-2.85m NAP).

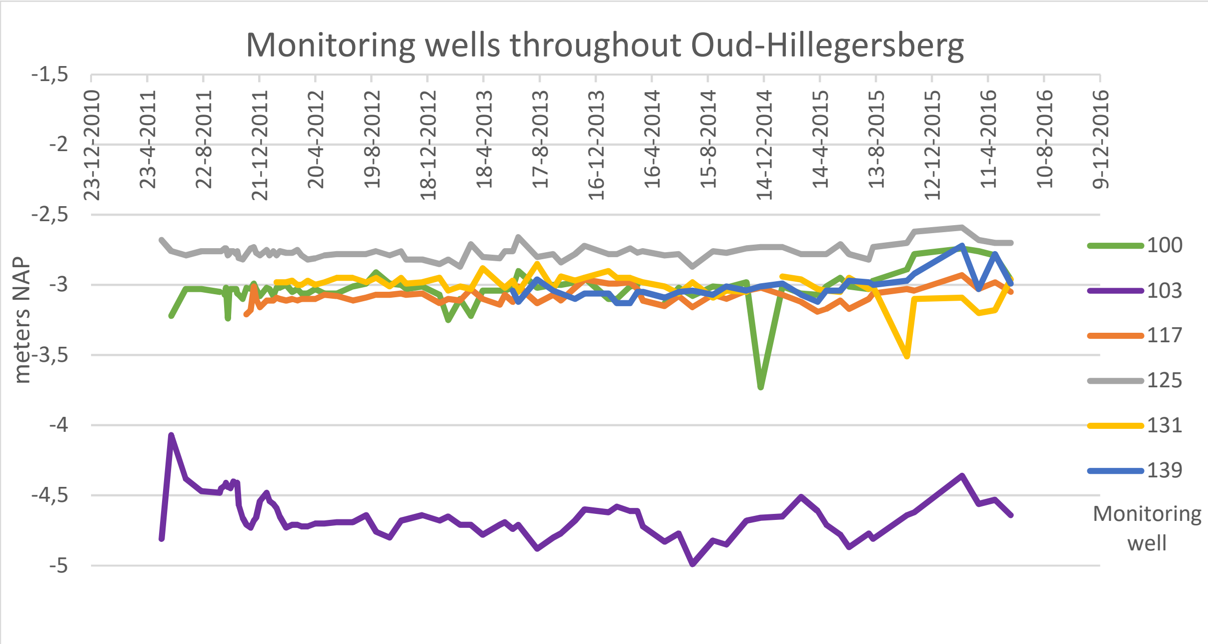



**Figure 6 Time series from monitoring wells in Oud-Hillegersberg from 24 May 2011 to 30 May 2016.**

**The Rotterdam Municipality maintains multiple monitoring wells in Oud-Hillegersberg to measure the unconfined groundwater. The stages are measured manually, about once a month. The groundwater stage throughout the neighbourhood is about -3m NAP, but dependent on the location and the season this value could be lower.**

## 2.6 Discussion and conclusions

The Oud-Hillegersberg area can be typed as an urban area, featuring long canals connected to lakes which surround the neighbourhood from the south and east. To the west and north lie low-lying polders inducing a downward flux of groundwater in Oud-Hillegersberg. The fluvial dune, on which several parts of the neighbourhood are situated, also plays a big part in the infiltration of phreatic groundwater. The deep groundwater stage is at about -5m NAP allowing infiltration of phreatic groundwater to the deeper parts of the subsoil. Surface water and precipitation feed the soil with water although evapotranspiration also removes moist from the soil, especially in the summer months.

Phreatic groundwater flow is affected by the heterogeneous soil in the Anthropocene layer and the fluvial dune emerging the surface in some parts. Time series from monitoring wells along the Oude Raadhuislaan show the difficulties in determining the groundwater flow. Due to the multiple monitoring wells in the neighbourhood it is possible to get a good view on the distribution of the phreatic groundwater table, which will come in handy for the calibration of the model.

# 3 Methods and theory

The aim of this chapter is to describe the methods that are used to answer the research questions. A numerical approach is taken to answer the research questions and the means and theory behind it are explained in this chapter. At first it is described what methods how the research questions will be answered. Subsequently the choice for a model, the groundwater calculus and the application of the model for Oud-Hillegersberg are discussed. These steps are required to answer the first and second research question which require a quantitative approach. Then the methods that are used to determine the effects of climate change on the Oud-Hillegersberg groundwater system are discussed. The chapter closes with a discussion and conclusion.

## 3.1 Research design

As already described in the first chapter the study is executed using three research questions. The focus of the first research question is the effectiveness of the infiltration drains during the summer of 2015. Through the use of two transient models, one with infiltration drain and the other without the infiltration drain, the effectiveness of the infiltration drains can be deduced. The difference between the results of the model with infiltration drain and the model without infiltration drain is the groundwater rise induced by the infiltration drains. The figure below shows schematically how the research question will be answered.

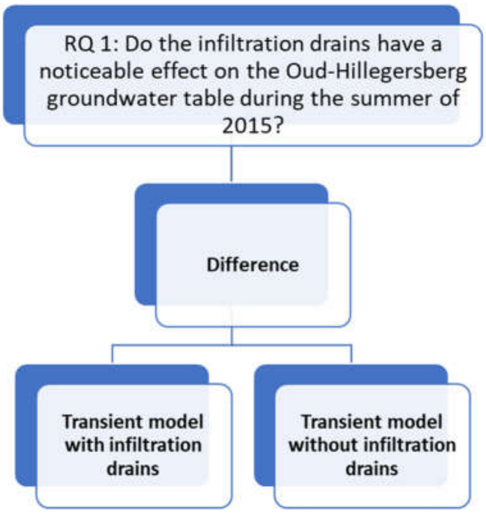



**Figure 7 Scheme research question 1**

The second research question also uses a modelling approach. This research question encompasses the reach of the groundwater rise induced by the infiltration drains into the side streets. The effect on the groundwater rise in the side streets will be described in the average situation using a steady-state model with the infiltration drain and a steady-state model without the infiltration drain. The difference between the two shows the general increase in groundwater rise. A dry situation is also considered using the results from the transient model with infiltration drain of the driest period during the summer of 2015 and the same dry period in a model without infiltration drain. The difference between these model results show the extent to which the infiltration drains induce groundwater rise during a dry period. Figure 8 shows a schematic representation of the approach used to answer research question 2.

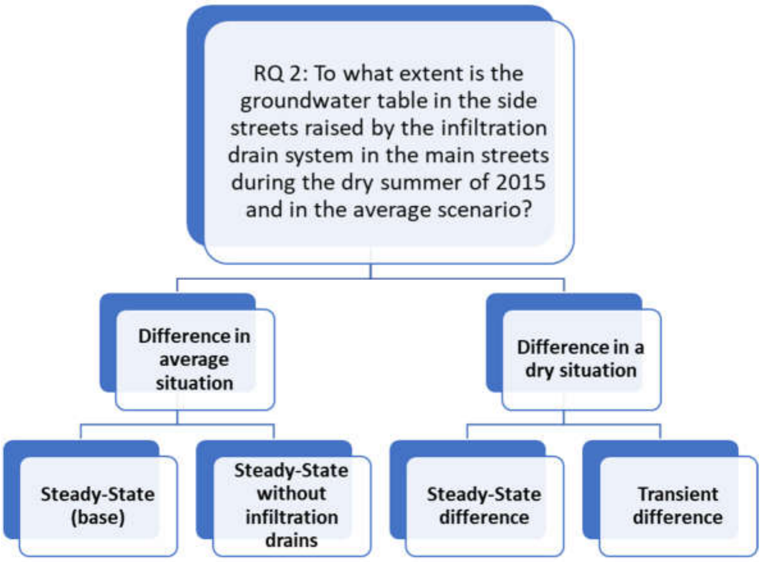



Figure 8 Scheme research question 2

The last research question concerns the robustness of the Oud-Hillegersberg groundwater system to climate change. To answer this topic a qualitative approach is used. Using the approach of the Stresstest Light initiated by the Delta Programme's Spatial Adaptation Delta Decision (Deltaprogramma Ruimtelijke Adaptatie, 2018) and analysing current extremes, the framework for a comparable study for Oud-Hillegersberg is formed. The summer of 2018 proved to be dry, having a return period for drought of once every 30 years according to the KNMI (2018a). An analysis of this dry summer and an understanding of the Oud-Hillegersberg groundwater system will help in gauging the robustness of the system to drought. Figure 9 shows the methods for the last research question schematically.

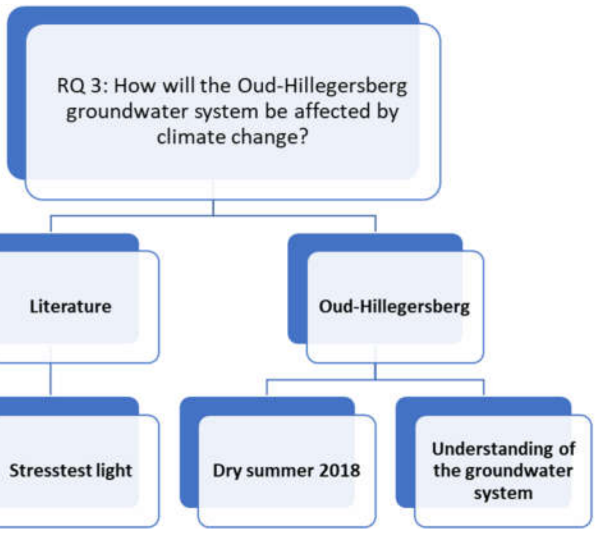



Figure 9 Scheme research question 3

**The three research questions are answered by a combination of quantitative and qualitative methods. Two transient models are used to answer the question on the effectiveness of the infiltration drains during the summer of 2015. To answer the question on the extent at which the effects of the infiltration drains is noticeable in the side streets two steady-state models are used**

**and a dry situation from the 201 summer. The last research question concerning the effects of climate change uses literature and knowledge of the Oud-Hillegersberg groundwater system to close this topic.**

## 3.2 Model selection

The research entails a phreatic groundwater problem in a heterogeneous soil. To give quantified meaning to the presented problem a numerical model is used. The principal program used in groundwater modelling is MODFLOW. Using MODFLOW three-dimensional groundwater flow can be modelled through solving a set of equations (U.S. Geological Survey, 2018; Vermeulen et al. 2017). The groundwater equations are solved for each cell in the model using the finite differences method. Models can be steady-state and transient.

Various user interfaces exist for MODFLOW. The Deltares developed user interface iMOD is used in this study. iMOD enables the user to conveniently edit large input files and iMOD is able to execute large computations quickly (Vermeulen et al. 2017). Deltares gave practical support for iMOD in the study. The grid based nature of MODFLOW, solving groundwater computations for each cell, allows for a detailed spatial analysis of the region being studied. Due to iMODs strong computational abilities this can be done fast and with a high resolution. A disadvantage of this approach is the large amount of input needed to run the model.

In the beginning of the study the use of the hydrological times series analysis program Menyanthes was considered. This program uses a stochastic approach to groundwater problems instead of the deterministic approach of iMOD. However the work with Menyanthes was quickly abandoned, because of insufficient timeseries of the monitoring wells.

**A numerical approach is used to answer the research questions. The program iMOD is used, which is a user interface for MODFLOW. The program uses a deterministic approach to groundwater modelling and solves groundwater equations for every cell in the model. The use of the time series analysis program Menyanthes was considered, but quickly abandoned due to a lack of sufficient data.**

## 3.3 Groundwater calculus

Before the iMOD model itself is discussed the calculus behind the model is disclosed. The numerical model is able to compute a groundwater head by using input and solving a set of equations. The principal equation to solve groundwater flow, from which groundwater head can be deduced, is Darcy's law. Darcy's law models flow through a porous medium and can be stated as:

$$Q_s = -K_s \frac{dh}{ds} A \qquad (3.1)$$

Equation 3.1 shows Darcy's law for one-dimensional discharge (Q) in the s-direction. $K_s$ represents the hydraulic conductivity of the porous medium in the s-direction, and A represents the area through which the flow flows. The term dh/ds is a negative pressure gradient (see the minus in the formula) and shows the change in hydraulic head over distance s. Since the term is negative it means that head decreases when distance increases.

In discrete form Darcy's law might look like this:

$$Q = \frac{KA(h_1 - h_2)}{L} \quad (3.2)$$

In this case ds has become discrete in L and dh in $h_2$ and $h_1$. This form of Darcy's law is at the core of MODFLOWs computations. The change in head is still negative and evaluates the head at distance 1 to the head at distance 2. L represents the distance from cell bound to cell bound; which can be in the x-direction, y-direction and z-direction. Equation 3.3 shows the basic form of the complete groundwater equation for all three directions of groundwater flow and the time-dependent part related to the storage (Harbaugh, 2005). SS is the specific storage (in Length$^{-1}$), which depends on the volume of pores in the observed cell and the change in volume of water in the cell related to the change in head in the cell. $\Delta h/\Delta t$ is the change in head over time, used for the transient model simulation, and $\Delta V$ is the volume of the observed cell. Additional terms for inflow or outflow other than groundwater flow in the observed cell (precipitation, evaporation, rivers and the likes) can be added to the left hand side of the equation. In the steady-state situation the sum of all the inflows and outflows of a model cell equal 0. Hence the entire right hand side of the equation is considered 0 and is not computed. Time is not included, since only a single solution exists and specific storage as a whole is not included in the computations.

$$\sum Q = SS \frac{\Delta h}{\Delta t} \Delta V \quad (3.3)$$

The model computes groundwater flow in three directions: the i-, j-, k-direction. Using the finite difference method the model is divided into cells organised in columns (i), rows (j) and layers (k). To compute the groundwater head in cell i,j,k, information from the six adjacent cells is used i.e. i-1,j,k and i+1,j,k; i,j-1,k and i,j+1,k; i,j,k-1 and i,j,k+1, see figure 10.

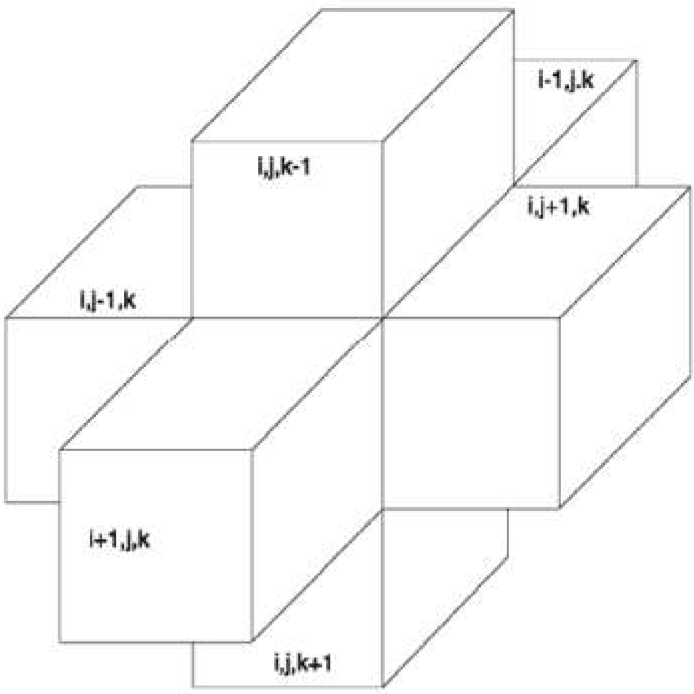



Figure 10 The six adjacent cells of cell i,j,k. Retrieved from Harbaugh (2005).

MODFLOW uses the backward finite differences method in the solving of the groundwater equation (Harbaugh, 2005). The backward approach of the finite difference method uses the resulting head from the previous time step (t = m-1) to the head computed for the current time step (t = m). Other approaches are the forward approach and a central approach, however these feature a stronger propagation of errors, opposed to the backward approach. To compute the groundwater head for the first timestep in a transient model an initial head is needed as input since there are no preceding time steps. In theory a steady-state model does not need an initial head as input to solve the groundwater equation. However by using an initial head, the steady-state model requires less iterations to come to the final result (Harbaugh, 2005).

**Groundwater flow is computed using Darcy's Law and its derivatives. MODFLOW uses the backward form of the finite differences equation to solve the groundwater equations for both steady-state and transient models.**

## 3.4 iMOD model

A set of four models is developed to answer the first two research questions. The first research question encompasses the effectiveness of the infiltration drains during the dry summer of 2015. Two transient models are developed to help answer this research question: a transient model with infiltration drains and a transient model without the infiltration drains. The models are alike except for the infiltration drains. The difference between the two transient model runs show the groundwater rise induced by the infiltration drains. Both models use computed daily input for recharge, using data from 2011 to 2016. Figure 11 shows the timeline of the transient models.


**Figure 11 Timeline of the transient models**

The model run starts on timepoint January 1st 2011 and runs to November 30th 2016. November 1st 2011 is regarded in the model as the date that the infiltration drains became active. The period from 1 January to 1 November 2011 is regarded as run up time for the model to go from the initial groundwater head to a computed groundwater head. The period from November 2011 to November 2016 encompasses a period of about 5 years. The results from this period are used to retrieve statistics about the groundwater head. The highlighted part is the summer of 2015 which is the focal point of the first research question.

Steady-state models with infiltration drain and without infiltration drain were developed in advance of the transient models to calibrate the majority of the input. After the performance of the steady-state models was deemed sufficient the transient models were developed. The steady-state models use the similar input as the transient models, however the single value for the net recharge was computed as the average net recharge using precipitation data and evaporation data from 2011-2015.

Both steady-state models are used to answer the second research question. The difference between the models show the groundwater rise. The reach into the side streets can subsequently be estimated. Additionally the reach into the side streets is estimated for a dry period, using the steady state model with infiltration drain and the results from the transient model run with infiltration drain for 7 July 2015, when the groundwater head in 2015 is at its lowest.

Figure 12 shows a schematisation of the Oud-Hillegersberg subsurface and serves as the basis for the iMOD model. The schematisation shows three layers with depositions; these are the anthropogenic layer, Holocene layer and Pleistocene layer. In the numerical model only two of these layers are regarded as layers: The anthropogenic layer and the Pleistocene layer are modelled as layers in iMOD, with respective input and output data. The horizontal flow component is dominant and as such both layers have their permeability defined as a transmissivity (in Length$^2$/Time).

The Holocene layer is modelled as a vertical resistance (in Time) between the other two layers. An input file from the Deltares developed Delfland model with just the vertical resistance for the Holocene layer was used as a base for the model developed in this study. This input file has proved to be useful in regional groundwater flow computations. The map from the Delfland model is coarse and does not feature a detailed plan of the fluvial dune, which is an important aspect of the Oud-Hillegersberg subsoil. The file was rescaled and adjusted for use in the model for this study, to a cell size of 1m by 1m and the fluvial dune was modelled using bores and CPTs. The fluvial dune features a higher permeability than the other parts modelled in the Holocene layer, as can be observed in figure 12. This decrease in the vertical resistance in the dune area is the main deviation from the original Delfland model.

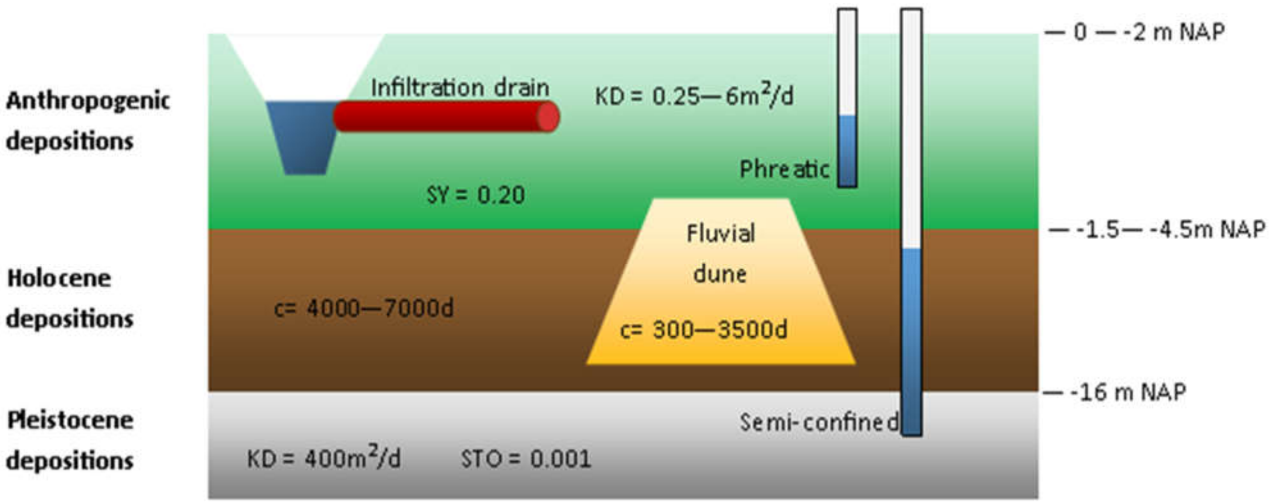



Figure 12 Schematisation of the Oud-Hillegersberg subsurface (not on scale)

The permeability and storage coefficient (STO in figure 12) for the semi-confined aquifer are values common for this type of aquifer and based on experience by Deltares. The permeability and specifiy yield (Sy) for the phreatic aquifer were based also on experience by Deltares, however for both properties the values were increased during multiple testing runs of the model. The final figures used are still acceptable as realistic properties and also perform well in the model. In the phreatic aquifer the storage coefficient is equal to the specific yield because the aquifer compression is too small to be of any meaning. MODFLOW registers the storage coefficient in the top layer as a specific yield and computes the changes in storage accordingly (Harbaugh, 2005).

MODFLOW does not have a package to simulate an infiltration drain. The drain package (DRN) cannot be used to simulate an infiltration drain, because it does not allow flow when the hydraulic head in the drain is higher than the surrounding head (Harbaugh, 2005). In this study the infiltration drain is modelled using the river (RIV) package in iMOD. This way the modelled infiltration drain features flow to and from the surrounding ground. The steady-state model and the transient model that do not feature the infiltration drains, simply have their infiltration rate put to zero, which prevents them from recharging the groundwater.

Precipitation and evapotranspiration are combined into one net recharge term in the model. The computations for the net recharge are executed in excel beforehand. Oud-Hillegersberg is an urban area featuring a high grade of paved areas. The cgOH (2014) estimated the amount of paved area to be 60% in the area and in total 50% of the area being connected to the sewerage system. The cgOH also estimated the amount of water discharge by the sewerage system to be 400mm. Considering the annual precipitation of about 930mm this results in 43% of the precipitation being discharged through the sewerage system. Through evapotranspiration the remaining effects of the precipitation are even more decreased. It is assumed that evapotranspiration only takes place in the 40% of Oud-Hillegersberg that is unpaved. Evaporation on paved areas is limited and is assumed to only occur in case there has been a precipitation event. Based on a study by DeltaSync (2013), the evaporation from paved areas is assumed to be 14% of the precipitation. As such evaporation from paved area in the model is the gross precipitation multiplied by the 60% paved grade and the 14% evaporation rate from the DeltaSync report.

**Four models are developed in this study, of which two are steady-state models and two which are transient models. Two of the models have the infiltration drains included, the other two do not. The daily recharge data used for the transient models is derived from precipitation and evapotranspiration and runs from 1 January 2011 to 30 November 2016. The date at which the infiltration drains became active is set at 1 November 2011 and as such the statistics for the model performance cover a 5-year period, supplementing the understanding of the Oud-Hillegersberg groundwater system during the summer of 2015. Input variables for the model are specified using data from timeseries, bores or CPTs; or are estimated with help from Deltares.**

## 3.5 Climate change: Stresstest light

In 2014 the Royal Netherlands Meteorological Institute (KNMI) released a set of four new climate scenarios based on findings from the IPCC report of 2013 (KNMI, 2015). The four scenarios contain either change in air circulation patterns or no change, and, either moderate temperature rise or high temperature rise, see figure 13.

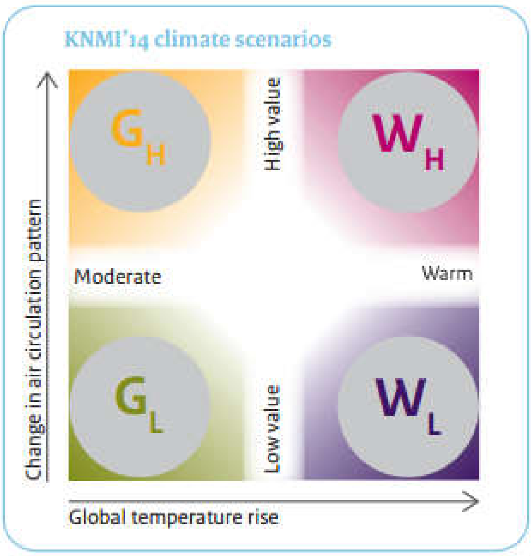


**Figure 13 KNMI'14 climate scenarios.** (Royal Netherlands Meteorological Institute (KNMI), 2015)

These changes will affect precipitation and evapotranspiration. For all four scenarios the yearly precipitation and yearly evapotranspiration will increase up to 2050, with precipitation values ranging from +2,5% ($G_H$ scenario) to +5,5% ($W_L$ scenario) on top of the 851 mm of reference mean yearly rainfall, and evapotranspiration values ranging from +3% ($G_L$ scenario) to +7% ($W_H$ scenario) on top of the reference evapotranspiration potential of 559mm (KNMI, 2015).

This increase in evapotranspiration is also visible when summer is considered: evapotranspiration shows an increase of +4% (for the $G_L$ and $W_L$ scenarios) to +11% (for the $W_H$ scenario) on top of a reference evapotranspiration potential of 266mm (KNMI, 2015). Precipitation values however range from -13% ($W_H$ scenario) to +1,4% ($W_L$ scenario) on top of the reference mean precipitation in summer of 224mm (KNMI, 2015). In other words there is a deficit of precipitation and, depending on the way climate change will unfold in the future, there will be a risk of drought. The KNMI scenarios show that the mean highest precipitation deficit, during the growing season (1 April to 30 September), is likely to increase with +0,7% ($W_L$ scenario) to +30% ($W_H$ scenario) (KNMI, 2015).

The Delta Programme Spatial Adaptation introduced the Stresstest Light as a standardized tool for municipalities and water authorities as a first move to identify weaknesses to climate change in their area of control (Deltaprogramma Ruimtelijke Adaptatie, 2018). The tool is intended to be used for both urban areas and rural areas. The Stresstest Light is used to identify weaknesses in four categories:

- Flooding (overstroming)
- Waterlogging (wateroverlast)
- Drought (droogte)
- Heat (hitte)

The website klimaateffectatlas.nl accompanies The Stresstest Light with data presented in a digital atlas. This Climate Impact Atlas uses the same four categories and different variables can be looked up in the atlas with maps for the current situation and for a modelled situation in 2050 using the $W_H$ scenario from the KNMI 2014 climate scenarios (Klimaateffectatlas, 2019). The $W_H$ scenario is used by the Climate Impact Atlas developers since it shows “the most forceful changes”.

The Stresstest Light includes two first steps, being 1a: first impressions on the basis of the Stresstest Light; and 1b: Usage of local and regional knowledge. The aim of the third research question is to conduct a partially Stresstest Light for Oud-Hillegersberg. Partially, since the topic of the study is the Oud-Hillegersberg groundwater system. The theme covered in this study is ‘drought’.

Local and regional knowledge used to answer this topic for Oud-Hillegersberg comes through literature, data and an understanding of the groundwater system. The research conducted on the groundwater system to develop the models used for the first two research questions has resulted in an understanding of the Oud-Hillegersberg groundwater system, which is applied to conduct a Stresstest Light. Recent data and understanding of the drought of 2018 will be applied as well to understand the effects of drought on the system. A drought like the one in 2018 has been estimated to have a recurrence of 30 years by the KNMI (2018a), and as such the data for this study will be relevant to determine the effects of a very dry year on the Oud-Hillegersberg groundwater system.

In the context of the Delta Decision Spatial Planning a research was conducted by Deltares, FUGRO and Wareco on the use and effectiveness of active groundwater management. In their phrasing active groundwater management is a focused effort to realise a desired groundwater level. This is achieved by discharging water from the system in wet periods and bring in water during dry periods (Deltares, FUGRO, & Wareco, 2017). By using surface water fed infiltration drains this goal can be achieved. Deltares, FUGRO and Wareco examined several locations in the Netherlands where active groundwater management is conducted and estimated the effectiveness of the measures taken, also taken into account the costs and benefits.

With the infiltration drains in place Oud-Hillegersberg has active groundwater management, so in theory the groundwater head should be more stable than it was before the installation of the infiltration drains. By assessing the impacts of the 2018 drought to the groundwater system its robustness to climate change can be estimated.

**To determine the effects of climate change on the Oud-Hillegersberg groundwater system a partial Stresstest Light is executed, through research on the effects of drought. A study of the 2018**

**drought and understanding of the local groundwater system are used to estimate the climate robustness of the Oud-Hillegersberg groundwater system to drought.**

## 3.6 Discussion and conclusions

To answer the first two research questions four models are developed: two steady-state models and two transient models running from January 2011 to November 2016. One steady-state model and one transient model have the effect of the infiltration drains modelled in, the others do not. The differences in outcomes between the models will answer the first two research questions.

The models are developed in iMOD, a Deltares developed user interface of MODFLOW. MODFLOW features solves the groundwater equation for all the cells in the model area using the finite difference method. Deltares provided support for the use of the model and helped as well with some input variables.

The fluvial dune is specifically modelled using bores and cone penetration tests to estimate its contours. It has a rather high permeability to simulate the strong drawdown effect in the dune area in Oud-Hillegersberg. The infiltration drains could not be modelled directly into MODFLOW due to MODFLOW not having a package for infiltration drains. Instead the infiltration drains were modelled as a subsurface surface water body using the river (RIV) package. The net recharge to the groundwater system is estimated using the precipitation and evapotranspiration and the ratio of paved area.

To answer the third research question a Stresstest Light is partially conducted for Oud-Hillegersberg. The Stresstest Light as a tool is initiated by the Delta Programme's Delta Decision on Spatial Planning, to help municipalities and water authorities to identify weaknesses to flooding, drought, waterlogging and heat. The effects of drought on the Oud-Hillegersberg groundwater system are studied through the analysis of a current extreme. Data from the 2018 drought is used to estimate the robustness of the Oud-Hillegersberg groundwater system to climate change.

# 4 Calibration

The numerical models are calibrated using groundwater timeseries from the Rotterdam Municipality as well as timeseries from locals. The area is divided into three parts for the calibration as will be described in detail in the first paragraph. The three subsequent paragraphs describe the performance of the model in the three different areas.

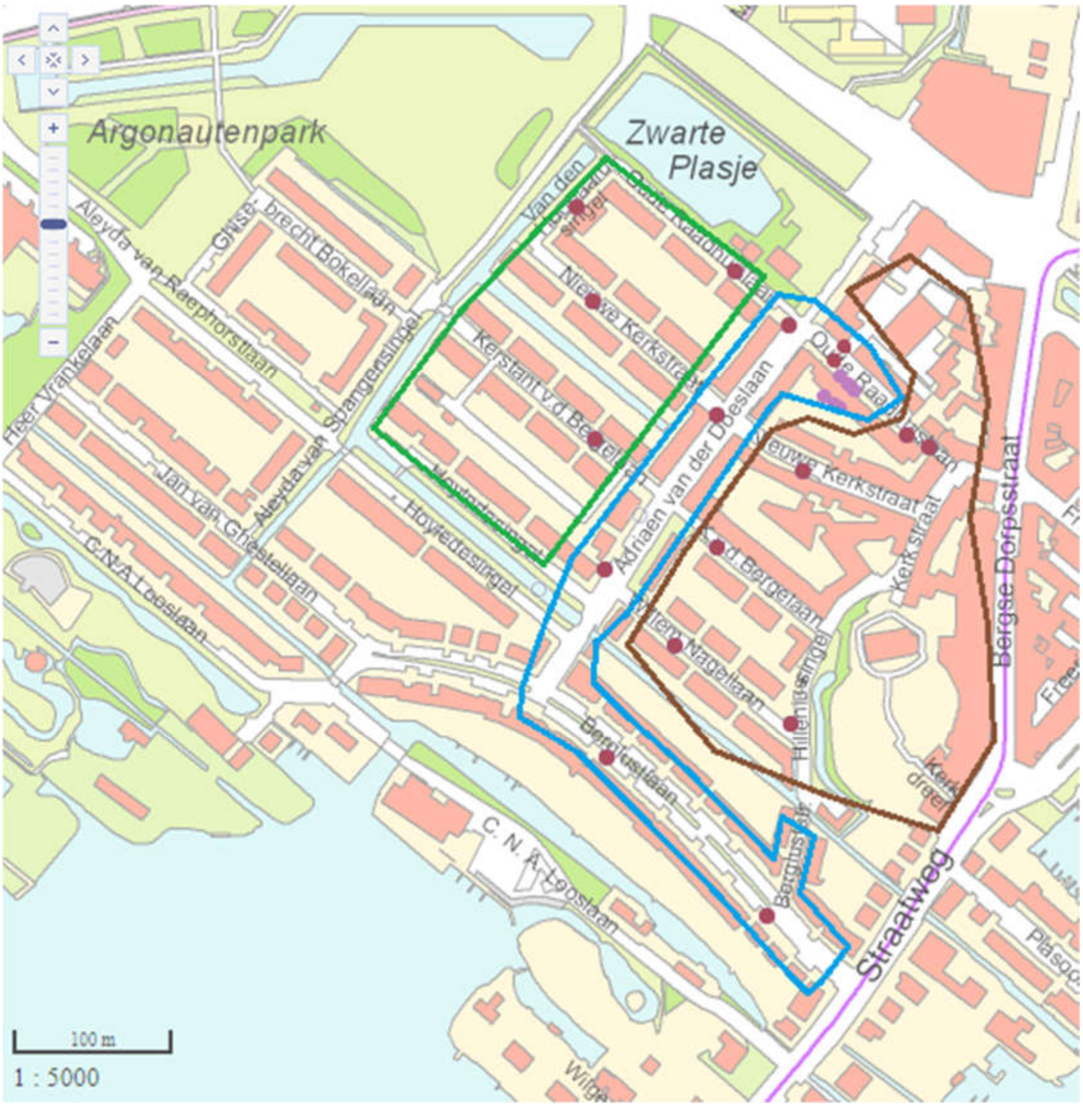



**Figure 14 Location and grouping of monitoring wells used for calibration. In burgundy red locations of monitoring wells of the Rotterdam Municipality, in purple the locations of private monitoring wells. Base map is from the Rotterdam Municipality.**

## 4.1 The approach for calibration

The output of the steady-state models and transient models is calibrated using time series from monitoring wells of the Rotterdam Municipality. The monitoring wells used for calibration are selected with regards to their proximity to the infiltration drain. Figure 14 shows that the monitoring wells used for calibration are split into three main groups. Each group features several monitoring wells in similar circumstances with regards to the vertical flow resistance in the subsurface and the distance to the infiltration drains. The group in blue represents the monitoring wells that are in the direct vicinity of the infiltration drain. This group also shows several monitoring wells owned by locals, see the monitoring wells marked in purple. The group in brown contains monitoring wells that are located in the area where the fluvial dune is present. The green group contains monitoring wells that are located to the west of the infiltration drain, where the dune is absent and the vertical flow resistance of the Holocene layer is high.

The groundwater time series from the monitoring wells of the Rotterdam Municipality are small datasets with about 10 measurements each year. Although measurements are taken about every month, the interval is not fixed and can vary from 2 weeks to 2 months. Due to the large gaps in the timeseries it is difficult to spot the full dynamics of the groundwater system. The model output features daily data and as such the dynamics in the model are really visible. For calibration observed timeseries and modelled timeseries for 2015 are used to determine the seasonal progress. Observed timeseries and modelled timeseries from 1 November 2011 through to 30 November 2016 are used to determine the statistics over a longer period.

**The model output is calibrated using observed groundwater timeseries from the Rotterdam Municipality. As Figure 14 shows the calibration is conducted with three specific regions in mind: the dune area, the western area and the area near the infiltration drain. This approach helps in typifying the groundwater flow in regions that are similar.**

## 4.2 Groundwater system near the infiltration drain

Seven monitoring wells near the infiltration drain are used for calibration. Of those monitoring wells three are located in Adriaen van der Doeslaan, two in Berglustlaan and two in Oude Raadhuislaan as is shown in the figure below.

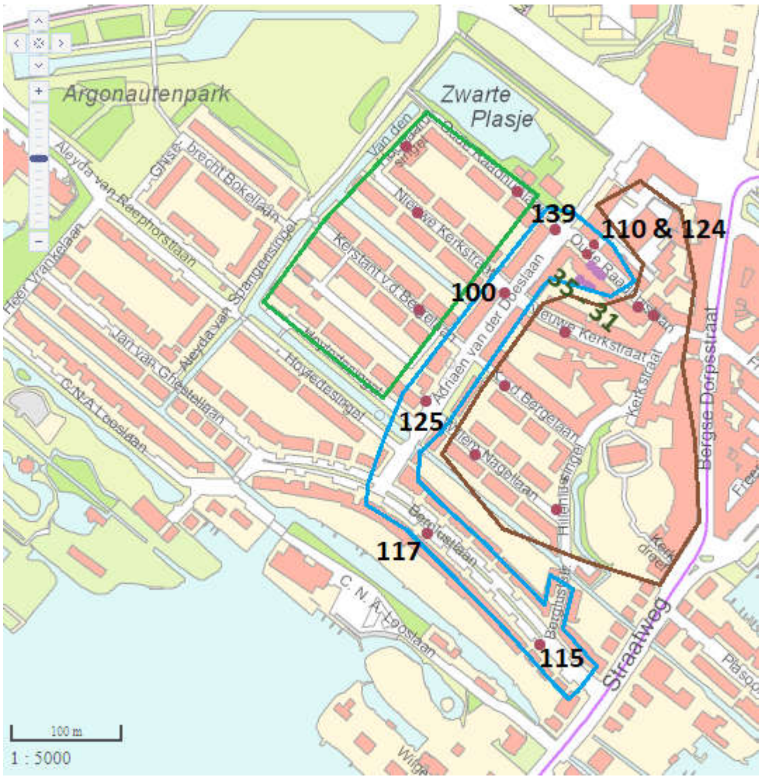



Figure 15 Location and labels of the monitoring wells in the area near the infiltration drain.

The two monitoring wells used for Oude Raadhuislaan are near each other, additionally timeseries from locals living nearby have been included for the evaluation of this location. The observed and modelled timeseries of the monitoring wells of the Adriaen van der Doeslaan, as well as Box and Whisker plots for each location are shown in figure 16. Be aware that the scale varies per graph.

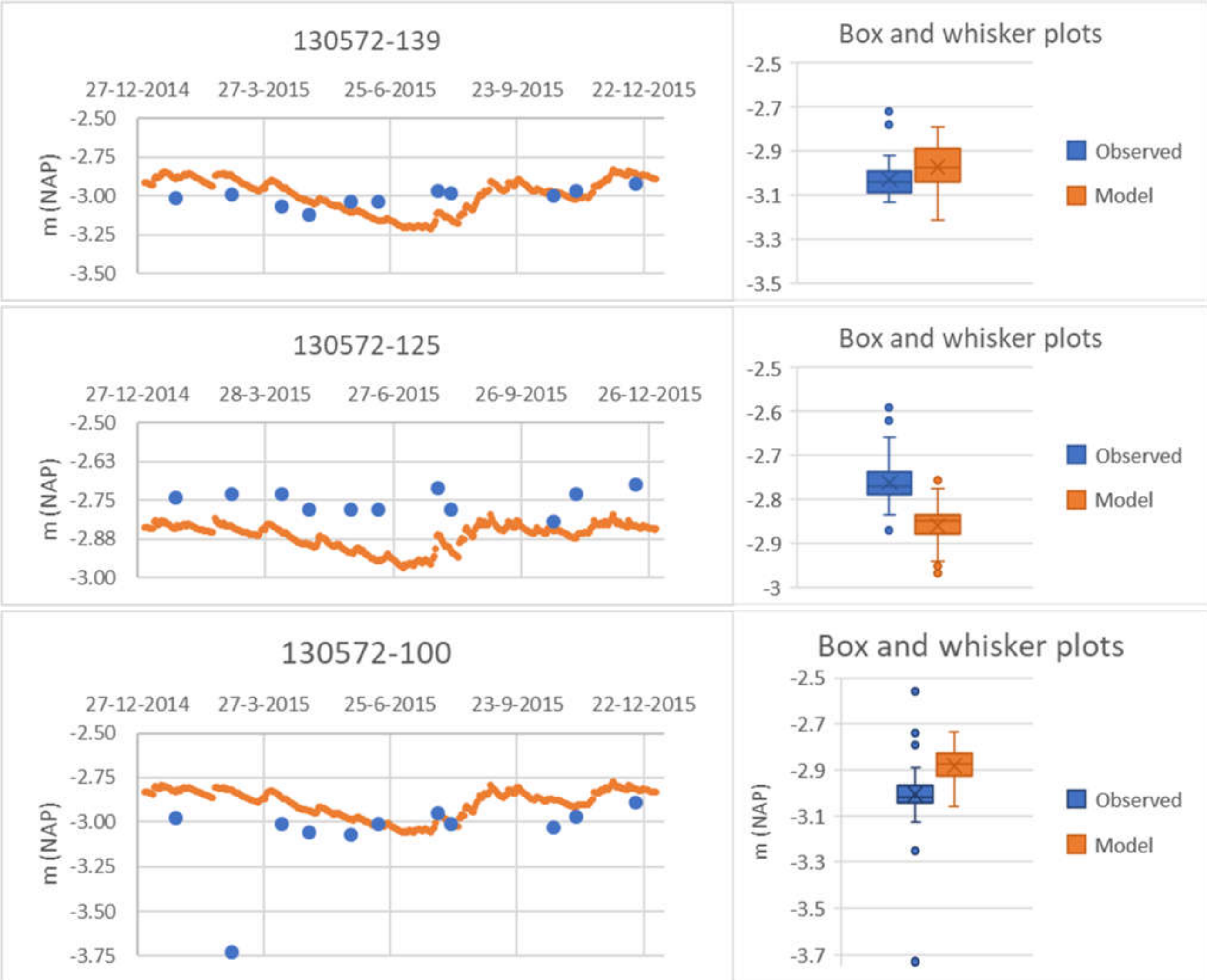



**Figure 16 Monitoring wells in Doeslaan with timeseries for 2015 and box and whisker plot.**

The modelled timeseries for the three monitoring wells in Doeslaan resemble the observed time series really well. The mean is generally off by a decimetre and the spread of the values is quite similar. The observed datasets feature several outliers, with the lower outlier in the 130572-100 dataset being conspicuous. The outlier can also be seen in the graph for 2015, it is presumably an anomaly.

The course through 2015 is recognizable. All graphs show a decline of the groundwater table in the first months of the year (both observed and model), afterwards a stronger decline through to summer. This decline is shown clearly in the model, but not in the observed data. Near the end of July a rain event is registered by both and autumn features an increase of the groundwater table. Overall the modelled timeseries do quite well, but are slightly more sensitive to precipitation and the lack thereof.

The timeseries and box and whisker plots for Berglustlaan are displayed in figure 17. The modelled timeseries match the observed timeseries really well. The model timeseries are slightly higher than the observed ones. Monitoring well 130572-117 features two outliers, both can also be seen in the graph for 2015. It is likely that this is once again an anomaly in the observations.

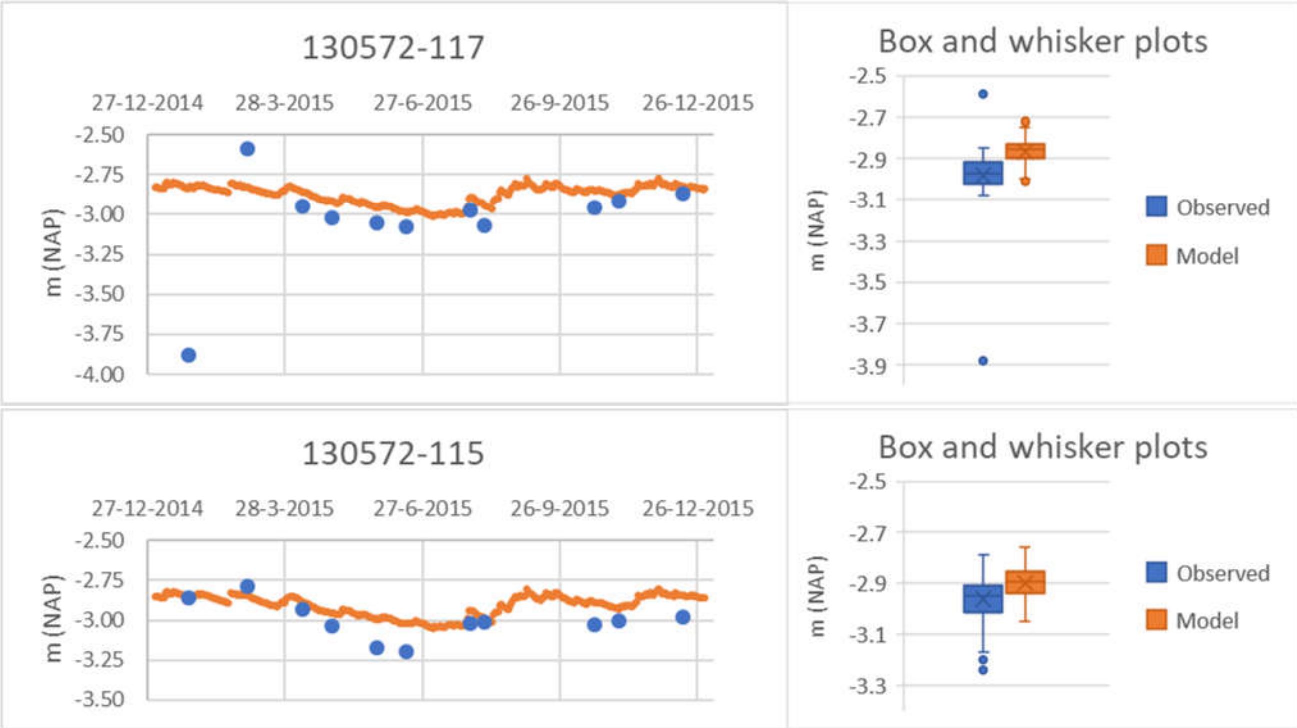



**Figure 17 Monitoring wells in Berglustlaan with timeseries for 2015 and box and whisker plot.**

The monitoring wells 130572-110 and 130572-122 are located in Oud Raadhusialaan, on opposite sides of the street; 110 on the north-eastern sidewalk and 122 on the south-western sidewalk. Timeseries from six private monitoring wells are used from locations to the south-east of monitoring well 122, with three monitoring wells being located in front yards and three monitoring wells being located in backyards. The monitoring wells were installed and gauged under supervision from Deltares, but are governed by locals. This part of the Oude Raadhuislaan is located on the fluvial dune, with only a thin layer of Holocene and Anthropocene deposits on top of it. Hence this area is affected by the infiltration drain that adds water to the system and the highly conductive fluvial dune that drains water.

Figure 18 shows the timeseries of the monitoring wells 110 and 122 for 2015 and features the model timeseries (the model timeseries location is set at the same location as monitoring well 122) for 2015 and to the right there are the box-and-whisker plots for the entire timeseries. The time series of the model and monitoring well 110 show a similar range of motion.

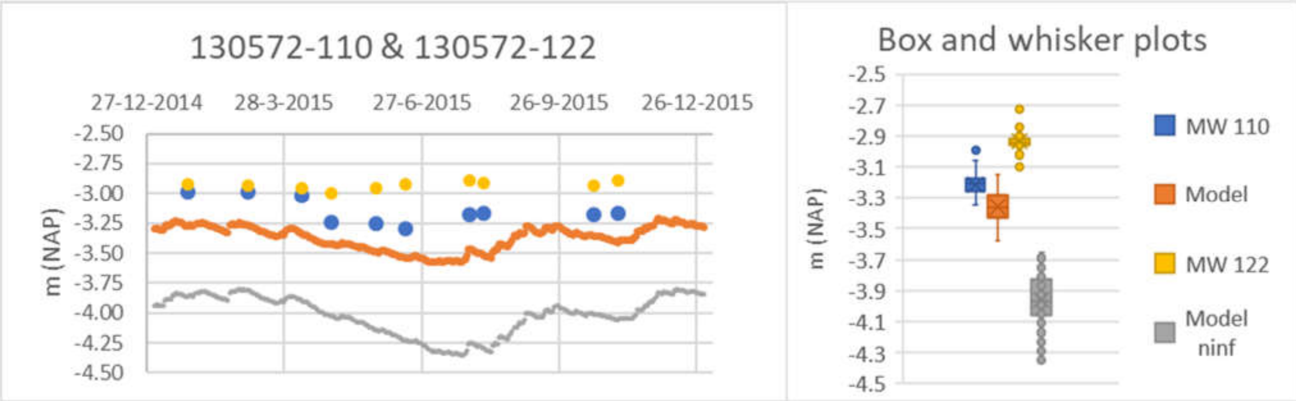



Figure 18 Monitoring wells in Oude Raadhuislaan with timeseries for 2015 and box and whisker plot.

The grey time series represent the model outcomes for the transient simulation without the infiltration drains. As expected the dynamics are stronger in this outcome. Figure 19 and figure 20 show the timeseries of six monitoring wells in Oude Raadhuislaan, owned and conducted by locals. Three monitoring wells are located in the front yards of three consecutive houses and the other three wells are in the backyards of the same houses. The timeseries are from October 2009 to summer 2012. The infiltration drain is in effect since autumn 2011, which can be seen in both figures. After the implementation of the infiltration drain in Oude Raadhuislaan the dynamics are smaller.

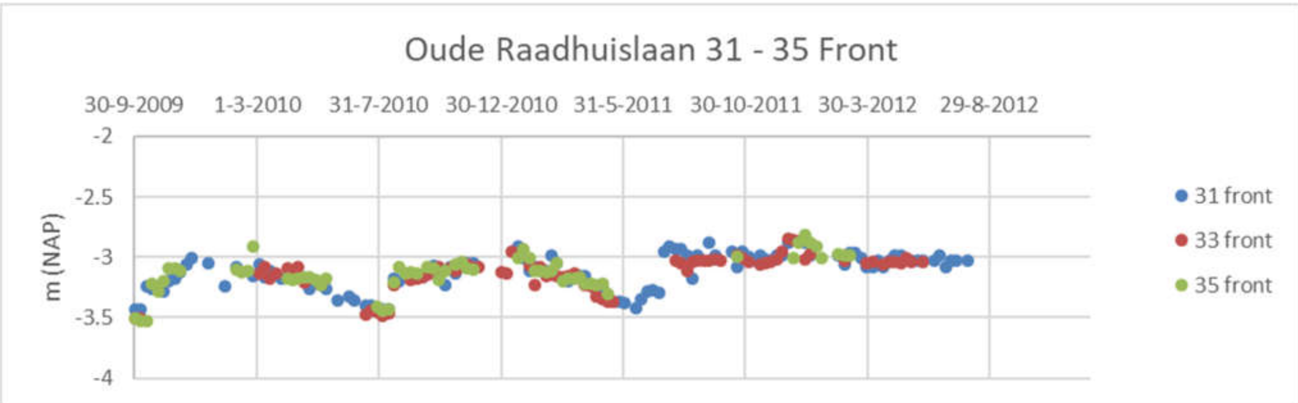



Figure 19 Timeseries by locals from Oude Raadhuislaan at the front.

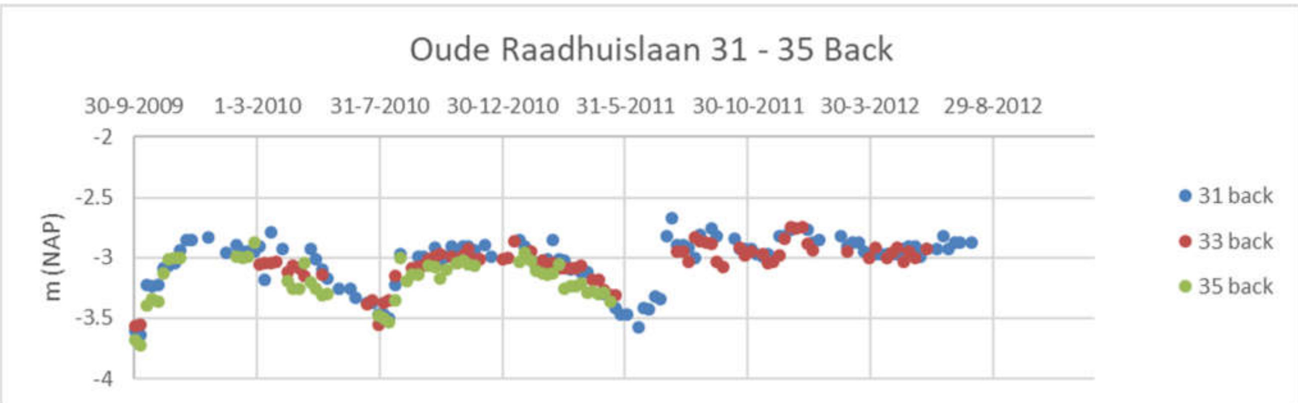



Figure 20 Timeseries by locals from Oude Raadhuislaan at the back.

The timeseries from both the front and the back of houses 31, 33 and 35 are relevant to gauge the models abilities to compute the situation without the infiltration drain (the so called 'model ninf' situation in figure 18). In this case the timeseries from the observations from autumn 2009 to autumn 2011 are considered and the entire modelled timeseries from 2011 to 2016 for the model without the infiltration drain. The results are put in table 2.

Table 2 Timeseries, observed and modelled, without infiltration drain.

| Timeseries | Mean | Range (spread) |
|---|---|---|
| **31 – 35 Front** | -3.2m NAP | -2.9m NAP — -3.5m NAP (0.6m) |
| **31 – 35 Back** | -3.1m NAP | -2.8m NAP — -3.6m NAP (0.8m) |
| **Model without infiltration drain** | -4m NAP | -3.65m NAP — -4.3m NAP (0.65m) |

While the model is about 8 decimetres off from the observed values, the spread is similar. This is especially the case for the observations from the 'front monitoring wells' and the model.

Combining the timeseries from autumn 2011 on for this part of Oude Raadhuislaan shows that the model with the infiltration drain is able to simulate the reality quite well. As the comparison in table 3 shows, the mean is a slightly below the means of the observed timeseries and the spread is slightly larger.

Table 3 Timeseries, observed and modelled, with infiltration drain.

| Timeseries | Mean | Range (spread) |
|---|---|---|
| **31 – 35 Front** | -3m NAP | -2.8m NAP — -3.1m NAP (0.3m) |
| **31 – 35 Back** | -2.9m NAP | -2.7m NAP — -3m NAP (0.3m) |
| **130572-110** | -3.2m NAP | -2.7m NAP — -3.1m NAP (0.4m) |
| **130572-122** | -2.95m NAP | -3m NAP — -3.3m NAP (0.3m) |
| **Model** | -3.35m NAP | -3.15m NAP — -3.6m NAP (0.45m) |

**The transient model is able to resemble the observed series quite well. This is especially the case for the timeseries from the monitoring wells along A. v.d. Doeslaan and the Berglustlaan. The mean values are generally similar and dynamics are also similar. The model shows slightly lower values for the location in Oude Raadhuislaan. This area is located partly on the fluvial dune. Due to the uncertainty of the permeability of the local subsoil, some deviations from the observations are expected for the model.**

## 4.3 Groundwater system in the dune area

Six locations used for calibration are located in the dune area, again with timeseries from monitoring wells as well as model timeseries. Figure 21 shows the labels and locations of these monitoring wells. The timeseries show stronger dynamics and lower average heads compared to the locations near the infiltration drains, however the magnitude of this effect varies per monitoring well although the effect is stronger at locations where the dune layer is thick.

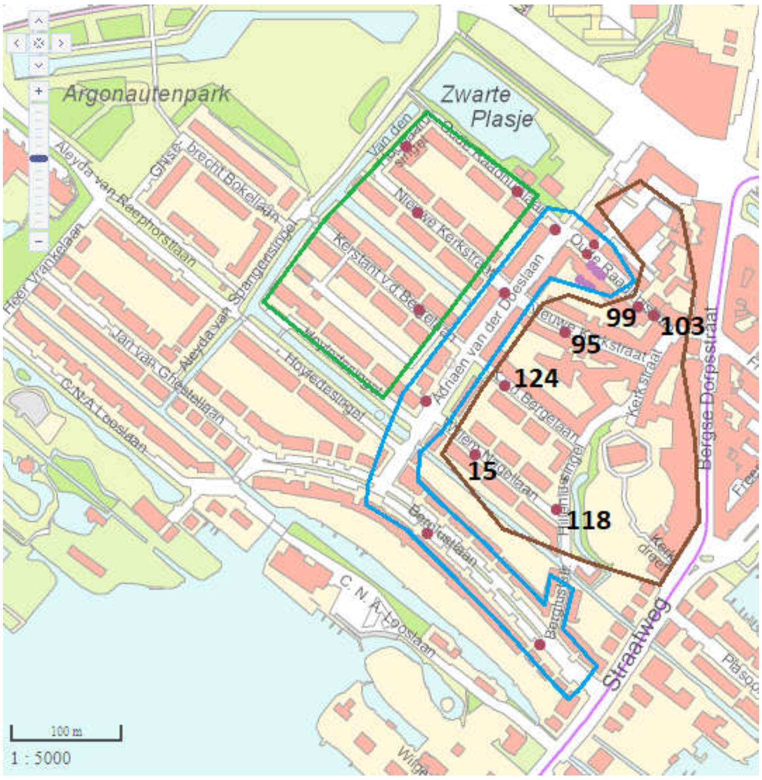
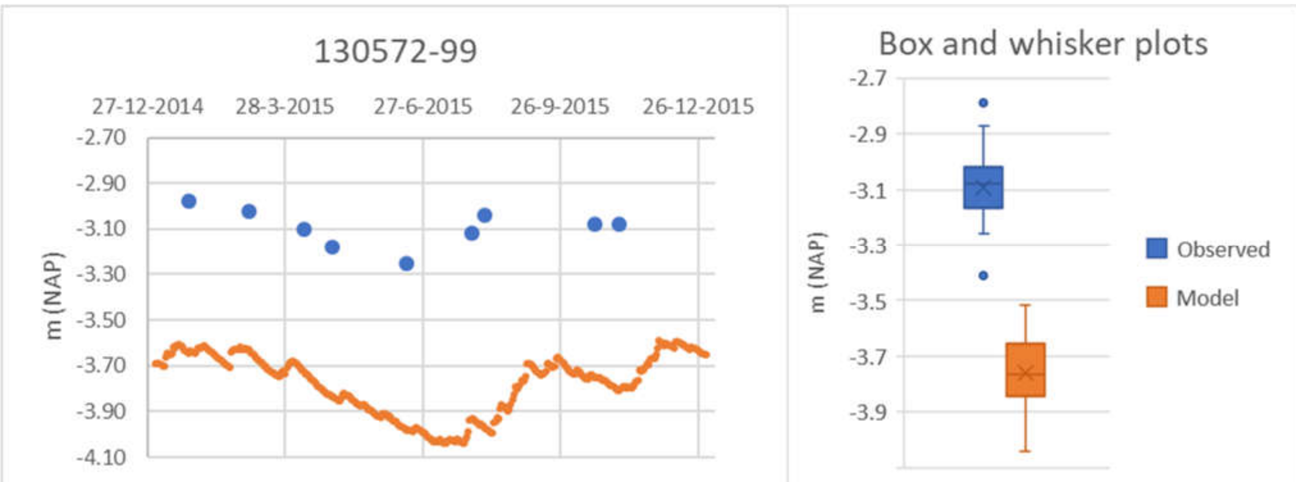



Figure 21 Location and labels of the monitoring wells in the dune area.

Monitoring wells 130572-99 and 130572-103 show interesting results, see figure 22. In both cases the modelled dynamics are comparable to the observed dynamics, as the box and whisper plots show and the graphs also. The values themselves are way off; in the case of monitoring well 99 the model features much lower values and in the case of monitoring well 103 the model features much higher values. Monitoring well 103 is different to the other monitoring wells in that it seems to gauge the groundwater head in the dune itself, although it is listed in the digital portal of the Rotterdam Municipality to be a monitoring well for phreatic groundwater (Gemeente Rotterdam, 2018).



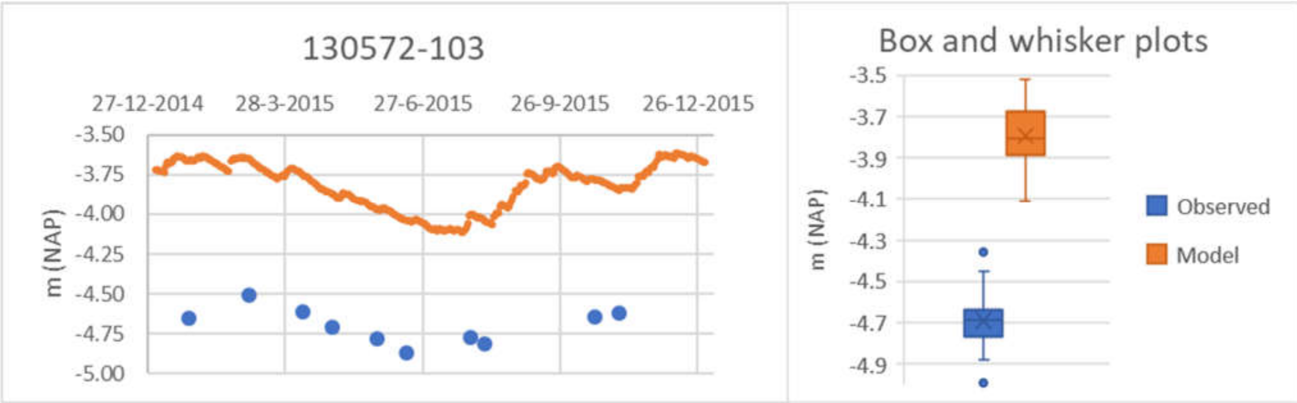



Figure 22 Monitoring wells near the junction of Kerkstraat and Oude Raadhuislaan with timeseries for 2015 and box and whisker plot.

Figure 23 shows that the model overestimates the draining effect of the dune on the locations. The observed timeseries from monitoring wells 130572-95 and 130572-124 show much higher values and much lower dynamics than the model timeseries. This seems to suggest that the draining effect of the dune is less than expected and that the infiltration drain still has effect up to these locations.

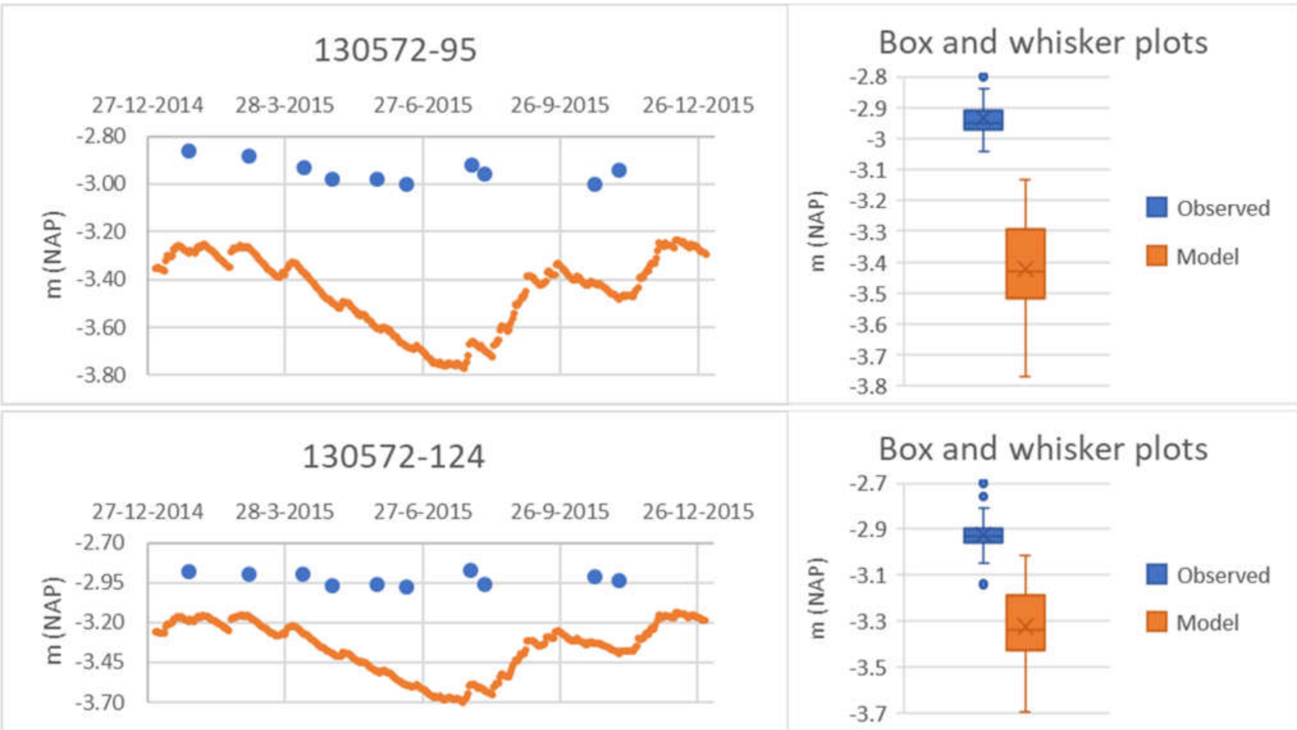



Figure 23 Monitoring wells equidistant from the infiltration drain in the dune area with timeseries for 2015 and box and whisker plot.

The last two monitoring wells considered for the calibration of locations in the dune area are monitoring well 130572-15 and 130572-118 located in Willem Nagellaan. The graphs and box and whisker plots for these monitoring wells are displayed in figure 24. Both locations are also influence by nearby sources of surface water south and east of the Willem Nagellaan and monitoring well 15 is also like monitoring wells 124 and 95 on an equidistant distance from the infiltration drains. The model dynamics are stronger than the observed dynamics, however the dynamics for monitoring well 118 are clearly matching. The observed dynamics for monitoring well 15 are very limited (also seasonally limited), this is likely due to the effect of the infiltration drain. The mean values for the observed time series and the model time series are not too far off.

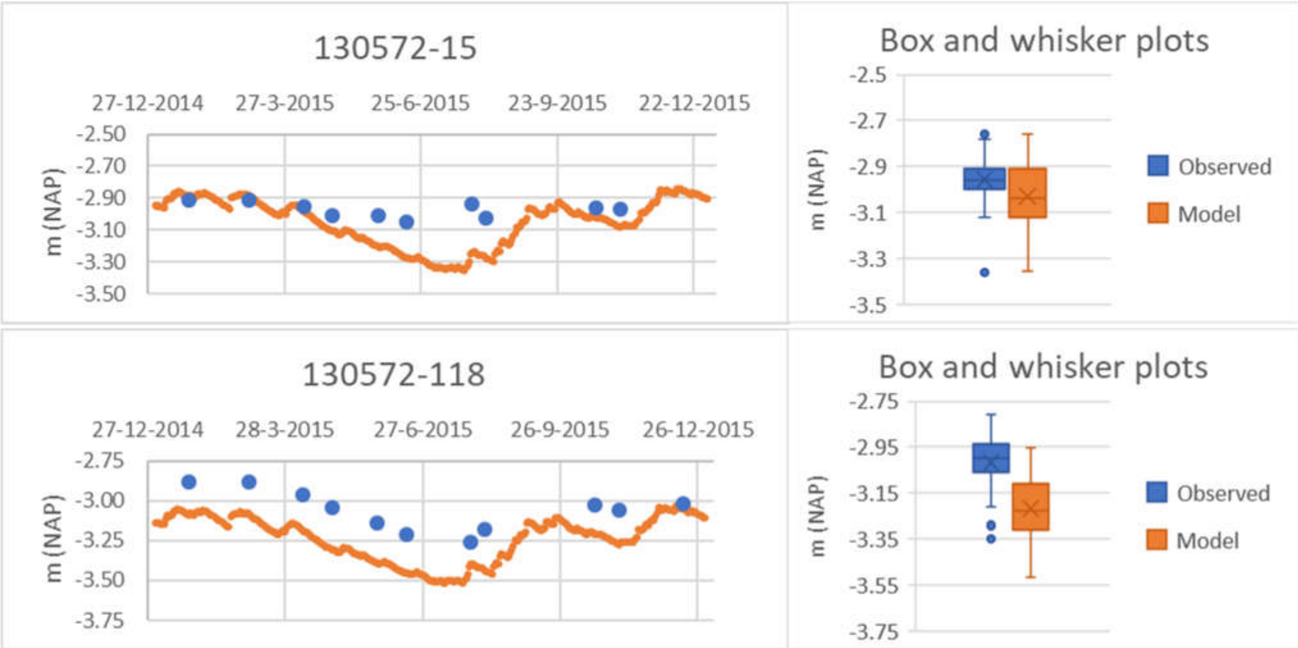



Figure 24 Monitoring wells in the eastern part of Willem Nagellaan with timeseries for 2015 and box and whisker plot.

**The model is able to reproduce the real-life dynamics quite well for several monitoring wells in the dune area. Monitoring wells 95 and 124 do not match very well which should be taken into account when the results of the different models and the real-life consequences are discussed.**

## 4.4 Groundwater system in the western area

The characteristics of the western area in Oud-Hillegersberg are the presence of several surface water bodies, by means of canals and an outdoor swimming pool, a thick Holocene layer with poor permeability and a groundwater flux towards the low-lying polder Schiebroek. Depositions of the fluvial dune in the subsoil are absent in this area, resulting in limited infiltration to deeper parts of the subsoil. The flow component is thus mostly horizontal in the phreatic zone. Timeseries from four monitoring wells, managed by the Rotterdam Municipality, are used for the calibration of the models for this area. The figure below shows the location of the monitoring wells used.

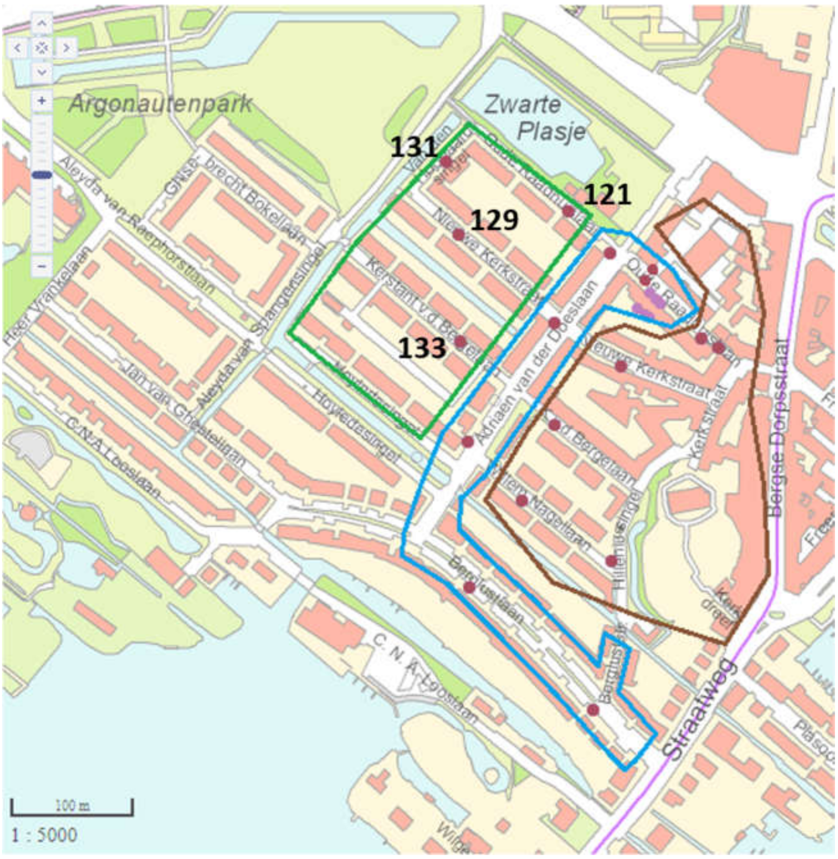


Figure 25 Location and labels of the monitoring wells in the western area.

The surface waterbody Van den Hoonaardsingel, and the same-titled street along it, lie near the edge of the modelled area. The timeseries from the monitoring well at this location are useful to determine the effect of nearby surface water to the dynamics of the phreatic groundwater head and to determine the effect of the groundwater flux towards the nearby low-lying park Argonautenpark on the groundwater head.

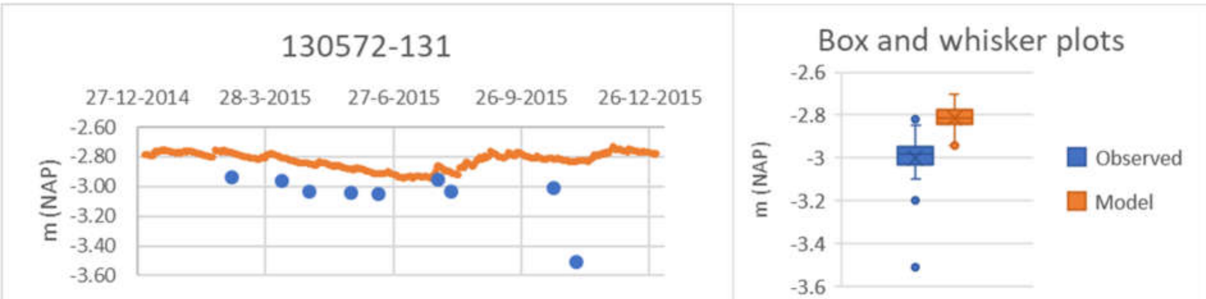



Figure 26 Monitoring well in Van den Hoonaadsingel (street) with timeseries for 2015 and box and whisker plot.

Figure 26 shows the graph with observed and modelled timeseries for 2015 and box and whisker plots for the modelled and observed timeseries from 1 November 2011 onwards. The dynamics are similar with the model featuring slightly less strong dynamics than the observed timeseries. The observed value for 4 November 2015 is the lowest in the graph and the box and whisker plot. This is likely another anomaly due to external factors or erroneous registration of data.

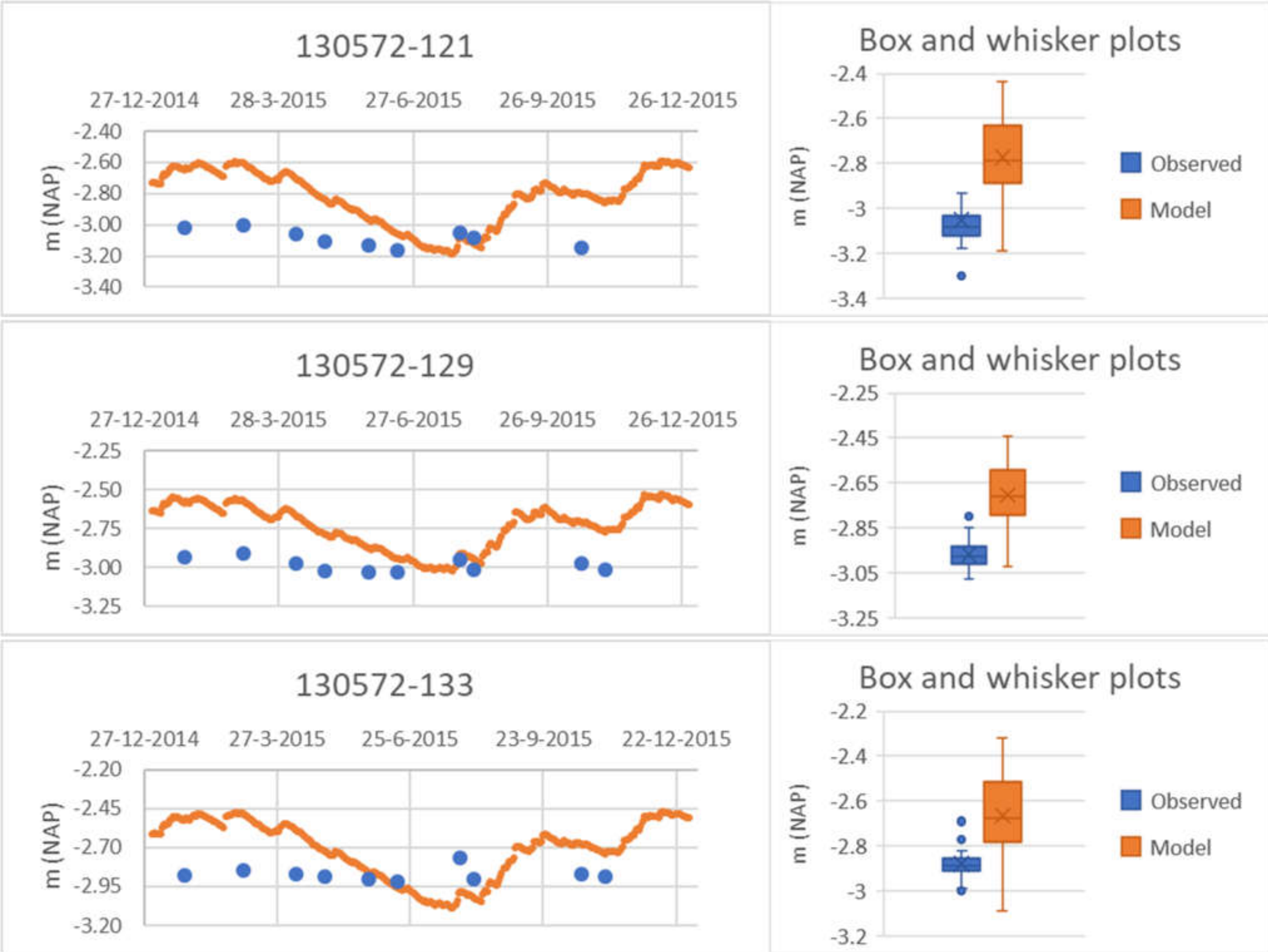



Figure 27 Monitoring wells 121, 129 and 133 with timeseries for 2015 and box and whisker plot.

Monitoring wells 130572-121 (Oude Raadhuislaan), 130572-129 (Nieuwe Kerkstraat) and 130572-133 (Kerstant van den Bergelaan) are situated in the side streets to the west of the infiltration drain in Adriaen van der Doeslaan. Figure 27 shows the graphs and box and whisker plots for these monitoring wells. The dynamics of these timeseries are similar. The model is much more sensitive to changes in recharge than the observations show there is. The model overestimates the phreatic groundwater head in spring, autumn and winter and is at the same level as the observed timeseries only during summer (except for monitoring well 133, where the model overestimates the drawdown). Despite the differences in model timeseries and observed timeseries the dynamics are recognizable to a small degree. The precipitation event near the end of July is present in all timeseries.

**The observed timeseries for the western area typically show limited dynamics. The mean groundwater head is about -3m NAP. The model generally features a mean of about -2.7 to -2.8m NAP, but stronger dynamics. The model dynamics do match the dynamics of the observed series, however the model overestimates the dynamics. The model and the observations seem to match the most during dry periods.**

## 4.5 Discussion and conclusion

The transient model time series deviate from the observed time series quite a bit throughout Oud-Hillegersberg. The subdivision in three parts helps to understand the differences better. The model performs well with regards to the areas in direct contact with the infiltration drain, both in regards to the mean values and the dynamics. The model also performs reasonably well for the 'western' area, towards Schiebroek. Dynamics are recognizable, but the mean observed values are lower. The area on and near the fluvial dune is the hardest to gauge. Model dynamics resemble the observations for the monitoring wells in Oude Raadhuislaan and Willem Nagellaan. The values are quite off for Oude Raadhuislaan, Nieuwe Kerkstraat and K. v.d. Bergelaan. The model time series of the latter two locations resemble the observed time series the least. On the other hand the model timeseries for Willem Nagellaan match the observed ones really well.

The strongest deviations in the model are thus shown in the dune area, notably in K. v.d. Bergelaan and Nieuwe Kerkstraat. Due to the difficulties to model the fluvial dune really well in the model, it is unsurprising that timeseries from these locations deviate the most.

# 5 Results

In this chapter the results of the research are described. The first paragraph introduces the average rise of the groundwater table. Understanding the average rise of the groundwater table induced by the infiltration drains helps to understand the groundwater rise during 2015. The focus of the second paragraph is the rise of the groundwater table modelled for the summer of 2015. The next paragraph evaluates the effectiveness of the infiltration drains to raise the groundwater table in the side streets. In the fourth paragraph the robustness of the groundwater system is further examined by evaluating the effects of the drought of 2018. The chapter ends with a discussion and conclusion.

## 5.1 Average rise of the groundwater table

This paragraph serves as an introduction to the results described in the subsequent paragraphs. The average groundwater rise is taken from the outcomes of the steady-state model with infiltration drains and the steady-state model without infiltration drains. The result is shown in Figure 28.

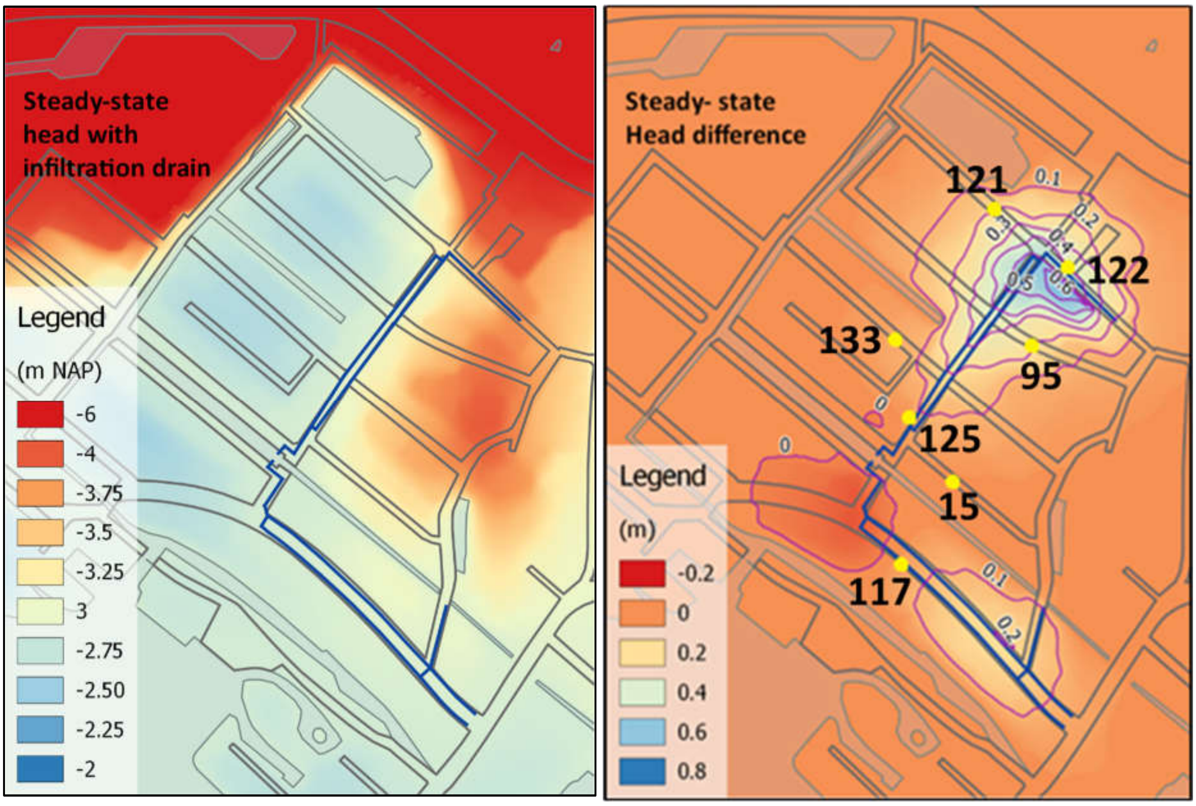



Figure 28 Steady-state head result for the situation with infiltration drain on the left and the steady-state head difference on the right.

As the figure on the left shows the groundwater head throughout the western and southern part of the area of interest is in the range of -2.5 to -3.00m NAP. In the area with the fluvial dune the groundwater head is significantly lower, ranging from -3.25 to about -4m NAP.

Comparing the two steady-state models, the strongest increase in groundwater head is near the crossing of A. v.d. Doeslaan and Oude Raadhuislaan, with an head increase of up to 0.6m. Groundwater head is raised along the infiltration drains and also flowing into the side streets, especially near the aforementioned crossing. The vertical flow resistance to the aquifer is low in this area, so the infiltration drains increase the groundwater head substantially. An increase of up to 0.2m is shown for Berglustlaan and Bergluststraat. The results also show a decrease of groundwater head in the western part of Berglustlaan and next to the inlets of the infiltration drains. The decrease is mostly about a decimetre. The Rotterdam Municipality (2013) noticed the draining effect of the infiltration drains in Oud-Hillegersberg in wet periods and Deltares, Wareco and Fugro (2017) also conclude that infiltration drains effectively reduce groundwater dynamics based on a series of case studies.

**The modelled average groundwater head increase is present along most of the infiltration drains, but especially near the crossing of A. v.d. Doeslaan and Oude Raadhuislaan. The rise of the groundwater head is the strongest in areas where the vertical flow resistance is low. Small decrease in groundwater head are observed in the western part of Berglustlaan and near the infiltration drain inlets.**

## 5.2 Groundwater dynamics during the summer of 2015

The summer of 2015 featured a long period of limited recharge, resulting in a decline of the groundwater table. With these circumstances the effect of the infiltration drains can be evaluated.

Figure 29 shows the head differences for 14 May and 14 July 2015. The difference is made up of the difference between the results for the transient model with infiltration drain and the transient model without infiltration drain. The figure for 14 May shows the state of the groundwater head before the summer and the figure for 14 July shows the groundwater head at its lowest during the 2015 summer. A complete biweekly series of the head differences from 14 May to 28 August can be viewed in Appendix A: Progress of groundwater drawdown.

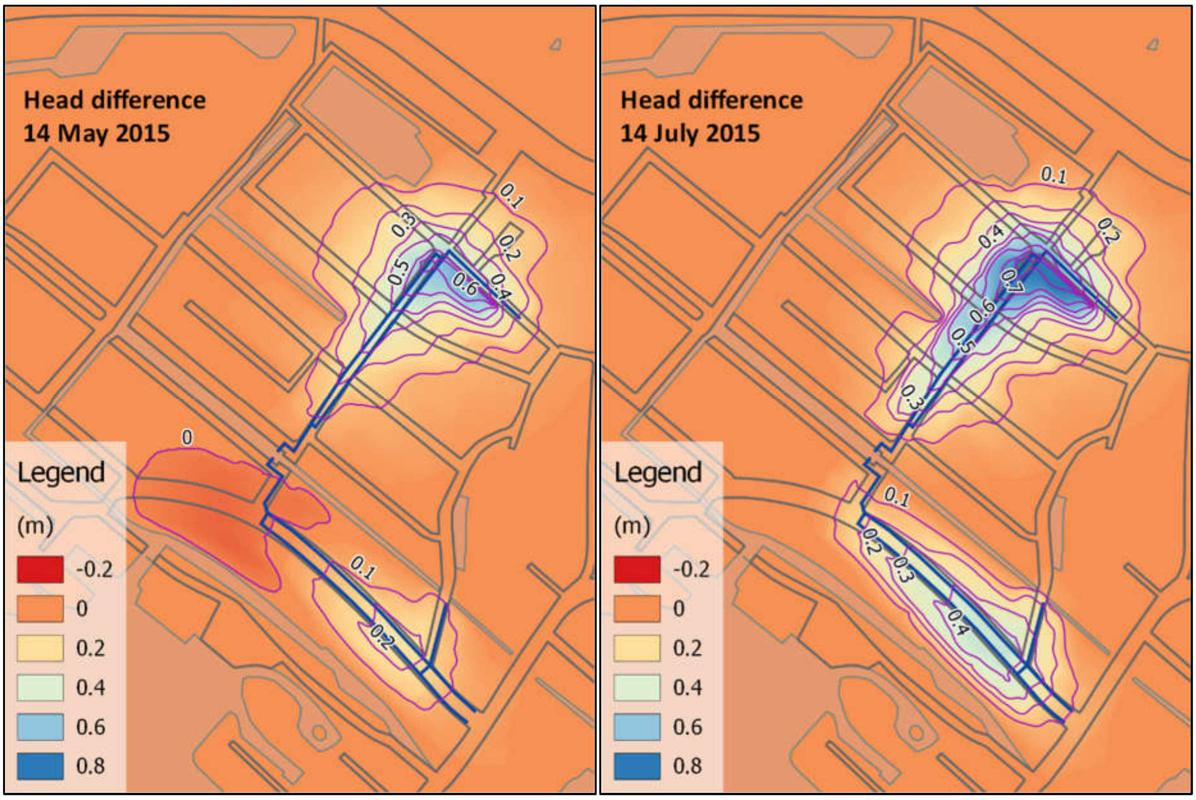



Figure 29 Head differences for 14 May and 14 July 2015

The head differences for 14 May and 14 July show a similar pattern compare to the steady-state head difference presented in the previous paragraph. Groundwater head rise is the strongest near the crossing A. v.d. Doeslaan and Oude Raadhuislaan and also the eastern and middle part of Berglustlaaan show an increase of the groundwater head. The result for 14 May also shows a decrease in groundwater head for the western part of Berglustlaan, just like the outcome for the steady-state models. For the situation in July this area features an increase of the groundwater head difference. In other words; now the infiltration drains do not drain the groundwater but instead water infiltrates in this area. The results for July also show a strong increase of the groundwater difference for the middle and eastern part of Berglustlaan of up to 0.4m groundwater rise. For the infiltration drain near the crossing Doeslaan and Oude Raadhuislaan the difference nears 0.8m.

Three examples will be used that show the drop of the groundwater head during the summer of 2015. These examples are locations along the infiltration drains, named after the respective monitoring well located at that location. Each example shows the outcomes for both transient models for the course of 2015.

**Figure 30 2015 Timeseries for both transient models for location 130572-125**

Figure 30 shows the timeseries of both transient models for 2015. The location is in A. v.d. Doeslaan near the infiltration drain. The figure shows that the groundwater head is much more stable with the infiltration drain in place. During the summer of 2015 the head drops by about a decimetre, however this drop is quickly recovered in the autumn. If the infiltration drains had not been there in the summer of 2015, the drop in groundwater head could be over 30cm according to the model. During the winter season the infiltration drain drains this area as the outcome for the transient model with infiltration drain shows lower heads in that period than the other transient model.


Figure 31 2015 Timeseries for both transient models for location 130572-122

Figure 31 shows the timeseries for the location 130572-122. This location is located in Oude Raadhuislaan, some 20 meters from the crossing with A. v.d. Doeslaan. During the summer of 2015 the groundwater head decreases to nearly -3.6m NAP. The dynamics in this area are much stronger than in the area of location 130572-125. This is likely due to being located on the fluvial dune. The timeseries for the model without infiltration drain show even stronger dynamics and are 60-80cm lower than in the model with infiltration drain. It can reasonably be expected that the infiltration drain is effective in raising the groundwater in this location.


Figure 32 2015 Timeseries for both transient models for location 130572-117

The third example is 130572-117, located in Berglustlaan. Figure 32 shows the timeseries for both transient models. The results for the model with infiltration drain show weaker dynamics compared to the model without infiltration drain. During the 2015 summer the groundwater head decreased to -3m NAP according to the model, compared to nearly -3.3m NAP for the model without infiltration drain. During the winter period the model with infiltration drain shows lower heads compared to the other model, indicating that the infiltration drain might drain groundwater when groundwater heads are high.

The results for transient models for the summer of 2015 show that the pattern for the drawdown of the groundwater head are similar to the pattern for the steady-state models. The infiltration drains effectively decrease the drawdown along the infiltration drains by a few decimetre as the first example (A. v.d. Doeslaan) and third example (Berglustlaan) show. A precipitation event in late July shows a rapid increase of the groundwater head of about a decimetre for these locations. In the area of the infiltration drain in Oude Raadhuislaan the groundwater head is still rather susceptible to changes. The dynamics are slightly smaller than in the situation without the infiltration drain. This area is located on the dune, so it is not surprising to see stronger dynamics in this area. The results also show that the infiltration drain is effective in raising the average groundwater head, so the extent to which wooden pile foundations are exposed to rot has decreased year round.

**The difference between the outcomes of the two transient models show the effectiveness of the infiltration drains through the rise of the groundwater head. During the summer of 2015 the groundwater head still lowered throughout Oud-Hillegersberg, however the results show that the amount of drawdown has decreased. Groundwater dynamics in most areas along the infiltration drains have stabilised, resulting in less drawdown during dry periods and less groundwater rise during wet periods. For the area fed by the infiltration drain located on the dune the groundwater dynamics have not changed as much as in the other areas. However the average groundwater head has risen steadily compared to a situation without infiltration drain.**

## 5.3 Rise of the groundwater table in the side streets

In the previous paragraph the effectiveness of the infiltration drain was evaluated locations along the infiltration drain itself. This paragraph concerns the groundwater rise in the side streets of the streets where the  infiltration drains are located. The goal is to determine up to how far the infiltration drains raise the groundwater head. The paved areas and streets perpendicular to the streets with infiltration drains are presumably the main distributors of groundwater to the surrounding built up areas and yards. As such it is expected that the groundwater distribution is like a 'tongue' into the side streets, due to the sandy layout of the street soils. The groundwater rise is evaluated for the average situation, a wet period and a dry period. The results for the steady-state models and the transient models for 2015 is used to determine the effects.

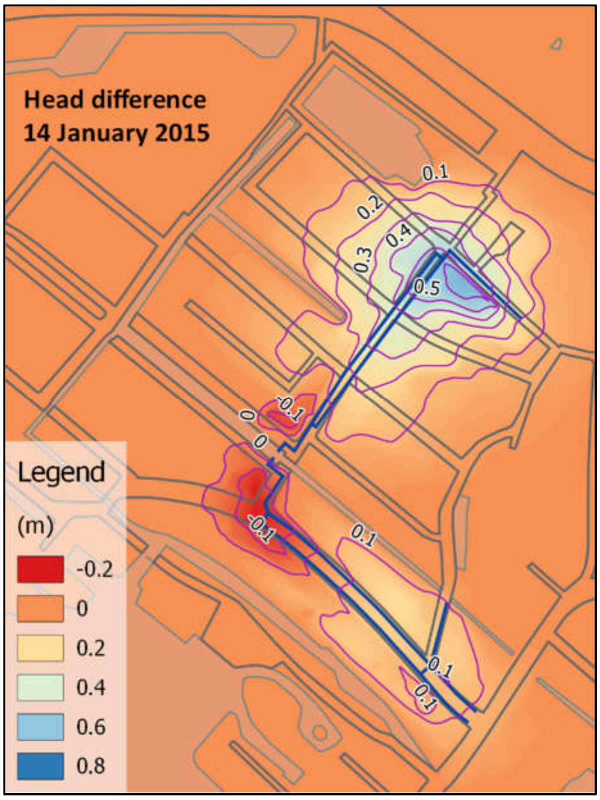



Figure 33 Head difference 14 January 2015

Figure 28 and Figure 29 show the outcomes for the steady-state simulations and the head differences for 14 May 2015 and 14 July 2015 respectively. Figure 33 shows the head difference for 14 January 2015. The figure for 14 January shows the same familiar pattern as the steady-state difference shows, with some minor differences. The groundwater head in the western part of Berglustlaan and around the infiltration drains' inlets has lowered compared to the situation without infiltration drain. Also the groundwater head in K. v.d. Bergelaan, west of the infiltration drain in A. v.d. Doeslaan, is more effected by the infiltration drain for both 14 January and 14 July compared to the steady-state difference.

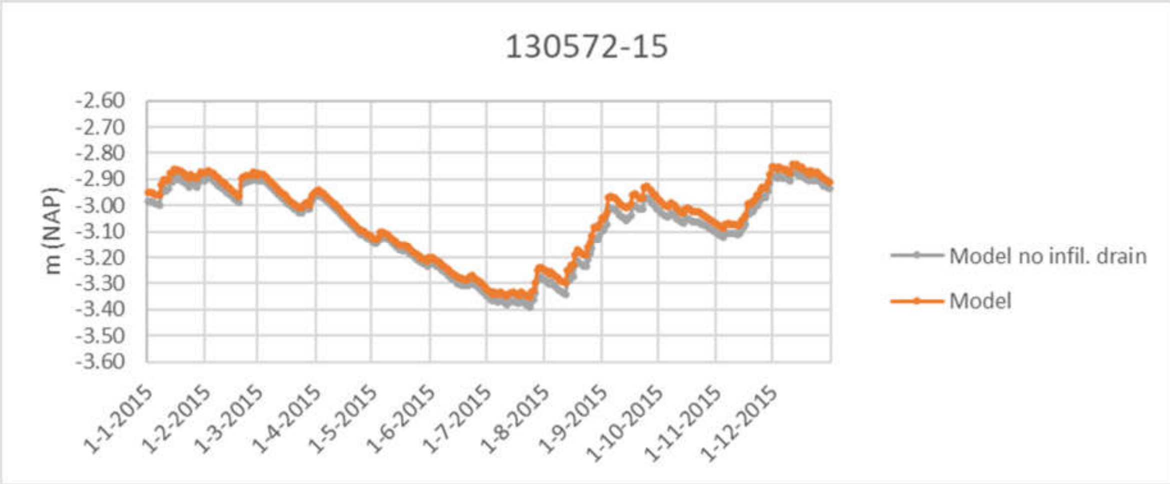



Figure 34 2015 Timeseries for both transient models for location 130572-15

With the steady-state, 14 January, 14 May and 14 July situations in mind four locations in the side streets of A. v.d. Doeslaan are examined in further detail. Figure 34 shows the 2015 timeseries for location 130572-15 which is located in Willem Nagellaan. The model results show that the entire dynamics are up to 0.5m throughout the year. The differences between the model with infiltration drain and without infiltration drain are almost negligible. This was to be expected with the figures for the steady-state and transient simulations in mind. It is not unlikely that the groundwater head in this location is unable to rise steadily due to the infiltration drain draining the area around the inlets and in the nearby areas of the A. v.d. Doeslaan.

The timeseries for location 130572-133 in K. v.d. Bergelaan are shown in figure 35. The pattern is similar to the pattern for the location in Willem Nagellaan, however the differences are larger in wet periods. During the spring months into the summer the difference in groundwater head between both models is negligible. However this changes in wet periods like January and February and especially Autumn when the groundwater head rises steadily. In these periods the groundwater head has increased by 0.1m due to the infiltration drain.


Figure 35 2015 Timeseries for both transient models for location 130572-133

Figure 36 shows the timeseries for location 130572-95 in Nieuwe Kerkstraat, east of the infiltration drain. This area is located on the dune, which the timeseries for the transient model without infiltration drain show. The modelled effects of the infiltration drain show a decrease of the dynamics from 0.6m to 0.45m. The groundwater head steadily decreases during spring and early summer and rapidly rises during late summer and autumn. The strong dynamics are the result of the sandy subsoil and the adjacency to the fluvial dune. Compared to the model without infiltration drains the groundwater head has risen by 0.2-0.3m which helps in covering the wooden pile foundations year round.

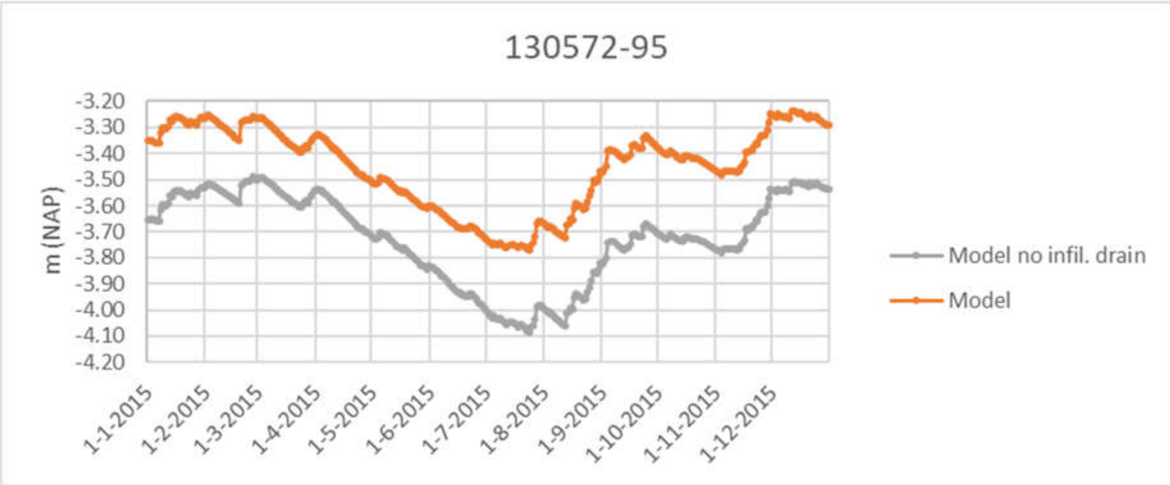



**Figure 36 2015 Timeseries for both transient models for location 130572-95**

The last example is a location in Oude Raadhuislaan, west of the infiltration drain in A. v.d. Doeslaan. The timeseries for this location are shown in figure 37. The dynamics for this area are strong with a difference of about 0.6m between the minimum and maximum value in 2015. The dynamics are quite strong with a steady decline of the groundwater head throughout spring and summer and a strong rise in late summer and autumn. On the whole the presumed average groundwater rise is about 0.2m year round.


**Figure 37 2015 Timeseries for both transient models for location 130572-121**

The timeseries for locations in side streets of A. v.d. Doeslaan show limited to strong dynamics. The groundwater head drops steadily during spring and summer and raises rapidly during late summer and autumn. The difference between the model with infiltration drain and without infiltration drain is limited and depends on the location. Locations further from the inlet tend to feature a larger average increase of groundwater head. It was expected that the groundwater would be distributed like ‘tongues’ into the side streets. Consulting figure 28, figure 29 and figure 33 this assumption is not confirmed. The figures do not show clear ‘tongues’ since the groundwater rise does not only take place in the streets themselves, but also in the built up area and gardens in the side streets. The groundwater head in the side streets themselves still rises more than in the adjacent built up area, but not enough to speak of ‘tongues’.

Near the intersection of Oude Raadhuislaan and A. v.d. Doeslaan the head increases a lot locally, up to 0.6m for the steady-state models and up to 0.8m during summer. Due to the infiltration drain in A. v.d. Doeslaan is the groundwater head has risen by 0.1m up to 90m away in the western parts of Oude Raadhuislaan and Nieuwe Kerkstraat and up to 70m in the eastern part of Nieuwe Kerkstraat. The 0.2m contour line follows up to a distance of 40-50m from the infiltration drain. This is similar for both situations.

**The groundwater head increases notably in the northern part of A. v.d. Doeslaan and its side streets, in the mean situation as well as during the summer and during a wet period. In the steady-state situation, 2015 summer and January 2015 the groundwater head up to 90 meters into the side streets rises by 0.1m. The groundwater rise is not limited to the streets, but also spreads to the adjacent built up area. It is likely that wooden pile foundations profit from the increase groundwater rise. Near A. v.d. Doesbrug the groundwater rise is limited due to the infiltration drain draining the local area. The groundwater head in the side streets in that region is negligible.**

## 5.4 Stresstest light Oud-Hillegersberg: Drought of 2018

A Stesstest light, as initiated by the Delta Programme Spatial Adaptation, is partly conducted for Oud-Hillegersberg. The focus is the effects of drought on the Oud-Hillegersberg groundwater system. The current extremes are examined to estimate the climate robustness of the groundwater system. Urban areas like Oud-Hillegersberg are highly heterogeneous in soil types and have a varying permeability of the surface, which makes it hard to estimate the effects of climate change. By analysing the robustness of urban areas to the current extremes, the future robustness can be estimated.

To examine the robustness to drought the summer of 2018 is examined, which has a return period of once every 30 years according to the KNMI (2018a). The summer of 2018 ranks third in the KNMI list of summers with the least amount of precipitation (KNMI, 2019).

The growing season in 2018 featured an extended period of drought. The Stresstest Light follows the KNMI’s approach of estimating the level of drought through the computation of the potential precipitation deficit. The potential precipitation deficit is computed by subtracting the potential reference evaporation from the precipitation, adding up the potential precipitation deficit of the previous day whenever that figure is positive (KNMI, 2018a). Equation 1 shows the computation in a mathematical manner. The precipitation deficit is computed for the entire growing season: April up to and including September.

$$P_{pot.def}(t) = \begin{cases} P_{pot.def}(t-1) - P(t) + E_{pot}(t) & for\ P_{pot.def}(t-1) \geq 0 \\ 0 - P(t) + E_{pot}(t) & for\ P_{pot.def}(t-1) < 0 \end{cases}$$

Equation 1 KNMI computation of the potential precipitation deficit.

The resulting potential precipitation deficit for 2018 averaged over 13 weather stations, shown in figure 38, in black. The red line shows the potential precipitation deficit in the year 1976, which still holds the record for driest year. The blue line represents the potential precipitation deficit of the median year, and the green line represents the 5% driest years. The series for 2018 follows a similar pattern as the series for 1976, except for the precipitation events in early May 2018, which do decrease the potential precipitation deficit significantly.

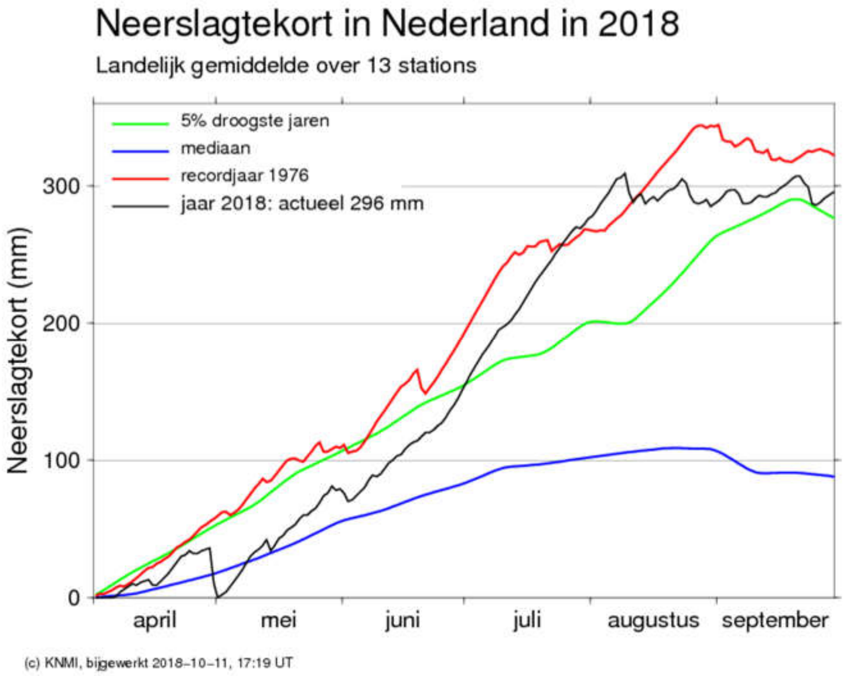



**Figure 38 Potential precipitation deficit averaged for 13 weather stations. 2018 in black.** (KNMI, 2018b)

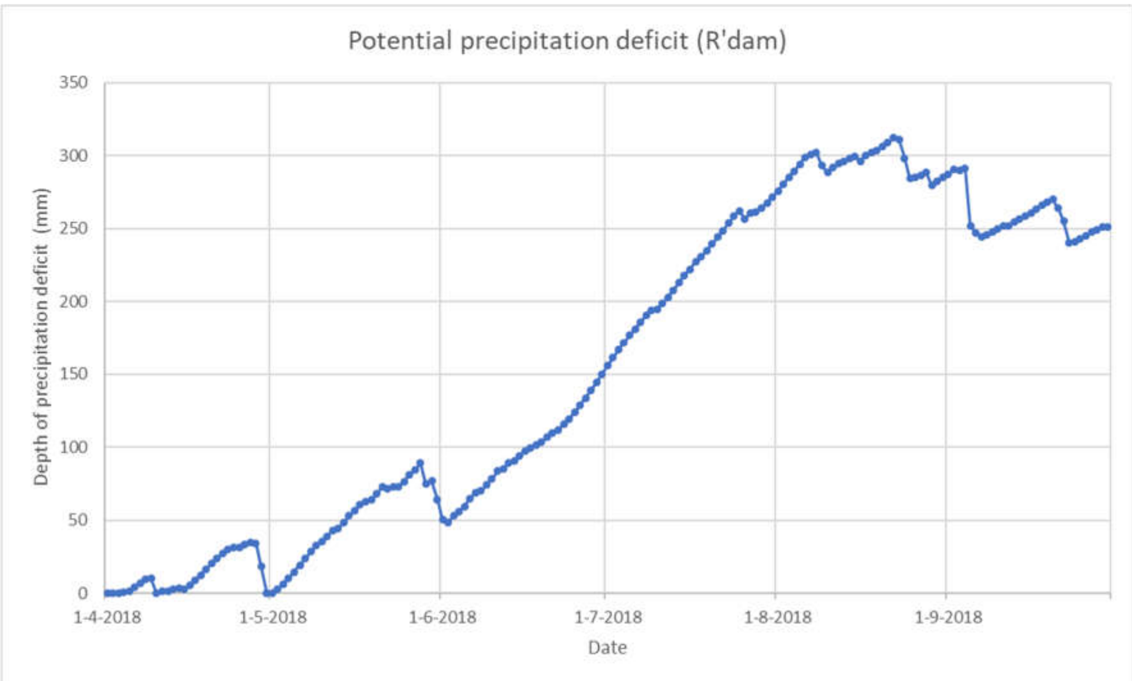



**Figure 39 2018 Potential precipitation deficit for weather station Rotterdam.**

Figure 39 shows the potential precipitation deficit computed for weather station Rotterdam, which is not included in the computation of the KNMI (2018a). The progress of the precipitation deficit is quite similar for Rotterdam and the averaged series. The deficit is at its largest in August, for the

KNMI graph early August, and for Rotterdam in the second half of August. By September precipitation events in Rotterdam result in a decrease of the deficit.

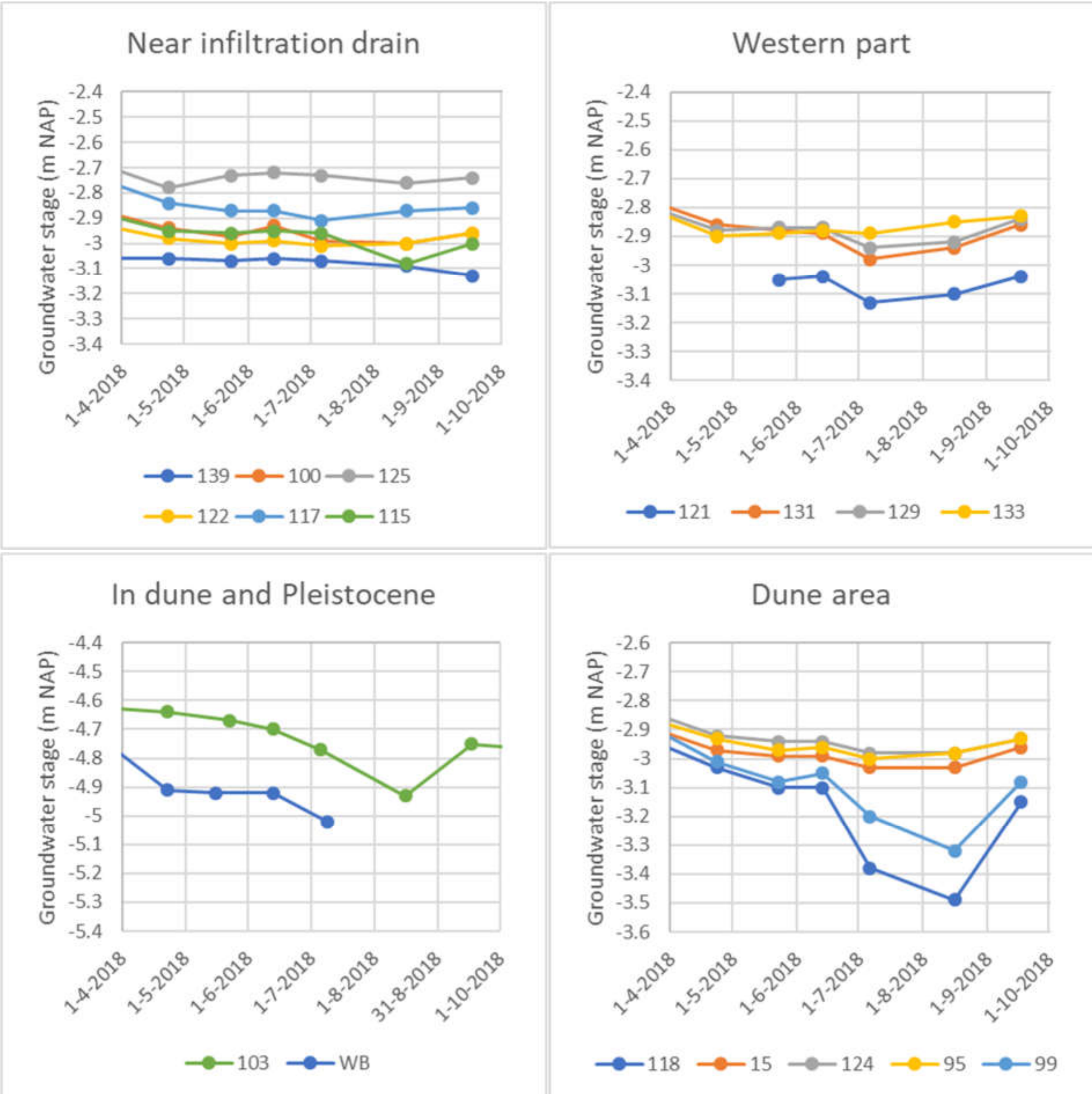



Figure 40 Groundwater timeseries growing season 2018.

The four graphs in figure 40 show the timeseries from monitoring wells in Oud-Hillegersberg during the growing season of 2018. The monitoring wells are maintained by the Rotterdam Municipality. Figure 41 shows the location of the monitoring wells. Each graph roughly represents the area where the monitoring wells are located.

The groundwater drawdown due to the drought in the area near the infiltration drains is limited, with only monitoring well 115 (located in Berglustlaan) showing a noticeable decrease of groundwater stage by 10-20cm. In the western part of Oud-Hillegersberg the drawdown is about 10-20cm, except for monitoring well 133 which seems unaffected by the drought. Drawdown in the dune area is about 10cm for monitoring wells 15, 95 and 124, while the drawdown for wells 99 and 118 is a substantial 40-50cm. Monitoring well 103 is located in the top of the dune and shows a drawdown of 30cm. Monitoring well WB is a monitoring well in Weissenbruchlaan, measuring groundwater in the Pleistocene aquifer. Compared to the groundwater head in the dune the head is 20-30cm lower in the Pleistocene. The drawdown in the dune follows a similar pattern as the drawdown in the aquifer, decreasing throughout the summer.

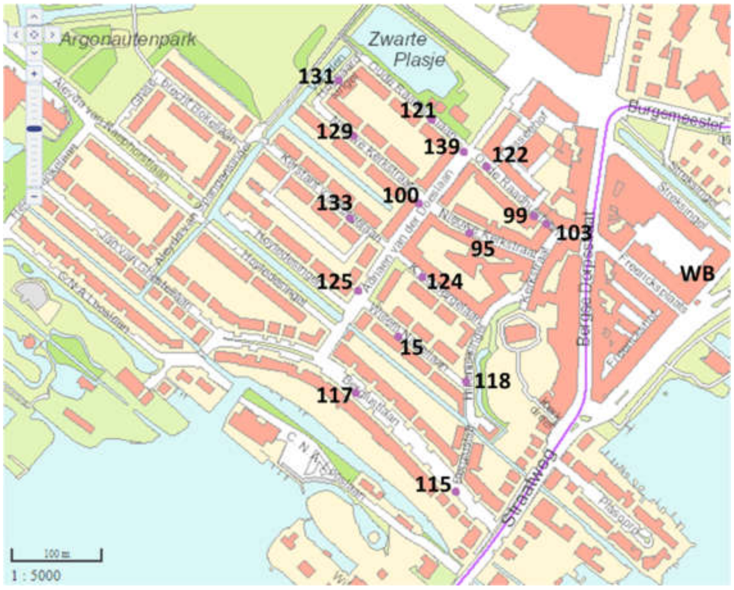



Figure 41 Location of the monitoring wells.

The results for the summer of 2018 show the sensitivity of the groundwater system to the drought. In the surroundings of the infiltration drains the drawdown is very small. In the western part of Oud-Hillegersberg groundwater stage drop temporarily by a decimetre. The groundwater timeseries for monitoring wells in the western part of the dune show a temporary drop of about a decimetre, while the monitoring wells in the eastern part of the dune (118 and 99) show a significant drop of groundwater stage. The monitoring wells in the western part of the dune are still within reach of the infiltration drain, what might explain why the groundwater levels did not fall substantially in these areas. The groundwater head in the dune (monitoring well 103) shows a gradual decline. This lowering of the groundwater stage in the dune is likely to affect the area atop of it: the area in which monitoring wells 99 and 118 are located. The head in the dune is driven by the head in the Pleistocene. With the head in the Pleistocene aquifer decreasing, the head in the dune decreases, in turn resulting in a lower phreatic groundwater head in the dune area.

The changes in these areas are the strongest and need careful monitoring, especially the eastern part of the dune during dry periods. The areas around the infiltration drains benefit hugely from the presence of the infiltration drains, which reduce the drawdown in dry periods and drain surplus groundwater in wet periods. With prolonged dry situations and wet situations becoming more common with climate change, attention should be shifted to the dune area, taking local measures to reduce the groundwater dynamics to an acceptable level.

**The 2018 drought is examined to estimate the robustness of the Oud-Hillegersberg groundwater system to climate change. The summer of 2018 featured a potential precipitation deficit of over 300mm. Groundwater stages dropped by a decimetre in various places, but by 40-50 centimetres in the dune area. The groundwater in the dune area, notably the eastern part near the church, shows a much stronger drawdown than other parts of Oud-Hillegersberg. This area requires attention if further artificial changes to the groundwater system are attempted. The areas around the infiltration drains have limited dynamics, which show that the infiltration drains work as intended.**

## 5.5 Discussion and conclusion

The transient models for the summer of 2015 show the increase of the drawdown, starting in spring and continuing until early August, when the groundwater heads start rising again. The transient model with the infiltration drain shows that the infiltration drains help in maintaining the groundwater head in the northern part of A. v.d. Doeslaan and its surroundings and in Berglustlaan. Both models show a substantial amount of drawdown in the dune area.

Due to the infiltration drain in the A. v.d. Doeslaan the groundwater head in the side streets is also raised. According to the model results the groundwater is raised by 0.1m up to 90m away from the infiltration drain in the steady-state scenario and the summer of 2015 scenario. This does show that the infiltration drains are able raise the groundwater head quite well in the side streets. However it should be noted that the models overestimate the dynamics of the groundwater system, so especially near the infiltration drain itself it is unlikely that the groundwater head would rise by over half a meter. It also seems to be that the groundwater head in the side streets near the inlet of the infiltration drains does not rise substantially, due to infiltration drains locally draining the area.

The analysis of the 2018 drought shows that the reaction is the strongest in the dune area, especially the eastern part. In this area the dynamics are the strongest due to the high permeability of the soil and due to the phreatic groundwater being more affected by groundwater in the dune and in the Pleistocene. The analysis of the 2018 drought shows similar results to the model outcomes for 2015. The dune area is more susceptible to dry periods compared to the other parts of Oud-Hillegersberg. This area will need extra attention in the future, with droughts becoming more frequent with climate change.

Near the infiltration drains the effects of dry or wet periods are limited; as such it can be concluded that the infiltration drains do work well. In dry periods the groundwater head does not lower by much, most likely due to the high level of paved area in Oud-Hillegersberg compared to the amount of vegetation. If vegetation had been abundant, more groundwater could have evaporated. While it is likely that the unsaturated zone has lost a lot of its moist, the groundwater heads are mostly unaffected.

# 6 General discussion and conclusions

At the end of the research the balance is drawn up and conclusions are made. The first paragraph in this chapter discusses the research. The second paragraph contains the conclusions made during the research.

## 6.1 Discussion

The hardest part of the research was to get the model right. A model does not exactly represent reality, however it is the aim to strive for an accurate model, so the conclusions drawn from the results are applicable to reality. With accuracy of the model comes scale, good model building and a good representation of the input data in the model. The topic of the research comprises a phreatic groundwater problem in an urban neighbourhood. The area studied is less than half of a square kilometre and features some complexity with regards to the soil. The complexities of the soil are the locality of the fluvial dune and the heterogeneity of the anthropogenic layer. The contours of the fluvial dune are not exactly clear and have been estimated as best as possible. The model can be improved on by adjusting the contours of the dune and by adjusting the permeability of the soil. However additional field data is needed to improve the model, especially data on the composition and properties of the soil in the anthropogenic layer.

The model shows strong dynamics and is very responsive to precipitation. Due to the way recharge is included in the model, as the combination of effective precipitation minus the effective evaporation, the responsiveness is strong. There is no computation of processes in the unsaturated zone, so the recharge is directly put into the equation. As such the model reacts strongly to precipitation events and evaporation. Negative recharge quickly results in drawdown because the groundwater in the model can be lost through evaporation as well as a general downward flux. The groundwater timeseries from the monitoring wells do not show this strong reaction to changes. The groundwater recharge is slower than assumed in the model. Considering evaporation: groundwater is not easily evaporated. After the moisture in the unsaturated zone has evaporated it is the question if the matrix potential is enough to evaporate substantial amounts of groundwater. With sparse amounts of vegetation in the area the evaporation is limited. A ratio for precipitation lost to the sewerage system is used in computation of the recharge, however this figure does not take into consideration whether the rainfall was intense or whether it was accumulated over a prolonged period. Hence the model overestimates the amount of effective rainfall. This might explain why the model results in the western part of Oud-Hillegersberg are generally higher than in the observed timeseries.

If the model used for this study should be expanded two main factors should be considered. In the first place the computation of processes in the unsaturated zone should be considered for use in the model. The focus of the model is the phreatic groundwater, so including a computation of processes in the unsaturated zone seems valid. The downsides are the time needed to implement the packages needed for the unsaturated zone computations and the data needed for those packages. The model will also take significantly longer to run with more equations to solve for each timestep. In the second place the location and permeability of the fluvial dune and the permeability and distribution of the soil in the anthropogenic layer could be considered. Additional field data is needed to improve these parameters.

Developing a phreatic groundwater model for an urban area of half a square kilometre with a transient component proved to be ambitious. Research like this and on this scale is uncommon but offers opportunities to better understand groundwater flow in urban areas. Heterogeneity of the soil is common in urban areas and is also difficult to model well. With limited data available on the distribution of the soil types in the anthropogenic layer, linking the soil properties to the land use offers a simple and decent method to model the soil in the anthropogenic layer. Even when the model results do not accurately approximate the observed timeseries, computing the difference for a situation with active groundwater management and without shows the benefit of a certain measurement taken. Developing a transient groundwater model for an urban area has the benefit of showing the drawdown in dry periods and the length of the periods. This is especially helpful in determining the amount of time the wooden pile foundations are dry throughout the year.

**The research conducted was ambitious with the goals to develop a transient phreatic groundwater model. The soil in this urban environment proves to be highly heterogeneous and the presence of the fluvial dune adds to the complexity. If the model is to be expanded an inclusion of processes in the unsaturated zone and an update of the contours of the fluvial dune and soil permeability is recommended. However both factors require additional field data and a considerable amount of time to be included properly. As the current model shows computing the difference in a situation with active groundwater management and a situation without shows a lot of information even when the model results do not equal the observations.**

## 6.2 Conclusions

The topic of this study is the effectiveness of the infiltration drains in Adriaen van der Doeslaan and Berglustlaan in Oud-Hillegersberg. The main elements are the effectiveness of the infiltration drains during the summer of 2015, the groundwater rise in the side streets of A. v.d. Doeslaan and the robustness of the groundwater system to climate change. In general it can be concluded that the infiltration drains have a positive effect on the groundwater system in Oud-Hillegersberg. The groundwater head has stabilised in the streets where the infiltration drains have been laid. This is shown in the model as well as in observed timeseries. The groundwater model constructed for this study has been able to mimic the real life situation well. The model also showed that the groundwater table in the side streets does rise, by up to 0.1m up to 90 meters away from the infiltration drain, in the mean scenario as well as the summer of 2015. These results are shown in figure 42. The groundwater rise is strong in areas near the infiltration drains where the vertical flow resistance is low. This is especially the case for the A .v.d. Doeslaan near the Oude Raadhuislaan and for the eastern part of Berglustlaan.

Locally the groundwater head in the A. v.d. Doeslaan increased by over half a meter. The groundwater drawdown in the western part of Oud-Hillegersberg has decreased due to the infiltration drain in A. v.d. Doeslaan. It is hard to get a clear picture of the groundwater rise for the side streets K. v.d. Bergelaan and Nieuwe Kerkstraat to the east of the infiltration drain. The seeping effect of the fluvial dune is modelled too strong for this location, so the model results differ quite a bit from the observations. The magnitude of the groundwater rise is not clear but it is there. The groundwater rise in side streets near the inlet of the infiltration drain show less groundwater rise. This shows that the infiltration drains drain the area near the inlets.

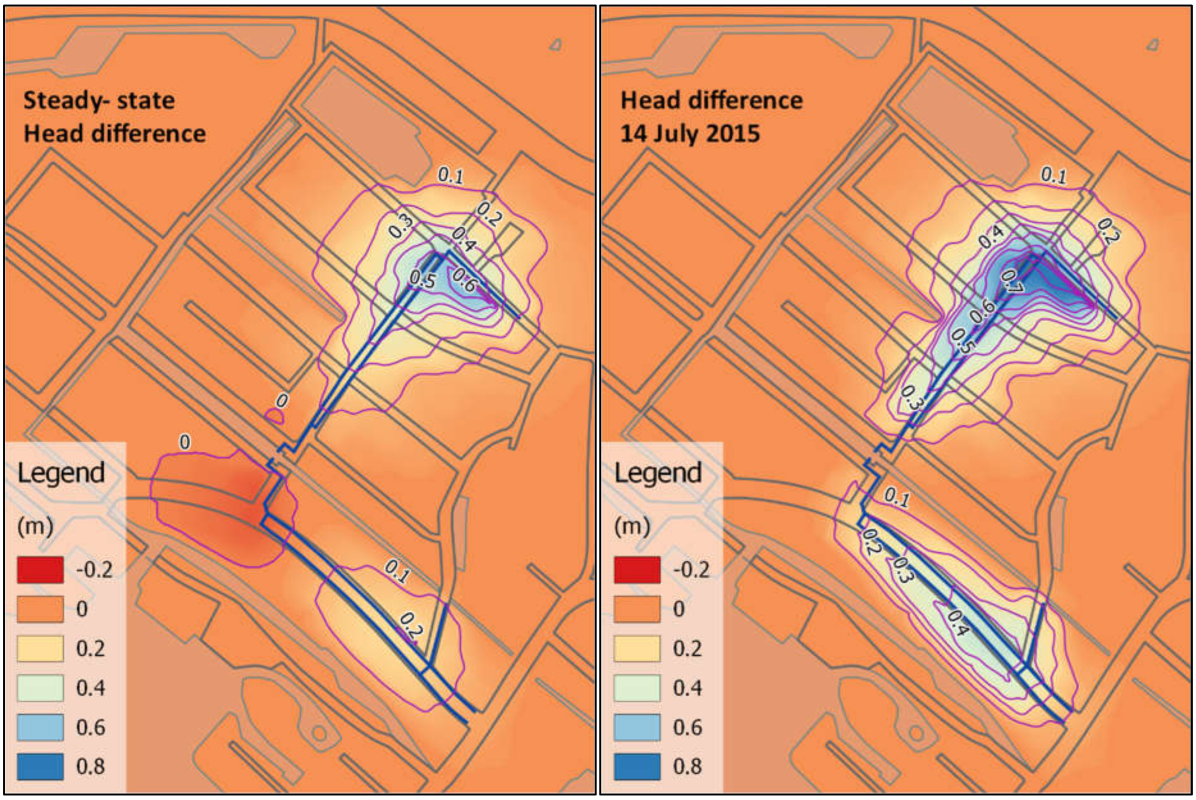



Figure 42 Steady-state head difference and head difference for 14 July 2015.

The groundwater system in Oud-Hillegersberg is well able to cope with extreme dry events. The infiltration drains aid in maintaining the groundwater table in main streets and side streets. Drawdown of the groundwater table are in the order of decimetres for the majority of Oud-Hillegersberg as the analysis for the 2018 drought shows. The groundwater head in the Pleistocene seems to be the driving factor. When this head lowers, the heads in the dune and phreatic layer lower too. Due to the dependency on the groundwater head in the Pleistocene the eastern part of the dune area requires extra attention, since the groundwater table can drop sharply.

**The infiltration drains prove to be able to stabilise the groundwater table in Oud-Hillegersberg well. Their effectiveness proves in the average situation as well as in dry situations. The groundwater system is not heavily influenced by strong droughts of wet periods, however the area in the eastern part of the fluvial dune shows stronger dynamics and requires attention.**

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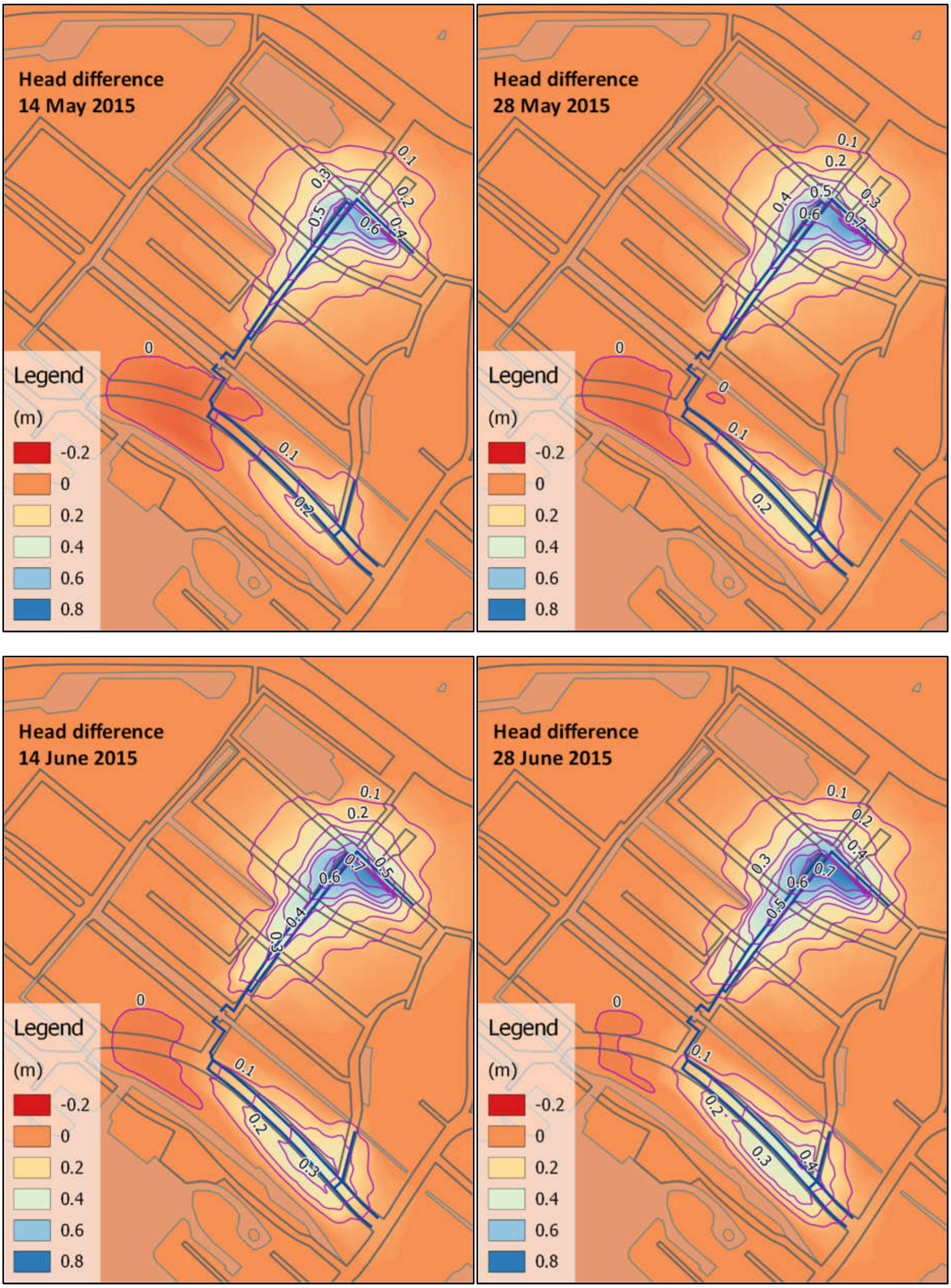
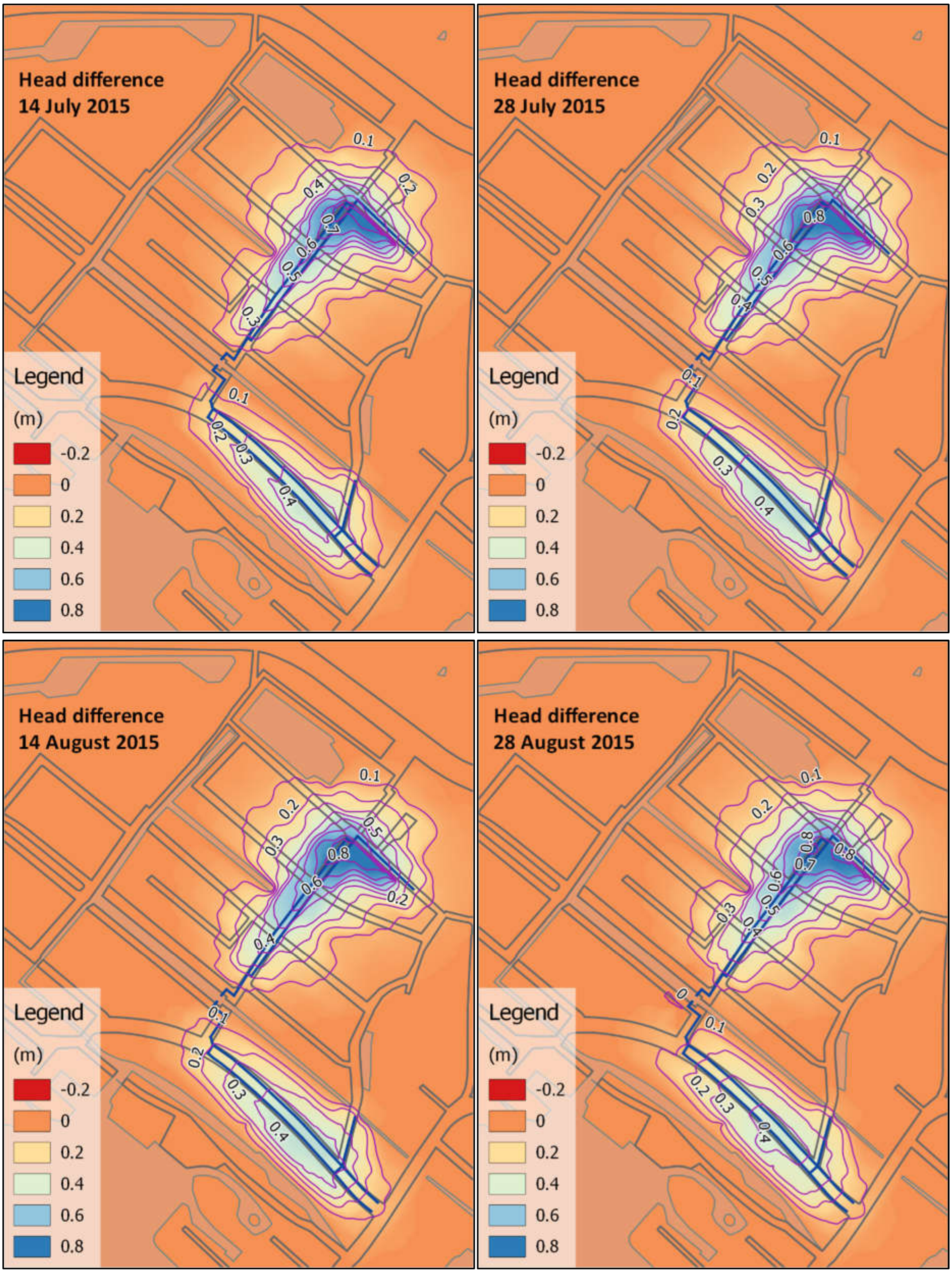
# Appendices

# Appendix A: Progress of groundwater drawdown

In this appendix the model results for the transient models are shown in maps. Each map shows the head difference for a particular date. A positive value shows the groundwater rise due to the infiltration drains. The results are biweekly, spanning from 14 May 2015 to 28 August 2015.




Head difference
14 July 2015
Legend
(m)
-0.2
0
0.2
0.4
0.6
0.8
Head difference
28 July 2015
Legend
(m)
-0.2
0
0.2
0.4
0.6
0.8
Head difference
14 August 2015
Legend
(m)
-0.2
0
0.2
0.4
0.6
0.8
Head difference
28 August 2015
Legend
(m)
-0.2
0
0.2
0.4
0.6
0.8