Application and Evaluation of the 3Di Groundwater Model in the Waalenburg Polder, Texel, the Netherlands

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Preface

This thesis is submitted as the final requirement of the degree of Master of Science. As such, it marks the end of my time as a student at the University of Twente and the start of a new period.

First, I would like to thank Martijn Booij and Denie Augustijn for the excellent supervision from the University. Their help in shaping my research by the use critical, but fair, feedback on my report and research methods have proven invaluable for executing my research and writing my report on an academic level. I greatly appreciate the time you spend in providing me with this guidance. Secondly, I would like to thank Wouter van Esse and Margot Leicher. Wouter's interest in the 3Di groundwater model has provided me with the opportunity to work on this thesis at Nelen & Schuurmans. Margot has done an excellent job in continuing the guidance of my thesis, her sharp feedback and focus on the research aim has helped me when I got caught up in day-to-day challenges.

I also render many thanks to all colleagues at Nelen & Schuurmans whom I spend time with at the office in Utrecht. They were always available to help me when I got stuck in some 3Di model error. I would like to especially extend this thanks to Nicolette Volp who has taken a great amount of time in explaining me the workings of 3Di and providing feedback on the final version of my report. Furthermore, I would like to thank the people at Hoogheemraadschap Hollands Noorderkwartier for providing me with an interesting case on a beautiful island.

Finally, I would like to thank my parents, family and friends for their support during my studies at the university and the writing of this thesis.

I hope you enjoy reading my thesis.

Daan Kling
Oss, November 2019

Summary

Hydrological models are developed in order to support the decisions and strategic plans of operational water management by governments. These models can be used to analyse, understand and explore solutions for water management. The models used by water authorities have a wide range in size and complexity. This includes, but is not limited to, hydrodynamic models and groundwater models. One of the models used is the 3Di Hydrodynamic model, a process-based, hydrodynamic model for flooding, drainage and other water management studies such as regional water distribution.

The 3Di Hydrodynamic model was recently expanded with the addition of a groundwater domain, the 3Di groundwater model. This research focuses on the evaluation of the 3Di groundwater model for a polder area on its accuracy and its sensitivity for changes in time-independent model parameters and model design choices.

This is done by the creation of a model for the Waalenburg polder on the island of Texel, the Netherlands. This model is based on a highly detailed elevation model and information on from data models of the water system including, locations and depths of channels and heights of weirs for the surface water domain. By the use of the REGIS II model, a schematisation of the phreatic aquifer is included for the groundwater domain.

A sensitivity analysis was done for the time-independent model parameters, hydraulic conductivity and storativity. This analysis showed that the mean of the simulated groundwater levels is most sensitive for changes in its hydraulic conductivity, increasing values of hydraulic conductivity cause lower mean groundwater levels. The standard deviation in simulated groundwater levels was shown to be sensitive for the storativity of the ground. The same volume of water can create a bigger change in groundwater levels for grounds with lower storativity. This sensitivity analysis was used to calibrate the model for its hydraulic conductivity and storativity. The calibrated model is further evaluated on its accuracy. The simulated model results correlate well compared to the measured groundwater levels, little deviation is shown in the mean results of the model and measurements, and the variability of the model results is in accordance with the measurements. The model performance for computing groundwater levels provides confidence in the ability of the model to simulate the groundwater flows, especially so for the winter period.

The effects of design choices in temporal resolution of precipitation time series input, surface water level boundary conditions and the model grid have been investigated. The calibrated model gives good results using daily time series for precipitation and evapotranspiration. It was shown that refining the resolution of the precipitation time series to 5 minutes did not affect the results in a significant way.

Boundary conditions along the model edges that are not in direct connection with ditches along modelled areas do not have a significant impact on groundwater levels within the area. They do however have an impact on the discharges through ditches in the surface water domain.

It was shown that a well-performing model could be created using a grid of 20 m by 20 m for the majority of the area of interest. The grid size is mostly dictated by the surface water system as a calculation cell cannot include multiple surface water levels. It was shown that grid size does affect the groundwater levels. A finer grid may lead to an increase in groundwater levels of up to 30 cm. Due to this fact, changes in grid size may lead to the need for re-calibration of the model.

It can be concluded that with the 3Di groundwater model it is possible to simulate groundwater levels within a polder with good accuracy, especially for winter periods. The mod-

elled mean groundwater level is sensitive for the hydraulic conductivity and the modelled variability in groundwater levels is sensitive to the storativity. These sensitivities can be used to calibrate a model of a particular area.

The model design is adequate for the simulation of groundwater levels during wet periods. The current state of the 3Di groundwater model may lack the ability to simulate the groundwater recharge of high precipitation events after a dry period as depicted by the overestimation of in the period July 2017 through November 2017.

The two-dimensional approach of the 3Di Hydrodynamic model makes it so spatial variation in parameters for both surface and groundwater can better be taken into account. Interaction between the surface and phreatic groundwater domain is resolved simultaneously relieving the need for iterative runs of multiple models, which often result in high computation times.

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1 Introduction

This introductory chapter serves to outline the motivation for this research, to describe the state of the art of the research field, to define the research objective and pose the research questions. Section 1.1 will provide the background behind this research. Section 1.2 provides an overview of current groundwater models. The research gap is identified in section 1.3, followed by the research objective and research questions in section 1.4. Finally, the outline of the thesis will be provided in section 1.5.

1.1 Background

The Netherlands is a low-lying country, situated in the estuarine basin of several major European river systems. Water is in abundance in the Netherlands (Delsman et al., 2008). This is especially true for in the western and northern part of the country situated mostly beneath sea level. In these areas, the groundwater levels are rarely beneath one metre below the surface. These areas are drained by a dense network of ditches regulated by levees and pumps. The eastern and southern parts of the Netherlands are situated above sea level, the relief is more varied and surface water is concentrated in brooks.

The Netherlands is a pioneer country in water management (OECD, 2014), with its long history of water management, dating back to as early as the 11th century AD. Dykes and dwelling mounts were erected to cope with high river discharges and water was drained from so-called polders using the famous Dutch windmills. In the current day, water management in the Netherlands is still concerned with safety against flooding, but also with droughts during hot summers, salt intrusion, pollution of surface water and groundwater and so on. Climate change and sea-level rise, coupled with land subsidence due to peat oxidation increase the concern for these issues.

The Ministry of Infrastructure and Water Management is responsible for water management of the main surface waters, including the safety against flooding and the distribution of water. For the strategic and operational management of both surface and groundwater, local water authorities are responsible. On the island of Texel, this water authority is Hoogheemraadschap Hollands Noorderkwartier (HHNK).

In order to support the decisions and strategic plans of operational water management, hydrological models have been developed. These models can be used to analyse, understand and explore solutions for water management. The models used by water authorities have a wide range in size and complexity. This includes, but is not limited to, hydrodynamic models and groundwater models.

1.2 Hydrodynamic Modelling of Groundwater and Surface Water

Today's groundwater modelling consists of complex modelling tools that are characterised by power, capability and sophistication that was unthinkable even a few years ago (Hunt and Zheng, 2012). A multitude of models exists for modelling groundwater as shown by Kampf and Burges (2007). Some noteworthy examples are MODFLOW (Langevin et al., 2017) and FEFLOW (Diersch, 2014). MODFLOW is a finite-difference groundwater model developed by the United States Geological Survey. It has multiple versions of the code as it has been developed over time and has been used in many situations and studies. FEFLOW is a finite element model developed by the Danish Hydraulic Institute. Both of these models have been used in many studies worldwide(Anderson et al., 2015).

Both MODFLOW and FEFLOW are, at their core, models that only simulate groundwater and surface water is mostly used as a boundary condition. Surface water can be included in models by either the coupling of different models or the use of other models. Kollet et al. (2017) show the capabilities and approaches of integrated and coupled models. There is a great range in spatial and temporal scales for which these models are being developed and used.

Within the Netherlands, a multitude of models is being used by consultancies and authorities. In order to create an integrated national ground- and surface water model, models are combined into the Nederlands Hydrologisch Instrumentarium (NHI), the 'Netherlands Hydrological Instrument' as described by De Lange et al. (2014). The NHI consist of 4 main models. Firstly, a MODFLOW model for saturated groundwater flow. Secondly, a one dimensional, vertical model for unsaturated groundwater flow in the vadose zone, Soil-Water-Atmosphere-Plant model (MetaSWAP, van Walsum et al., 2010). Next, the water availability and demand from the hinterland is derived from the Surface Water model for Sub-Catchments (MOZART, Delsman and Prinsen 2008). Lastly, a one-dimensional real time control tools (RTC-tools) model for the main national and major regional distribution of surface water (Schwanenberg et al., 2015). This configuration is shown in figure 1.

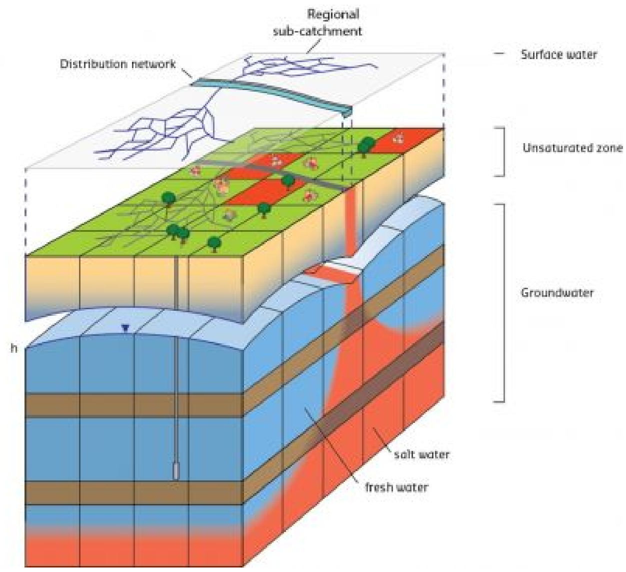


Figure 1: Schematisation of the Netherlands Hydrological Instrument (De Lange et al., 2014)

The 3Di Hydrodynamic model is a process-based, hydrodynamic model for flooding, drainage and other water management studies such as regional water distribution (Nelen & Schuurmans, 2019). It is a highly detailed two-dimensional surface water model capable of handling one-dimensional channel and weir flow combined with a two-dimensional, single layer phreatic groundwater model (Stelling, 2012). By the use of the quadtree sub-grid method the two-dimensional surface water model is able to take into account a highly detailed elevation model without increasing the number of calculation cells as described by Casulli and Stelling (2011) and Stelling (2012). This combination is unique, as most models focus on one domain or do not take into account elevation models in such a detailed way. This level of detail is not yet available in the NHI models.

The 3Di Hydrodynamic model is still being expanded to be used in more cases. Recently, the groundwater domain was added to 3Di in order to further understand the water system in urban areas - both above and under the surface - to make an integral approach of dealing with water-related issues such as flooding and droughts. 3Di aims to accommodate both the expert (e.g. a hydrologist) and non-expert (e.g. a decision maker) to gain insight in water systems (Nelen & Schuurmans, 2018). Within this research, the groundwater domain within the 3Di Hydrodynamic model will be referred to as the 3Di groundwater model.

1.3 Research Gap

As stated in section 1.2, the addition of the groundwater domain is a relatively new development of the 3Di Hydrodynamic model. This means there is yet to be gained experience in modelling with the 3Di groundwater model. So far, tests have been focused on small isolated cases in urban areas (Nelen & Schuurmans, 2018). The model has not yet been used in a polder area in which water levels are heavily regulated by control structures. It is not known if the model is applicable for use in these kind of areas. It is also unknown how sensitive the model is for changes in both internal parameters and model design choices. Lastly, it is not known how accurate the 3Di groundwater model is in simulating time series of groundwater levels within such an area. The studies done by Nelen & Schuurmans (2018) have so far not resulted in realistic simulations of groundwater levels over time. The water authority HHNK and Nelen & Schuurmans would like to investigate these aspects in order to evaluate the applicability of the 3Di groundwater model on other areas, such as a polder area.

1.4 Research Objective and Research Questions

So far studies using the 3Di groundwater model have focused on small-scale, urban areas. A further exploratory study is needed to provide a better understanding and more insight into the model. In this study, it was chosen to use the Waalenburg polder on the island of Texel, the Netherlands. The area has a dense network of measuring wells in place for measuring the effects of a nature development project. The measurement done in the Waalenburg polder provides data that can be used as a test case for the groundwater model. This study will evaluate multiple aspects of the 3Di groundwater model in order to gain further understanding of the model and its applicability in a polder system such as the Waalenburg. These aspects are sensitivity, accuracy and model design.

Model *sensitivity* is defined as the relative change of the results of the model for a change in parameter or boundary condition against the calibrated model. Within this research, the sensitivity will focus on the time-independent parameters of the groundwater equation, the hydraulic conductivity and storativity (as further explained in section 2.4.2). These parameters serve as the main calibration parameters. The *accuracy* is defined as the difference and relation between the simulated and observed time series of groundwater levels measured using root-mean-square error (RMSE) and the Kling-Gupta Efficiency (KGE, Gupta et al. 2009). It was chosen to include both an easily absolute metric, the RMSE, and a more thorough dimensionless metric, the KGE, for a more in-depth evaluation of accuracy. *Model design* as defined by Anderson et al. (2015) involves translating the reality into a numerical groundwater flow model by designing the grid, setting boundaries, assigning values of aquifer parameters, hydrologic stresses and, for transient models, setting initial conditions and selecting time steps.

The objective of this research is as follows:

> *Evaluate the applicability of the 3Di groundwater model for a polder area on its accuracy and its sensitivity for changes in time-independent model parameters and model design choices, by creating a model of the Waalenburg polder and comparing the results with observed time series.*

In order to achieve the objective, a model of the area first needs to be set up in addition more insight is needed in the workings of this model. The research will be guided by the following research questions:

1. *How sensitive are simulated groundwater levels for changes in hydraulic conductivity and storativity, the time-independent model parameters?*

2. *How accurate are the modelled time series of groundwater levels compared to the observed time series?*

3. *What is the effect of the model design choices on the modelled groundwater levels?*

1.5 Thesis Outline

Chapter 2 will describe the study area, the Waalenburg polder, followed by an introduction to the 3Di Hydrodynamic model and the data used in this research. Chapter 3 will describe the methods for answering the research questions as posed in section 1.4. This chapter is followed by the results in chapter 4. The research, its results and their relation to the research objective are discussed in chapter 5. This is followed by the conclusions and recommendations in chapter 6.

2 Case Study and Model Description

This chapter will describe the case study used in this research in section 2.1, followed by an introduction of the hydrologic system in section 2.2. Next, the data sources are explained in section 2.3. Finally, in section 2.4, this chapter concludes with a description of the 3Di model.

2.1 Case Study

The study area consists of the polder area Waalenburg on the island Texel, the Netherlands. Figure 2 provides an overview of this polder, originally created for use as agricultural land. In 1909 the first parts of this polder were converted back into a nature area by the acquisition of land by Natuurmonumenten. Since 2010, Natuurmonumenten has been acquiring more land to expand this nature area.

Groundwater and surface water levels of the polder are being controlled by pumps and weirs. As the polder area can not be recharged using freshwater (as is true for the whole island of Texel), the water levels in the area are strongly dependent on precipitation. The area is managed in order to store as much of this water as possible. During summer the groundwater levels are generally 20 to 30 cm lower compared to the winter. For the whole island of Texel an adaptive water management policy is in place (Provincie Noord Holland, 2016). This policy gives the water authority the legal authority to manage the surface water levels between an upper and lower limit, anticipating on groundwater levels, historic and current weather situations and predictions with the goal of storing as much water as possible to reduce the risk of droughts.

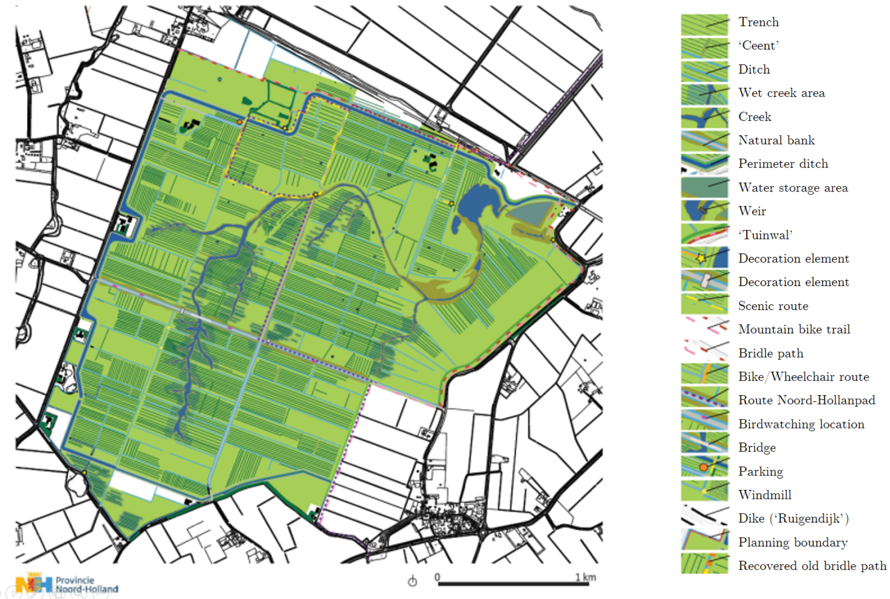


Figure 2: Map of the nature area in Waalenburg polder (in green) including the proposed canal along its perimeter (adapted from Provincie Noord Holland 2016).

The area is being developed in order to realise a coherent landscape system in which the geomorphology, mainly the old creeks, form the basis. The current natural significance of the area consists of its many gradients in moisture, ground texture and salinity and in combination with important vegetation types and high amounts of farmland birds (Provincie Noord Holland, 2016). For the natural development of this area, an increase in the groundwater table is required. This increase is up to -0.5 m+NAP from levels around -1.6

m+NAP to -1.4 m+NAP. A canal is planned in order to separate this nature area from the agricultural lands. Apart from hydrologically separating the area, the canal was also designed to discharge the excess water from the surrounding agricultural lands.

From June 2017 to June 2018 a baseline measurement of the area before applying the changes in the water system was performed by Royal HaskoningDHV (2018). This baseline measurement serves for use in the evaluation of the effects of changes in the water system. These measurements will be used as the basis for the research described in this thesis.

2.2 Hydrologic System of the Area

This section describes the main water system of the area using schematic maps of the area and data from the baseline measurements.

2.2.1 Surface Water System

The island of Texel is divided into four main sub-catchments as depicted in Figure 3. The dune area on the western side of the island is not included in these sub-catchments. The water of these sub-catchments is discharged by pumps located on the eastern side of the island. The Waalenburg polder discharges its water towards the northeast where it is pumped into the Wadden Sea. It is a typical Dutch water system where the surface water system of a region is divided into water level management areas or "peilgebieden" by the water authority, where water is kept at a stable level. In case of a polder, these areas are typically bounded by structures such as weirs and dykes. The management area has four weirs supplying water over the boundary on the western side and one weir discharging in the northeast located at the Genteweg.

Information about all the waterways within the polder and the structures is available in a data model (DAMO) provided by the water authority HHNK (W. van Gerwen, personal communication, 18 February 2019). The DAMO database is a GIS database consisting of spatially referenced line and point elements for channels, culverts, weirs and other water control structures. These lines and polygons are linked to tables providing information about these elements. This information includes bed levels and the width of channels and ditches.

2.2.2 Groundwater System

The regional groundwater system of the island of Texel was studied by Witteveen+Bos (2000) as part of the project "Groot Geohydrologisch Onderzoek Texel". Furthermore, for the evaluation of the proposed changes, a groundwater model was set up by Royal HaskoningDHV (2015). The groundwater of Texel is fully dependent on the rainfall and by the surrounding sea. A freshwater lens is present on top of the more dense salt groundwater that comes from the surrounding sea.

Groundwater in the Waalenburg polder is under mean sea level and has a lower mean groundwater level than its surrounding area. This means that it is susceptible to groundwater leakage from this surrounding area. This leakage is saline groundwater and is measurable in the ditches in the polder (Royal HaskoningDHV, 2015). This water is then discharged towards the canals in the polder.

Phreatic groundwater flows through the 10 m thick sandy top layer of the groundwater system and forms a freshwater lens. This layer lies on top of an aquitard of boulder clay. This aquitard is called the formation of Drente (Witteveen+Bos, 2000). The top of this aquitard and thus bottom of the phreatic aquifer varies from -9 m+NAP to -10 m+NAP over the whole studied area. The thickness of this aquitard varies from 2 to 12 m according

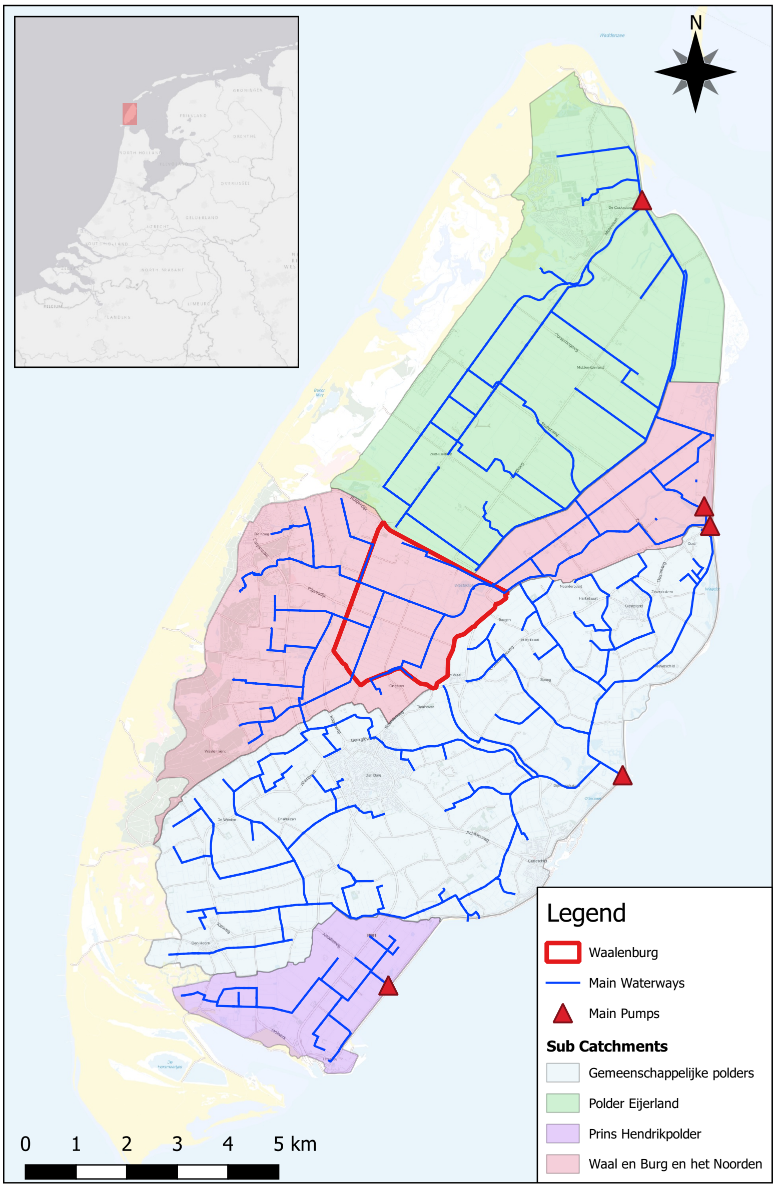


Figure 3: Schematic overview of catchments and waterways on the island of Texel

to the REGIS II model (Vernes and van Doorn, 2005). The deeper groundwater system exists of multiple aquifers. The next 40 m under the first aquitard, from -22 m+NAP to -62 m+NAP, lies a saline aquifer of sandy layers with an occasional low conductive layer. As stated above this layer leaks water to the phreatic aquifer. The next thick aquitard is located at -62 m+NAP to -72 m+NAP and acts as the separation for the next aquifers that are 30 to 100 m thick consisting of well conductive sandy layers to less conductive complex layers. Due to the thickness of the second aquitard, these layers are not expected to affect the phreatic groundwater directly.

2.3 Data

For use in this research data is needed in order to set up the model of the area. The previous sections already mentioned the use of the Data model DAMO for the water system and the REGIS model for the geohydrologic system. This section will further elaborate on the sources of this data and their specifications. The data sources used are summarised in Table 1.

2.3.1 Baseline Measurements

In order to evaluate the effect of the proposed changes to the water system, a baseline measurement was done by Royal HaskoningDHV (2018). Within the Waalenburg polder, there exists a network of groundwater monitoring wells. These have been placed over a long period of time for different purposes and for different periods of time. The baseline measurement includes an inventory of these wells and has checked the wells and locations for validity and continuity. Several wells in the area were too close to waterways or drainage pipes, therefore do not represent the groundwater table well. Ultimately, 11 of the wells were selected based on their location within the study area and the availability of daily measurements. Of these wells, only the filter located in the phreatic groundwater layer was used within this research. The time series of these valid wells were downloaded from DINOloket (2019).

Surface water levels are also measured in the area. This network consists of more points than groundwater wells. Surface water measurements are done at weirs but also at other places of interest in the area. A number of monitoring systems were put in place by the water authority for the use of the baseline measurement. The placement of these measurement systems, however, was in October 2017 a few months after the official baseline measurement was started. These provide measurements every 15 minutes using telemetry. Other stations in the area have daily measurements available. Lastly, Natuurmonumenten does manual measurements of the water level at weirs roughly every 2 weeks. The locations of the continuous groundwater and surface water measurements are shown in Figure 4.

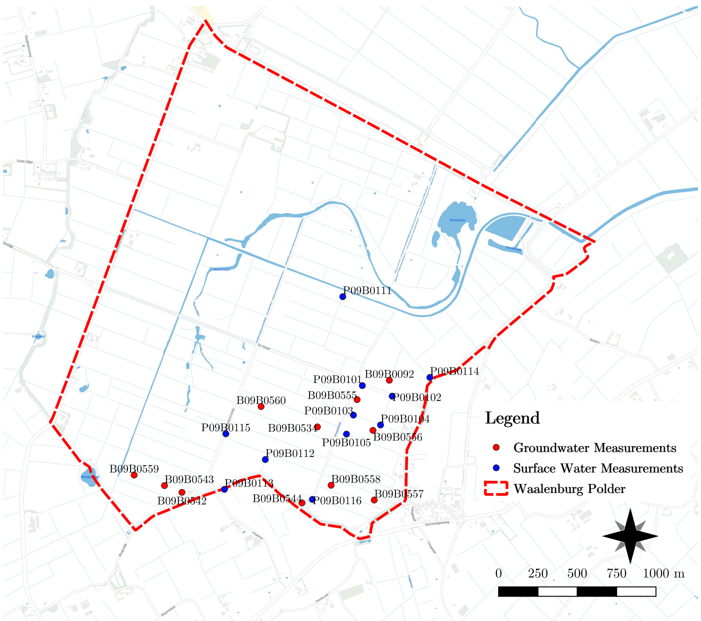


Figure 4: Locations of groundwater and surface water measuring stations.

2.3.2 Other Data Sources

Apart from the baseline measurements for both ground and surface water measurements, this research makes use of other sources. These sources are explained below and summarised in Table 1. This table also includes the sources explained in the previous sections.

For the hydraulic conductivity, a map made by the foundation for soil mapping was used

Table 1: Summary of the data sources used in the research.

	Source	Type	Temporal Resolution	Spatial Resolution
Precipitation	KNMI Nationale regenradar	Time series Time series	Daily 5 minute	1 station 1 km x 1 km
Potential evapotranspiration	KNMI	Time series	Daily	1 station
Actual evapotranspiration	GLEAM model	Time series	Daily	0.25° x 0.25°
Elevation	AHN (PDOK)	Raster	-	0.5 m x 0.5m
Groundwater levels	DINOloket	Time series	Daily	18 locations
Surface water levels	DINOloket HHNK Natuurmonumenten	Time series Time series Manual	Daily 15 minutes ∼2 weeks	11 locations 7 locations 37 locations
Hydraulic conductivity	REGIS II Stiboka	Rasters Map	- -	100 m x 100 m scale 1:20,000
Storativity	Cultuurtechnisch Vademecum	Tables	-	-
Water System	DAMO	GIS Model	-	-

(Stiboka, 1951). Values for storativity were extracted using tables in the agricultural handbook (Werkgroep Herziening Cultuurtechnisch Vademecum, 1988). The digital elevation model of the Netherlands, the AHN, is provided by PDOK (Publieke Dienstverlening op de Kaart, 2014). This model consists of a raster of 0.5 m by 0.5 m for the whole of the Netherlands.

For precipitation, the research will make use of both daily and 5-minute rainfall data. Daily precipitation is measured by the KNMI at Den Burg (KNMI, 2018). The National Rainradar project as described by Royal HaskoningDHV; Nelen & Schuurmans (2013) provides interpolated raster cells of 100 m by 100 m for rainfall data every 5 minutes.

Potential evapotranspiration at Den Burg is estimated by the KNMI (2018), according to the Makkink Evapotranspiration Model as described in KNMI (1988). Actual evapotranspiration is extracted from the Global Land Evaporation Amsterdam Model (Miralles et al. 2011; Martens et al. 2017), which provides global daily evapotranspiration with a resolution of 0.25° by 0.25° (approximately 25 km by 25 km). This model uses satellite data and a running water balance for use in estimating actual water evaporation.

2.4 Model Description

This section will describe the main concepts of surface water and groundwater flow in the 3Di Hydrodynamic model. It is not meant to represent full derivations of these formulas nor does it include all functions of the 3Di Hydrodynamic model. A full derivation of the numerical schemes are described by Stelling (2012) and Volp et al. (2013). For a full description of all the functions within the 3Di Hydrodynamic model, the reader is referred to the 3Di documentation (Nelen & Schuurmans, 2019).

2.4.1 Surface Water

Surface water within 3Di can be modelled in 2D, 1D and a combination of both. In the 2D case, water levels above the bed surface are calculated using the 2D depth-averaged shallow water equations using a finite volume approach. These 2D averaged shallow water equations are not always suited for calculations of flow in all circumstances. In these cases, such as flow through culverts or over weirs a 1D representation of these structures can be connected with the 2D grid.

For the computation of 2D flow 3Di makes use of quadtree grid refinements and the subgrid method for surface water flow as described in Casulli and Stelling (2011) and Stelling (2012). This approach is unique to quadtree grid refinement makes it possible to refine the model grid for areas of interest. In space, refinements are placed by dividing neighbouring cells by factor four. As flows are determined by the use of the edges of the cell the quadtree needs to be balanced. A quadtree is defined as *balanced* if for every cell in the mesh its sides are intersected by the corner points of neighbouring cells at most once (de Berg et al., 2008). This ensures grid variations are smooth, which enhances an accurate solution of the equation.

The subgrid method makes it possible to include elevation information on a more detailed level than the coarseness of the calculation grid. Only one water level is computed for a calculation cell, but due to the use of the subgrid elevation, part of the calculation cell can remain dry as depicted in Figure 5. The volume in the calculation cell is non-linear function of of the water depth based on the high detailed subgrid elevation.

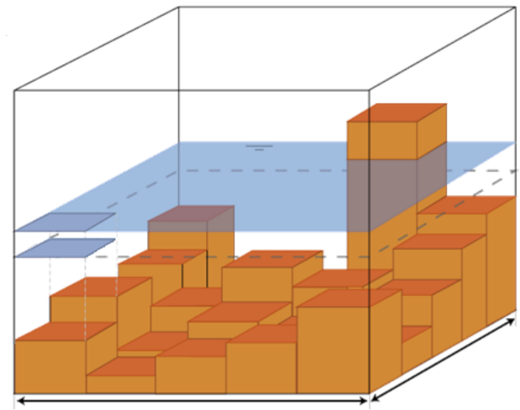


Figure 5: A schematic view of a single computation cell with an underlying subgrid, where a part of the domain is dry (Volp et al., 2013)

On the edges of these calculation cells, it is determined whether or not it is possible for water to flow to its neighbouring cells based on the subgrid surface level elevation on the cells edge and the current water depth.

2.4.2 Groundwater

The groundwater model of 3Di only considers phreatic groundwater and is based on 2D averaged law of Darcy under the Dupuit assumption. This implies: (1) flowlines are assumed to be horizontal and equipotential lines parallel and vertical and (2) the hydraulic gradient is assumed to be equal to the slope of the free surface and to be invariant with depth. This leads to equation 1.

$$\frac{\partial}{\partial x}\left(KA_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(KA_y\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}-R \tag{1}$$

In which h (m) is the height of the phreatic surface measured from the base of the aquifer in meters. In this research, these height are be transformed to the Amsterdam Ordnance Datum (m+NAP) for ease of interpretation. A_x and A_y (m^2) are the cross-sectional areas in the x and y direction, K (m/day) is the hydraulic conductivity which is assumed to be isotropic, S $(-)$ is the storativity and R (m^3/s) is recharge rate. For a full derivation of these equations, the reader is referred to, for example, Bear and Cheng (2010).

Equation 1 provides a clear insight into the importance of the time-independent model parameters hydraulic conductivity (K) and storativity (S). Within 3Di the storativity is represented by a single, spatially variable value which represents the potential storage in the phreatic aquifer. The unsaturated zone is not considered.

2.4.3 Forcing

In 3Di the surface water domain is affected by the boundary conditions and forcing. Boundary conditions can be either based on water levels, velocity, discharge or the slope of water levels. Apart from these boundary conditions, the forcing of the system is the precipitation.

For the groundwater domain, this is different. Boundary conditions at the model edge can only be closed, no-flow boundaries. Its main types of forcing are evapotranspiration, leakage and seepage and infiltration and exfiltration.

Evapotranspiration, leakage and seepage are combined within 3Di into one flow term, the "leakage layer". This layer defines a volume that is added or subtracted to the groundwater domain in the form of discharge in (m^3/s). Infiltration and exfiltration are explained in the next section.

2.4.4 Coupling of the Groundwater and Surface Water Domains

The ground and surface water domains not fully coupled. Exchanges calculated are connected via infiltration and exfiltration. The infiltration process can either be constant or make use of the Horton infiltration model (Horton, 1933).

Exfiltration happens when the groundwater level in the computational cell reaches the level of the lowest available bed elevation of a computational cell. This water is added to the surface water domain. When this is the case the groundwater level used in the calculation of groundwater fluxes will be set equal to the surface water level and the resulting pressure is accounted for in the groundwater domain. It has to be noted the groundwater storage above the minimum bed level of a calculation cell is not accounted for as the groundwater above the minimum bed level is transferred to the surface water domain.

2.4.5 Time Steps

Time steps within 3Di can be set to values in seconds. The model itself, however, does have a built-in function to ensure numerical stability and adjusts the time step accordingly. One of the requirements for a stable model is the Courant-Friedrichs-Lewy (CFL) condition (Courant et al., 1928). As both surface water and groundwater are simultaneously calculated the model must be stable for both kind of flows. This criterion is not likely to be broken by the groundwater flows as flow velocities are smaller than flow velocities for overland flow.

3 Method

This chapter will describe the methods used in order to answer the research questions. To start, the creation of the model of the Waalenburg polder is described in section 3.1. The creation of the model does not provide answers to the research questions directly but is essential in providing answers to the research questions. Next, in section 3.2, the model calibration for hydraulic conductivity and storativity, by the use of a sensitivity analysis in order to answer research question 1 is described. The results of the model are evaluated on accuracy in section 3.3, in order to provide an answer to second research question. Lastly, in section 3.4, it is described how the effects of design choices on the model results are investigated in order to provide an answer to the third and final research question.

3.1 Creation of the Waalenburg Model

The water system was described in section 2.1. This water system has to be turned in to a schematisation within the 3Di Hydrodynamic model. This section will describe this creation of the model that will be used for this research. The reference model will be created using as much information available as described in the sections 2.2.1 and 2.3. The following section is subdivided in subsections for surface water, groundwater and forcings. An overview of the resulting model is shown in Figure 6.

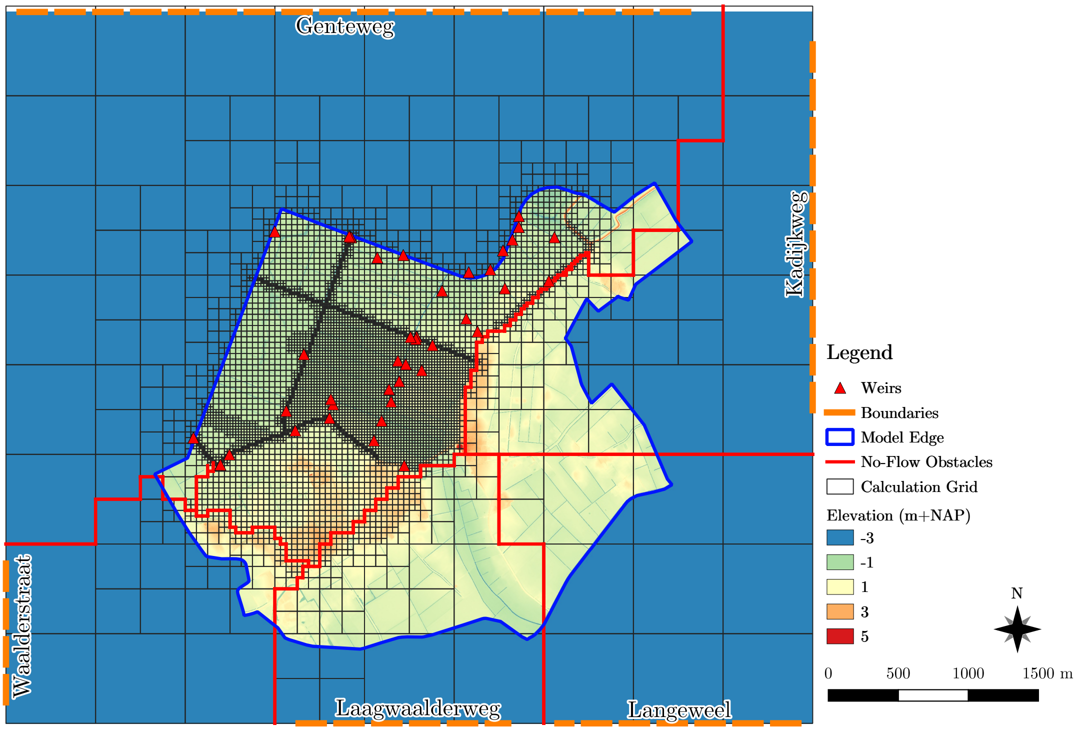


Figure 6: Overview of the model of the Waalenburg polder

3.1.1 Surface Water

Surface water flow is mainly dependant on the elevation in the area and is managed by weirs. Precipitation is either infiltrated or runs off towards one of the many ditches. The flow paths are determined based on the elevation model.

The AHN is a digital elevation model (DEM) of the Netherlands with a resolution 0.5

m by 0.5 m. The techniques used to construct this DEM are not able to measure the bathymetry of water bodies, as the water surface cannot be penetrated. This means only the dry parts of the banks can be measured. The result is an elevation model that excludes bathymetry of water bodies. The DEM is interpolated from bank to bank where values are missing. This interpolation results in the depth of the channels being underestimated. The DEM also does not include connections of waterways where culverts are present as these lie underground.

In order to include the bathymetry of the system of ditches and canals in the DEM, the DEM has to be edited using the available data from the DAMO water system database. Using the polygons of the ditches and canals and their linked depths in this database, the raster cells of the DEM that are touched by these polygons are edited. Figure 7 shows a cross-section of the model where the AHN is deepened to include the channel depth of the data model. A similar procedure was done for culverts. The raster values of the DEM were edited on the locations of the culverts in order to connect the channels in 2D. In essence, these culverts are transformed into canals.

It has to be noted that due to the resolution of the DEM, adaptations to the elevation model are likely to result in an overestimation of the volume in the surface water domain. Canals and ditches are likely to be a bit wider and have a steeper bank as is also depicted in Figure 7. These adaptations are however needed to ensure the surface water domain is able to discharge the water in the model without the need of many 1D connections.

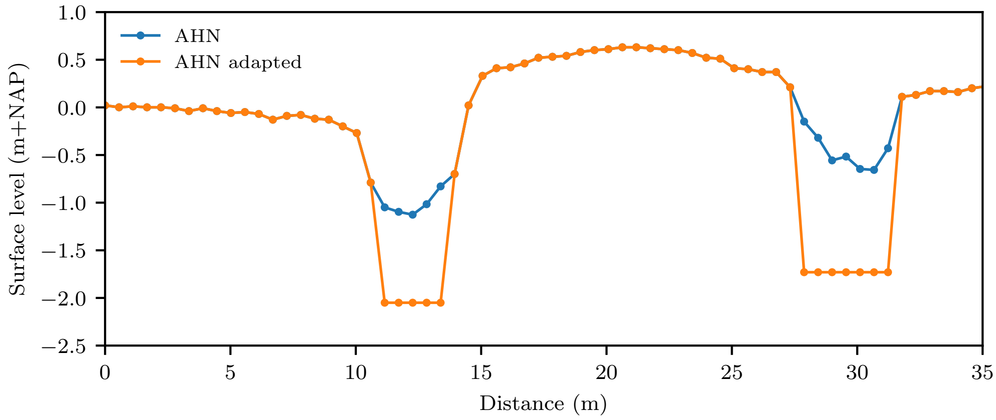


Figure 7: Schematisation of adaptations to the digital elevation model.

Weirs
Within the Waalenburg polder, the water system is further regulated using weirs. As the weirs are not present in the elevation model they are included as 1D elements in the model. Table 8 in Appendix A provides the crest levels for the weirs in the Waalenburg polder. The names and locations of the weirs in the model are taken from the DAMO database. The crest levels for summer and winter are determined based on maps and measurements done by Natuurmonumenten (D. Dam, personal communication, 6 March 2019). Within the model, all weirs are set to their winter crest levels from 15 September 2017 to 18 March 2018. The locations of these weirs are depicted in Figure 6.

3.1.2 Groundwater

The 3Di groundwater model uses an impermeable layer as bottom boundary. The aquitard described in section 2.2.2 has little variability in depth in the area of interest. It is slightly closer to the surface in the north-western part of the polder but this part of the area is not modelled in detail. Therefore, a constant value of -10m NAP was chosen for the bottom boundary of the model.

It can be seen in equation 1 in section 2.4.2 that groundwater flows in the 3Di Hydrodynamic model are mainly determined by the storativity (S) and hydraulic conductivity (K) of the phreatic aquifers. These variables are often spatially varying as soils are too. The values for storativity and hydraulic conductivity will be found by calibration as explained in section 3.2.

3.1.3 Boundaries and Model Grid

In order to construct a model, it is needed to determine system boundaries. Section 2.2.1 describes the water management area ("peilgebied") which bounds the Waalenburg polder. Groundwater flow, however, is generally not bounded by dykes and weirs. For groundwater systems calculated using the Dupuit assumptions, free water surfaces are often used as boundary conditions. As the model incorporates both overland and groundwater flows the boundaries have to be chosen in a way that both groundwater and overland flows can both be simulated.

Therefore, the model boundary consists of the main waterways as shown in section 2.2.1 in Figure 3. The water levels of these channels are measured at weirs and are thus known. For calculation purposes and to ensure the water levels are correct at the boundaries the DEM is edited to a level of -3 m+NAP outside of the model edge. This level is equal to the level of the deepest canal in the polder.

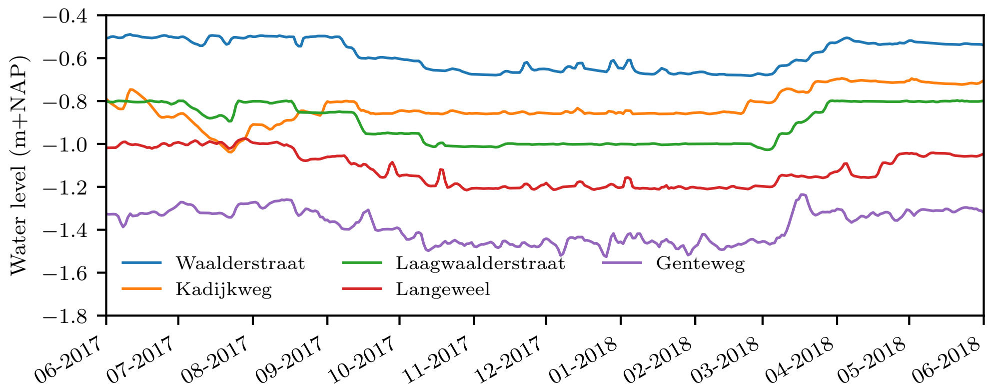


Figure 8: Time series for the boundaries derived from water levels measured at weirs.

The model grid is mostly dictated by the surface water system. As a calculation grid cell only have one water level, different ditches cannot be contained in one cell. The grid of the model varies from 10 m by 10 m at places where two ditches are close together to 640 m by 640 m along the model edge. The area of the model that includes the measurements has a maximum grid size of 20 m by 20 m. No-flow obstacles were defined from the grid edged to separate the boundary conditions and make direct surface water flow between the channels used as boundaries not possible. These are depicted by the red lines along the grid cell edges in Figure 6. At the edges of the model grid, Dirichlet boundary conditions in the surface water domain are defined using the time series shown in Figure 8. For the groundwater domain under these surface water levels at the edge of the grid, no-flow boundaries are defined.

3.1.4 Forcing

The three main forcings of the model are groundwater seepage and leakage, precipitation and evapotranspiration. These forcings can be implemented into 3Di as time series. The following sections will provide further explanation of the data used for forcing within the model.

Precipitation and Evapotranspiration

The main driving forces of the system outside the boundaries are precipitation and evapotranspiration. The precipitation is measured by KNMI at Den Burg (KNMI, 2018) is used in this model. Evapotranspiration was estimated using Global Land Evaporation Amsterdam Model (Miralles et al., 2011). It was chosen to use the actual evapotranspiration from GLEAM model over the potential evapotranspiration according to the Makkink model (KNMI, 2018) as the 3Di groundwater model is not able to convert potential evapotranspiration into actual evapotranspiration. Although the resolution of the GLEAM model is coarse, the potential evaporation corresponds well with the estimated Makkink evapotranspiration. In winter the GLEAM potential evaporation is lower this is to be expected as the Makkink evaporation model overestimates the evaporation in winter according to the report by the KNMI (1988).

Both time series consist of daily sums of precipitation and evapotranspiration. Within the model, these totals are forced upon the model as a daily varying constant flux. As the area is relatively small and the measuring location at Den Burg is close it is assumed there is no spatial variation in both time series. Evaporation from open water surfaces was not taken into account as surface water levels are used as boundary conditions for the model and evaporation would be grossly overestimated. The time series used in the model are depicted in Figure 9.

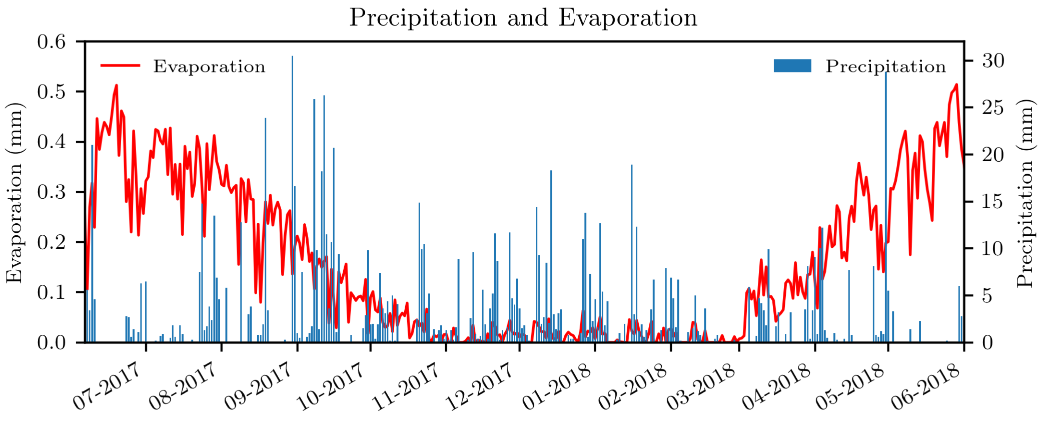


Figure 9: Time series for evaporation and precipitation.

Infiltration

The infiltration capacity of the reference model is also set to a constant value greater than the maximum precipitation intensity. This makes that all rain that falls is able to infiltrate into the ground if there is sufficient storage available. It can be assumed that most of the precipitation infiltrates into the ground as described by de Vries (2007) and this makes it possible for the precipitation to do so. The infiltration value is set to a value of 100 mm/hour. This does not mean that surface runoff cannot take place as saturation excess surface runoff is still possible when the groundwater domain is saturated.

Groundwater Leakage
Groundwater leakage cannot be directly measured and is often a model result. Witteveen+Bos (2000) and Royal HaskoningDHV (2015) have reported values for groundwater leakage in the Waalenburg polder. Royal HaskoningDHV (2015) notes that salinity measurements point out that leakage at the farming lots mostly takes place in the canals, a higher electroconductivity values were measured in the canals compared to the groundwater.

For use in the reference model, a constant leakage rate of 0.5 mm/day was assumed from deeper aquifers towards the phreatic aquifer. This value corresponds with values calculated using the regional groundwater model for the whole island of Texel by Witteveen+Bos (2000) and is in the same order of magnitude as leakage flows calculated by Royal HaskoningDHV (2015).

Net Fluxes and Initial Values
The values for the source and sink fluxes of the system are combined into a constant leakage flux through the bottom and a net precipitation on top due to limitations of the model. Precipitation can thus be artificially lower or higher depending on the evapotranspiration. This is not expected to result in model errors as the infiltration capacity is never a limiting factor in the reference model.

The initial surface water levels from an uncalibrated model run will be used. The surface water levels of these initial surface water levels are linearly interpolated in space in order to acquire initial groundwater levels between canals and ditches.

3.2 Sensitivity Analysis and Calibration

In order to provide an answer to the first research question and to calibrate the model, a sensitivity analysis is done for the hydraulic conductivity and storativity of the model. These are the time-independent model parameters included as mentioned in section 2.4.2.

3.2.1 Sensitivity for Hydraulic Conductivity and Storativity

Using the model as created in section 3.1 a sensitivity analysis will be done for the storativity (S) and the hydraulic conductivity (K) as described in equation 1 in section 2.4.2. For the use in the sensitivity analysis the storativity and hydraulic conductivity in the model will be spatially uniform. Ranges of values for hydraulic conductivity are chosen according to values found from in the REGIS model (Vernes and van Doorn, 2005), and the maps (Stiboka, 1951) provided by the water authority. The range in values for storativity in phreatic aquifers was extracted from Werkgroep Herziening Cultuurtechnisch Vademecum (1988).

The values for hydraulic conductivity are varied between 0.25 m/day and 1.75 m/day with an interval of 0.25 m/day. In order to investigate potential outliers, a hydraulic conductivity of 2.5 m/day was also included. The storativity was varied between 2.5% and 17.5% with an interval of 2.5%. The intervals for both hydraulic conductivity and storativity were chosen to limit the amount of runs but still provide insight into the variability.

For all combinations of hydraulic conductivity and storativity, a model run is done using a uniform field for both hydraulic conductivity and storativity. The mean value and standard deviation of simulated groundwater levels are determined at the groundwater monitoring wells that are located within the Waalenburg polder and selected in section 2.3.1. The period for the sensitivity analysis is 1 November 2017 through 31 March 2018. This winter period was selected because during this period the weir levels remain constant and the relatively uncertain evaporation flux is low. Thus, the resulting calibration will not be affected by errors in the forcing flux. The sensitivity of the mean value and standard deviation in simulated groundwater level time series for changes in hydraulic conductivity and storativity will provide insight into the model behaviour.

3.2.2 Model Calibration

Using the results of the sensitivity analysis the Root-Mean-Squared-Error (RMSE, eq. 2) is determined in order to find the best model fit per measuring well for the period 01 November 2017 through 31 March 2018.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(h_{obs}(j) - h_{sim}(j)\right)^2} \tag{2}$$

In which $h_{obs}(j)$ and $h_{obs}(j)$ are the observed and simulated groundwater levels in m+NAP for each time step and n denotes the number of time steps used in the calculation of the RMSE. The RMSE at the measuring wells selected in section 2.3.1 is used to calibrate the model. Bennett et al. (2013) note that the RMSE is a widely used metric is for evaluation of model performance which aids in communication and understanding of model performance. The RMSE is able to take both overestimation and underestimation of the measured time series into account by squaring the difference between the simulated and observed time series it penalises larger errors more than small errors.

The best model runs using all combinations of homogeneous storativity and hydraulic conductivity as described in the previous section are determined per measuring well. The optimal values for storativity and hydraulic conductivity are then interpolated in order to achieve a calibrated model.

It has to be noted that interpolation of hydraulic conductivity is technically not correct. It is not known if the hydraulic conductivity does have any relation in space. The maps of the hydraulic conductivity by Stiboka (1951), however, do suggest that there is little variability in hydraulic conductivity. Additionally, because there has not been major mechanical movement of ground in the area it is likely that the hydraulic conductivity of the aquifer exhibits no sudden changes. Therefore, it was chosen to interpolate the values of hydraulic conductivity using inverse distance weighting.

3.3 Model Evaluation

The model will be evaluated on its accuracy and applicability for this polder to answer the second research question. This evaluation is done for the whole period of the baseline measurement. The accuracy of the model results will be measured using the Kling Gupta Efficiency (KGE, Gupta et al. 2009) as shown in equation 3.

$$\text{KGE} = 1 - \sqrt{(\text{KGE}_R - 1)^2 + (\text{KGE}_\mu - 1)^2 - (\text{KGE}_\sigma - 1)^2} \tag{3}$$

$$\text{KGE}_\mu = \frac{\mu_{sim}}{\mu_{obs}} \tag{4}$$

$$\text{KGE}_R = \frac{\text{Cov}(h_{sim}, h_{obs})}{\sigma_{sim}\sigma_{obs}} \tag{5}$$

$$\text{KGE}_\sigma = \frac{\sigma_{sim}}{\sigma_{obs}} \tag{6}$$

In which KGE_μ is the bias ratio between mean simulated and observed groundwater levels, KGE_R is the Pearson correlation coefficient between simulated and observed groundwater levels (h) and KGE_σ is the variability ratio. The KGE_R gives insight into the linear relationship between the simulated and observed time series and can thus tell if the modelled groundwater levels behave in a similar way to the measured data. The KGE_μ provides insight into the systematic error of the model result and KGE_σ provides insight in the variability of the model results compared to the variability in the observed groundwater levels. The optimal values for the KGE and its parts are 1.

The KGE is a more robust and elaborate measure for model efficiency than for instance, the Nash-Sutcliffe Efficiency (NSE, Nash and Sutcliffe 1970). According to Knoben et al. (2019) there is a tendency in current literature to interpret KGE values analogous to NSE values: negative values indicate "bad" model performance, whereas positive values indicate "good" model performance. The traditional mean flow benchmark (NSE = 0) would result into $\mathrm{KGE} = 1 - \sqrt{2}$. Meaning that all simulations with a value of $-0.41 < \mathrm{KGE} \leq 1$ could be considered reasonable model performance. Because this research is exploratory it was chosen to not set a benchmark for the KGE.

3.4 Sensitivity to Design Choices

The reference model was created and calibrated. This section will focus on the fourth research question and will evaluate the effect of the design choices on the model results in order to verify whether these choices are valid and to gain further insight in the model behaviour. As it is not feasible to investigate all design choices it was chosen to evaluate the boundary conditions, the resolution of the precipitation input and the calculation grid size.

3.4.1 Boundary Conditions

To evaluate the effect of the surface water boundary conditions at the model edge, the boundaries are increased and decreased by 50 cm over the whole simulation period. This is done for the boundary conditions based on the time series of the Laagwaalderstraat, Waalderstaat, Langeweel and Kadijkweg as depicted in Figure 6.

The effect of changes will be evaluated on the absolute water levels at the measuring wells. The effect of the boundary conditions on the groundwater levels can be used in order to validate the chosen boundaries of the system. If the system is sensitive to changes in these boundary conditions, the boundaries may need to be chosen further from the area of interest. Furthermore, the effect of changing these boundary conditions also gives insight into the model's reaction to a change in the water system albeit not the proposed changes.

3.4.2 Temporal Resolution of Precipitation

The reference model makes use of daily precipitation sums as measured by the KNMI (2018). This precipitation is constant over the day. This approach does not account for the variability in rainfall during the day. Heavy rainfall events might have different effects on the groundwater levels than a constant low-intensity event of the same amount. The effect of the temporal resolution can be used to indicate whether or not the time step of the input is correctly chosen.

A precipitation time series with a resolution of 5 minutes is also available from the Regenradar (Royal HaskoningDHV; Nelen & Schuurmans, 2013). These values are interpolated from measurements done throughout the Netherlands. The sums of daily precipitation events do correspond quite well with the KNMI measurements at Den Burg.

The effect of the time scale of the input forcings will be evaluated by using the Regenradar precipitation with time steps of 5 minutes. Effects of the finer rainfall data are compared to a model run using the daily sums of the Regenradar values in order to make a fair comparison. Evaporation and leakage inputs will remain unchanged from the reference model. Effects will be evaluated for simulated groundwater levels at the measuring wells.

3.4.3 Calculation Grid

The grid sizes in the reference model were mainly determined by the distance of the ditches in the system. The 3Di hydrodynamic model does not allow for calculations of different water levels within one calculation cell. The reference model has a typical grid size of 20 m by 20 m.

In order to evaluate whether this is sufficient for modelling a polder system like this, a farming lot in the middle of the system will be simulated using different grid sizes. A local grid refinement is made in order to see the effects on the results for grid sizes of 10 m by 10 m and 5 m by 5 m. Due to the nature of quadtree grid refinement and the reference model having particular placements of 1D elements, other grid refinements are not possible. These refinements are shown in Figure 10.

The effects of the calculation grid will be evaluated at the locations of measuring wells B09B0555 and B09B0556 and using a cross-section of the farming lot containing measuring well B09B0555. This location was chosen for its location away from boundaries and its inclusion of the measuring wells.

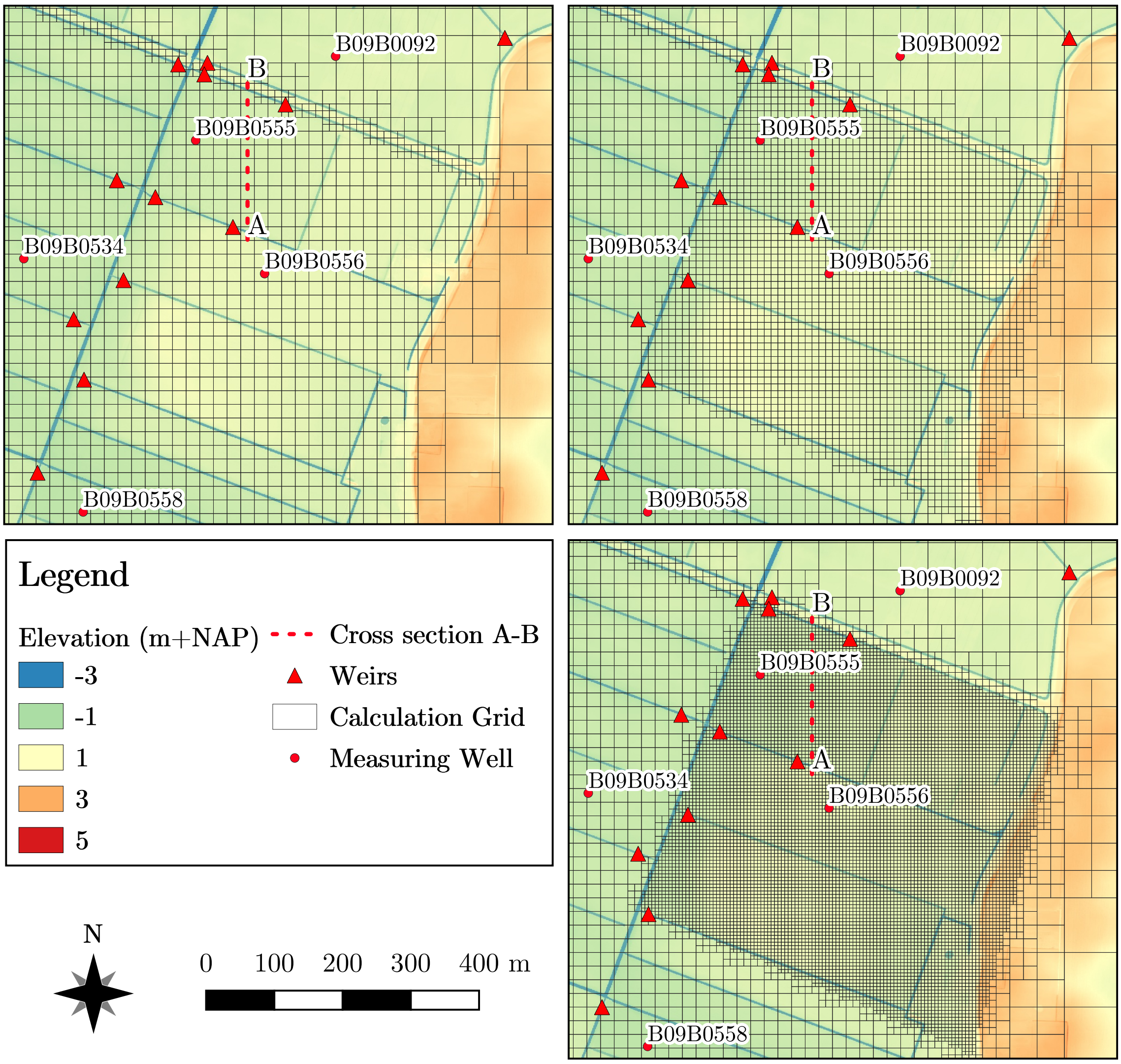


Figure 10: Local refinements for grids of 20 m, 10 m and 5 m within the model of the Waalenburg polder.

4 Results

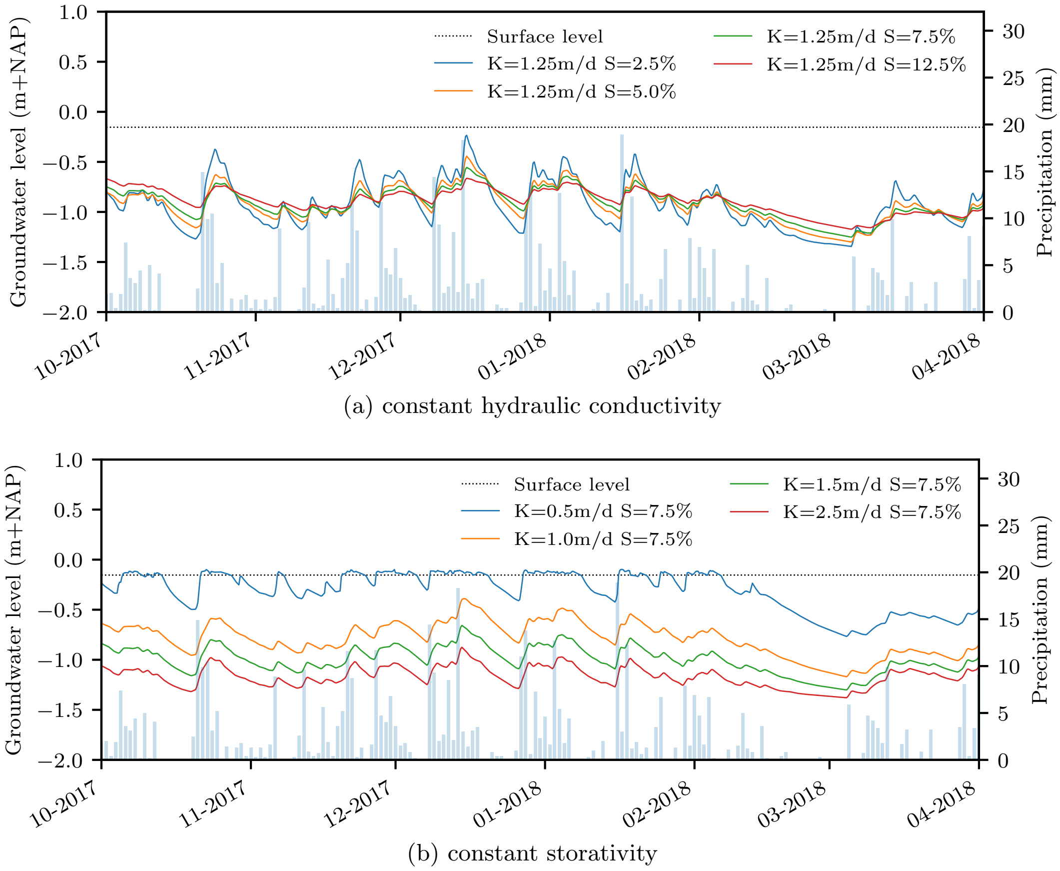
This chapter will present the results of the model of the Waalenburg polder created and provide the results of the method as described in chapter 3. This chapter will start with the sensitivity analysis and calibration of the model in section 4.1 in order to provide an answer to the first research question. Next, in order to answer the second research question, the model results are evaluated in section 4.2. Finally, in section 4.3, the effects of model design choices are shown to provide an answer to the third and final research question.

4.1 Sensitivity Analysis and Calibration

The model of the Waalenburg polder was created as explained in section 3.1. Section 4.1.1 will show the results of the sensitivity analysis in order to answer research question 1. The results of this sensitivity analysis will be used in the calibration of the model in section 4.1.2.

4.1.1 Sensitivity for Hydraulic Conductivity and Storativity

In order to investigate the influence of the hydraulic conductivity and storativity, a sensitivity analysis was performed using homogeneous values for hydraulic conductivity and storativity as described in section 3.2. The effect of changes in storativity and hydraulic conductivity at measuring well B09B0555 are depicted in two ways. Firstly, in figure 11 for the period 1 November 2017 through 31 March 2018.



(a) constant hydraulic conductivity

(b) constant storativity

Figure 11: Effects of changes in (a) storativity and (b) hydraulic conductivity for the modelled groundwater levels at measuring well B09B0555

Secondly, the mean and standard deviation of the simulated groundwater levels as a function of storativity and hydraulic conductivity for measuring well B09B0555 are shown in figure 12. This measuring well will serve as an example as other points in the system behave in similar ways. The results for other measuring wells are provided in Appendix B.

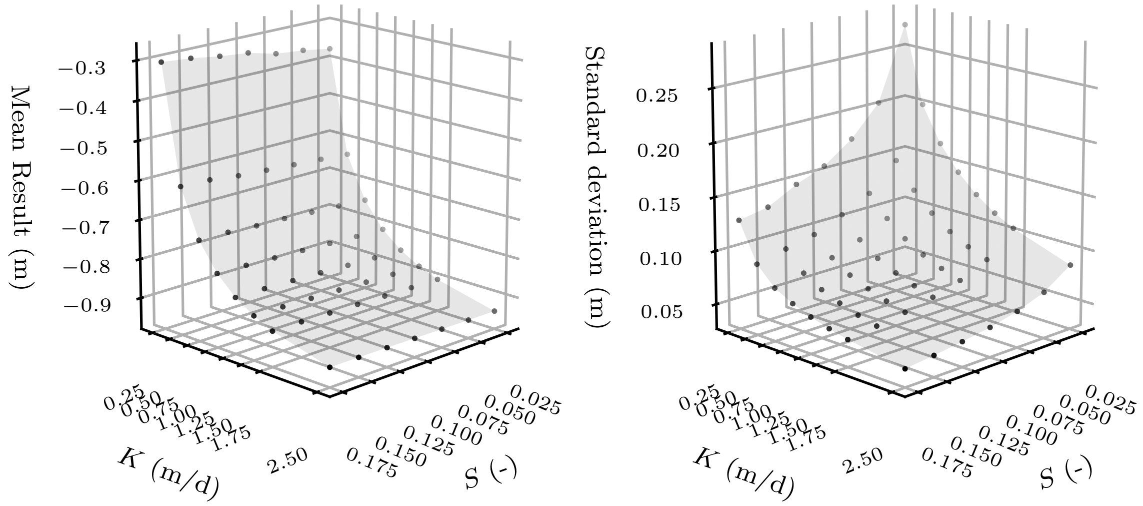


Figure 12: Changes in mean and standard deviation of the modelled groundwater level as a function of hydraulic conductivity and storativity at measuring well B09B0555

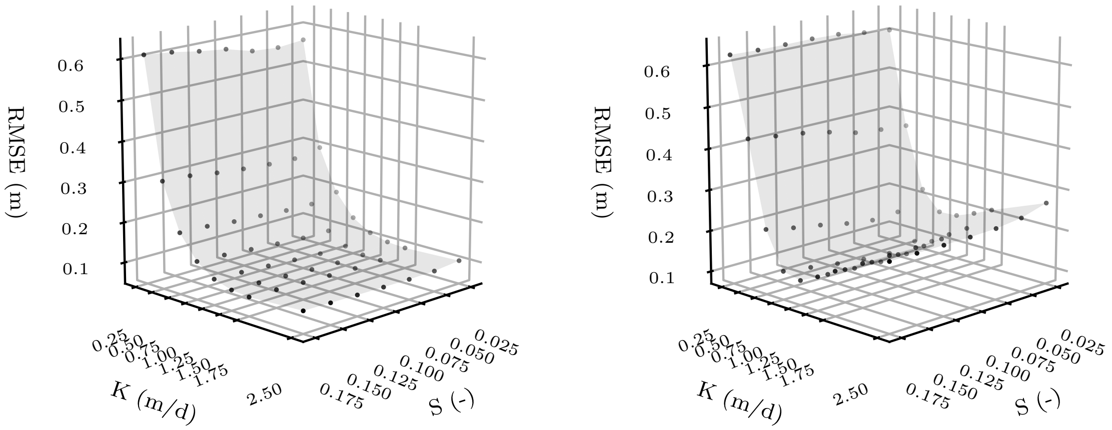
Changes in hydraulic conductivity cause changes in the mean groundwater level, a lower hydraulic conductivity results into a higher mean groundwater level until the groundwater domain is fully saturated. This relationship is not linear. This is to be expected as the water takes longer to flow towards the ditches when the hydraulic conductivity decreases. The difference in mean values decreases with increasing hydraulic conductivity. When the hydraulic conductivity is high groundwater levels are closer to the water levels in the ditches. The standard deviation of the groundwater level decreases with increasing hydraulic conductivity. For some measuring well, however, the standard deviation decreases at a low hydraulic conductivity. This is explained by the fact that the groundwater is capped by the surface level and therefore does not further increase causing a decrease in standard deviation. Examples of this are measuring wells B09B0092 and B09B0534 as shown in Appendix B.

Changes in storativity do not seem to affect the mean groundwater levels much within the used range of values. The standard deviation is however much higher for lower storativity values. Generally speaking, the same volume of water can cause a larger change in groundwater level as the storage if the storativity in the cell is lower and thus, this result is expected.

4.1.2 Model Calibration

The RMSE was calculated as described in section 3.2.2 for the period 1 November 2017 through 31 March 2018 for uniform fields of hydraulic conductivity and storativity as used in the sensitivity analysis. The resulting values for measuring wells B09B0555 and B09B0534 are shown in Figure 13. The other results can be found in Appendix C. These figures show that the model error mostly depends on the hydraulic conductivity. Storativity does not seem to affect the RMSE much within the chosen range.

Table 2 shows which model runs done in the sensitivity analysis yielded the best values for RMSE. The optimal hydraulic conductivity values per well were interpolated using inverse



(a) B09B0555 (b) B09B0534

Figure 13: RMSE of modelled groundwater levels as a function of hydraulic conductivity and storativity for measuring wells (a) B09B0534 and (b) B09B0555

distance weighting for use in the calibrated model. It was chosen to exclude the points B09B0543, B09B0559 and B09B0560 in further analysis of the results. These measuring well seems to have a systematic error and the best values for RSME do no correspond to the measuring wells that are located on the same farming lot. According to the local water authority, these measuring wells were also problematic in time series analysis and might be the result of these measurements not being valid (D. Dam, personal communication, 30 September 2019). For the storativity, the difference in RMSE values for model runs using the same hydraulic conductivity was small and randomly distributed in space. It was therefore chosen to use a constant value of 7.5% for storativity in the calibrated model. The resulting grid can be found in Appendix D. The RMSE per measuring well of the calibrated model is also shown in Table 2. The RMSE of the calibrated model are slightly higher than the best run as determined in the sensitivity analysis. For some wells, this is due to the calibrated model having a different value for storativity and the effects of interpolated hydraulic conductivity values of neighbouring cells.

Table 2: Optimal parameter values for the best runs of the sensitivity analysis using uniform fields of hydraulic conductivity (K) and storativity (S), their RMSE and the RMSE of the calibrated model per measuring well for 01-11-2017 through 31-03-2018.

	Optimal Value		RMSE	
	K (m/day)	S (%)	Best Run (m)	Calibrated Model (m)
B09B0092	1.25	7.5	0.120	0.121
B09B0534	1	7.5	0.107	0.107
B09B0542	0.5	7.5	0.086	0.087
B09B0543*	0.25	10.0	0.146	0.202
B09B0544	0.5	7.5	0.094	0.099
B09B0555	1.25	7.5	0.080	0.079
B09B0556	1.25	10.0	0.114	0.117
B09B0557	0.75	7.5	0.077	0.077
B09B0558	0.5	12.5	0.067	0.090
B09B0559*	1.5	15.0	0.084	0.321
B09B0560*	2.5	5.0	0.089	0.327

* This measuring well is left out of calibration and further results.

4.2 Model Evaluation

In order to answer the second research question, the accuracy of the model is evaluated. This is done for the surface water domain in section 4.2.1 and the groundwater domain in section 4.2.2.

4.2.1 Surface Water

Surface water flows in the model do follow the logical flow paths. Weirs in the area discharge water towards the main ditches corresponding to the water system as described in section 2.2.1. The ditches in the system are fed by the precipitation that directly falls on the cells, by discharges from neighbouring cells and through exfiltration of groundwater. For the locations where the surface water levels are continuously measured the model does simulate the measured water levels well as can be seen in the figures of Appendix E and summarised in Table 3. The KGE values for the surface water measurements for the complete simulation period are always positive. Low values of the KGE are mostly explained by values for KGE_R and KGE_σ, the correlation coefficient and the variability ratio. The correlation coefficient is low and the variability ratio is far from 1. However, the KGE_μ shows values close to 1, which means the mean values is of these water levels are correctly simulated. The differences in surface water levels are minimal and are not expected to have a significant effect on the groundwater levels between these ditches.

Surface water runoff towards ditches only takes place when the storage capacity of the groundwater domain is exceeded as the infiltration capacity is never exceeded in the model. In the calibrated model infiltration excess surface water runoff takes place in September as the groundwater domain is saturated for many farming lots.

Table 3: KGE values for simulated surface water levels.

	KGE (-)	KGE$_\mu$ (-)	KGE$_R$ (-)	KGE$_\sigma$ (-)
P09B0101	0.767	0.996	0.831	0.839
P09B0102	0.113	1.036	0.472	0.289
P09B0103	0.828	1.003	0.932	1.158
P09B0104	0.199	1.023	0.665	0.272
P09B0105	0.896	0.990	0.941	0.915
P09B0111	0.243	0.933	0.405	0.537
P09B0112	0.262	0.956	0.605	1.622
P09B0113	0.561	0.934	0.779	1.374
P09B0114	0.868	1.000	0.904	1.092
P09B0115	0.007	0.985	0.330	0.268
P09B0116*	-	-	-	-

* This time series is incomplete and therefore no KGE values are calculated.

4.2.2 Groundwater

Groundwater levels in the calibrated model do seem to follow the measured values quite well, as is shown by the calibrated model result for B09B0555 shown in figure 14 and the figures for the other measuring wells as included in appendix F. By visual inspection, it can be seen that the model has a similar mean and deviation from this mean compared to the measured results.

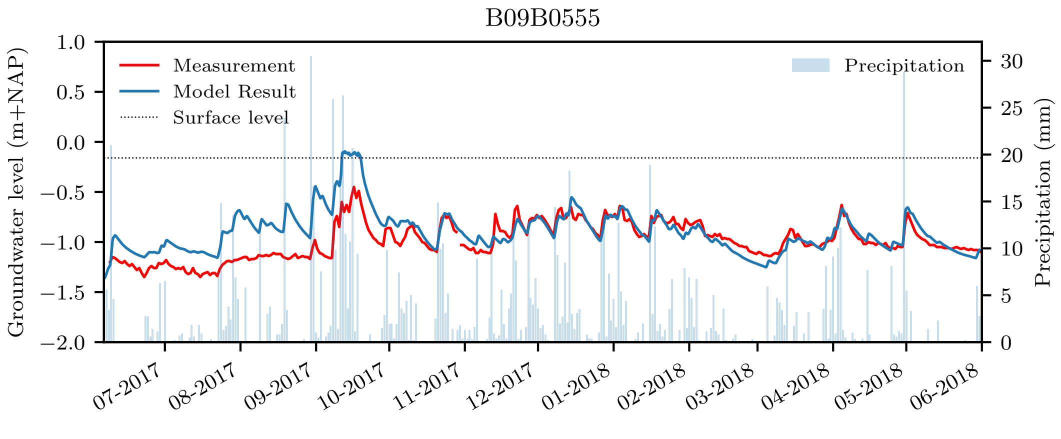


Figure 14: Measured and simulated groundwater levels, the surface level and daily precipitation at measuring well B09B0555.

The model results do show an overestimation of the groundwater level from June to November 2017 for all measuring wells. The rainfall events in these months seem to cause a larger increase in groundwater levels than is measured, for some locations the groundwater domain is even saturated. This might be due to the fact that the infiltration capacity of the model is never exceeded and thus more water is infiltrated than would happen in reality. After a dry period, precipitation may cause an increase in soil moisture but this does not necessarily lead to an increase in groundwater level. The evaporation flux during this period might also be underestimated this is however not likely to be the cause of this error as then we would expect similar problems at the end of the simulated period. The model error might also be due to measuring errors in the precipitation data as the surface water measurements within the area also do not show large increases in water level within this period and precipitation events can happen very locally.

In order to evaluate the modelled time series of groundwater levels, the Kling-Gupta Efficiency is calculated. This was done for the whole model run where data was available and from 1 November 2017 to 6 June 2018. This latter period was chosen to exclude the systematic error from June to November 2017. Table 4 summarises the Kling-Gupta Efficiency values and its components related to the difference in mean, standard deviation and correlation which all have an ideal value of 1. The model shows relatively high values for KGE of over 0.68 when excluding the first 4 months. The mean values of the model seem only to differ up to 5% for all measuring wells except B09B0544. The correlation coefficients KGE_R are generally over 0.7 meaning the modelled groundwater levels increase and decrease following the measurements. The values found for KGE_σ are close to 1 indicating that the standard deviation in modelled groundwater levels is in accordance with the ranges found within the measurements.

For use in evaluation of planned changes in the water system, a model with a high correlation coefficient and a standard deviation comparable to the measurements is needed. This will provide insight in what the effects the impact of changes are and within what ranges these effects are. A systematic underestimation of the mean might not be desirable but is deemed inferior to the other KGE components for modelling the system's behaviour. If the model would be used to calculate maximum and minimum groundwater levels at specific places over a longer period of time, the systematic error is, however, more important.

Table 4: Kling-Gupta Efficiency and its components per measuring well.

	Complete Run				01-10-17 through 06-06-18			
	KGE (-)	KGE_μ (-)	KGE_R (-)	KGE_σ (-)	KGE (-)	KGE_μ (-)	KGE_R (-)	KGE_σ (-)
B09B0092	0.573	0.780	0.651	0.890	0.856	1.009	0.869	0.942
B09B0534	0.370	0.842	0.422	0.806	0.772	0.969	0.811	0.875
B09B0542	0.543	0.886	0.557	1.017	0.782	1.013	0.846	1.153
B09B0544	0.530	1.002	0.532	1.044	0.788	1.113	0.821	1.009
B09B0555	0.602	0.907	0.638	1.138	0.825	1.002	0.860	1.106
B09B0556	0.315	0.888	0.329	1.080	0.684	1.042	0.746	1.183
B09B0557	0.340	0.967	0.446	1.357	0.822	1.033	0.843	1.076
B09B0558*	-	-	-	-	0.768	1.034	0.795	1.103

* This time series is incomplete and therefore no complete run KGE values are calculated.

4.3 Sensitivity for Model Design

The reference model was created and calibrated. This section will focus on the third research question and will evaluate the effect of the design choices on the model results. The following sections will also use the calibrated model result from the 1st of August 2017 onward as reference.

4.3.1 Boundary Conditions

Table 5 shows the effects of an increase and decrease by 50 cm for the time series of the free water surface boundaries located a the Laagwaalderstraat, Waalderstaat, Langeweel and Kadijkweg depicted in Figure 6. A change in boundary conditions along the model edge does not affect the overall system significantly. The ditches closest to, but not in direct connection with, the open water boundary conditions, have a slight increase or decrease in discharge for an increase and decrease in boundary conditions. This leads to a slight deviation in surface water level. The effect on groundwater levels at the measuring locations is negligible for most measuring wells. These differences of up to 1.6 mm for measuring well B09B0092 might even be attributed to differences in the variable time step of the model as explained in section 2.4.5.

Table 5: Changes in mean and standard deviation of simulated groundwater for changes in the water level used as boundary conditions compared to the calibrated model results.

	50 cm increase		50 cm decrease	
	ΔMean (cm)	ΔStd (cm)	ΔMean (cm)	ΔStd (cm)
B09B0092	0.164	0.001	0.056	0.055
B09B0534	0.034	0.020	0.059	0.064
B09B0542	-0.052	-0.042	-0.019	0.078
B09B0544	-0.003	0.039	-0.071	-0.075
B09B0555	0.045	-0.014	0.131	0.131
B09B0556	0.065	0.021	0.055	0.060
B09B0557	0.037	0.030	0.030	0.047
B09B0558	0.033	0.029	0.027	0.046

These minimal changes in groundwater are to be expected as the groundwater flows through the model are minimal. Even more, the water that does leak from these open water boundaries is quickly exfiltrated into the surface water domain and discharged through the 1D weirs. This is indicated by a higher flow over the weirs in the area. The increase by 50 cm leads to an increased average discharge by 11% over the whole simulation period. The decrease by 50 cm causes a decrease in discharge of 6%. For weirs in the area that are affected by these changes, the changes in the yearly total discharge are in the order of 2500 m^3. A relatively small deviation for such a major change in boundary conditions.

These results show that the model result is not significantly affected by changes in surface water levels imposed on the model edge. This implies that the boundaries were chosen at an appropriate location. The results also imply that changes in surface water levels of surrounding canals do not affect the groundwater levels that are not in direct connection with these canals. The water is discharged through the surface water domain.

4.3.2 Temporal Resolution of Precipitation

The effects of the use of a different time series for precipitation is depicted in Figure 15. The precipitation of the Regenradar is lower than the precipitation as measured by the KNMI. The resulting groundwater levels are therefore a few centimetres lower than the calibrated model results.

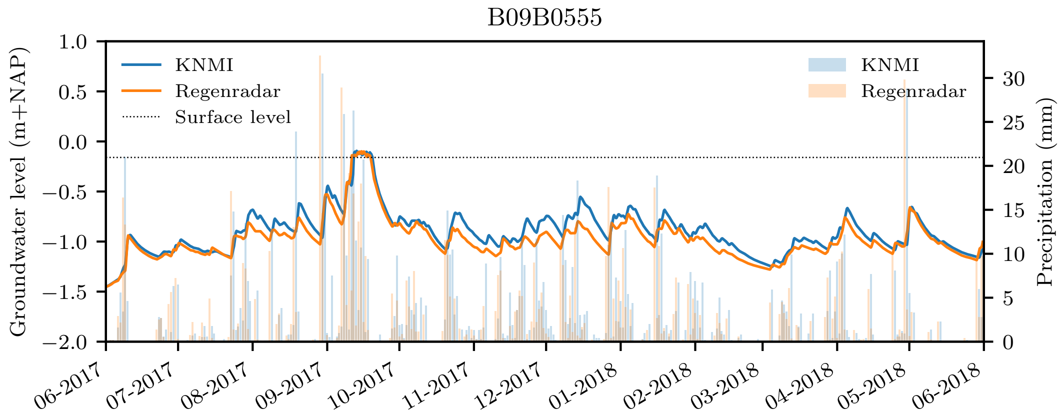


Figure 15: Simulated groundwater levels at measuring well B09B0555 for daily precipitation according to the Regenradar and the KNMI.

The main result, however, is the difference between the 5-minute precipitation data and its 24-hour aggregates. As can be seen in Table 6 a finer resolution in precipitation input from the Regenradar does not have much effect on the outcome of the model compared to the 24-hour aggregates. The difference in the yearly time series is hardly noticeable.

These results indicate that in the current model the temporal resolution of the precipitation does not influence the model results significantly. This is likely due to the infiltration capacity which is still hardly ever exceeded. This indicates that in the current model the temporal resolution of the precipitation is chosen appropriately.

Table 6: Means and standard deviations of simulated groundwater level for different resolutions of the precipitation input time series and the difference between them per measuring well.

	Temporal resolution of precipitation					
	5-minute		24-hour aggregate		Difference	
	Mean (m+NAP)	Std (m)	Mean (m+NAP)	Std (m)	ΔMean (cm)	ΔStd (cm)
B09B0092	-0.530	0.241	-0.527	0.245	-0.334	-0.385
B09B0534	-0.908	0.178	-0.906	0.179	-0.180	-0.141
B09B0542	-0.779	0.189	-0.778	0.187	-0.060	0.249
B09B0544	-0.800	0.139	-0.798	0.141	-0.236	-0.298
B09B0555	-0.974	0.206	-0.973	0.207	-0.071	-0.090
B09B0556	-0.880	0.198	-0.878	0.200	-0.202	-0.260
B09B0557	-1.172	0.147	-1.170	0.149	-0.148	-0.178
B09B0558	-1.194	0.138	-1.193	0.139	-0.137	-0.142

4.3.3 Calculation Grid

The model was run using different grid sizes as shown in Figure 10. The water levels at cross-section A-B, at the 1st of January 2018 is shown in Figure 16. Within the grid refinements, two measuring wells were located B09B0555 and B09B0556. At the location of these wells, the changes in mean and standard deviations were calculated and shown in Table 7. Part the resulting time series for the same wells can be seen in Figure 17.

In Figure 16 it can be seen that the groundwater level between the ditches shows an upward curve. When the supply of water on the farming lots from precipitation and leakage exceeds the groundwater flow towards the ditches the water table increases. An upwards curved water table between two ditches is the result. This is comparable to the behaviour described by Hooghoudt (1940). For cross-section A-B it can be seen that the groundwater level in the middle of the farming lot is higher when a finer grid resolution is used. The difference between the height of the water tables is up to 30 centimetres.

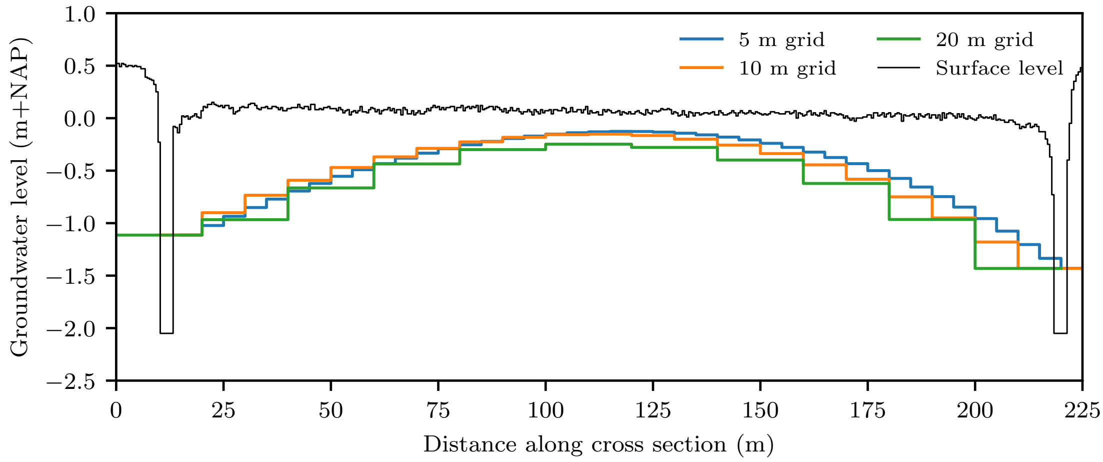


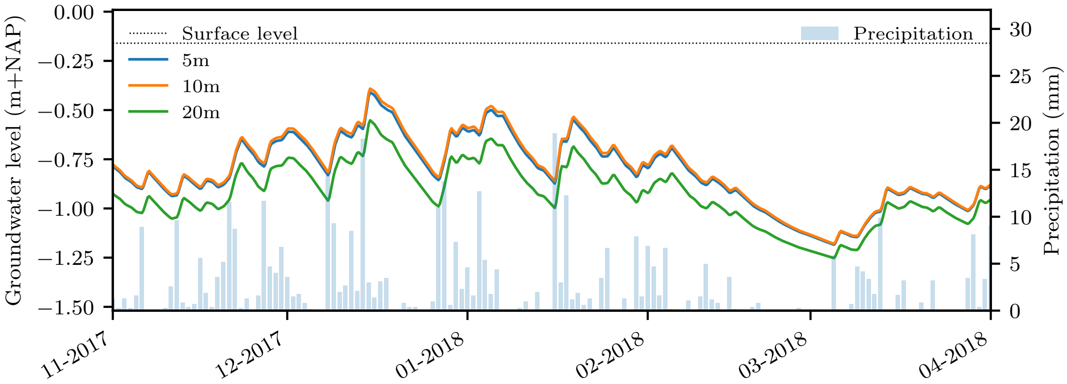
Figure 16: Cross-section of modelled groundwater levels of using different grid sizes on 01-01-2018 at cross-section A-B as shown in Figure 10.

In Figure 17 it can be seen that with increasing grid sizes the groundwater levels go down. For measuring well B09B0555 the effect is greater than for measuring well B09B0556. This is likely due to the fact the distance between the two ditches is artificially shortened by the coarse grid cells. When the distance between two ditches decreases the maximum value of the curvature between two ditches is lowered as well.

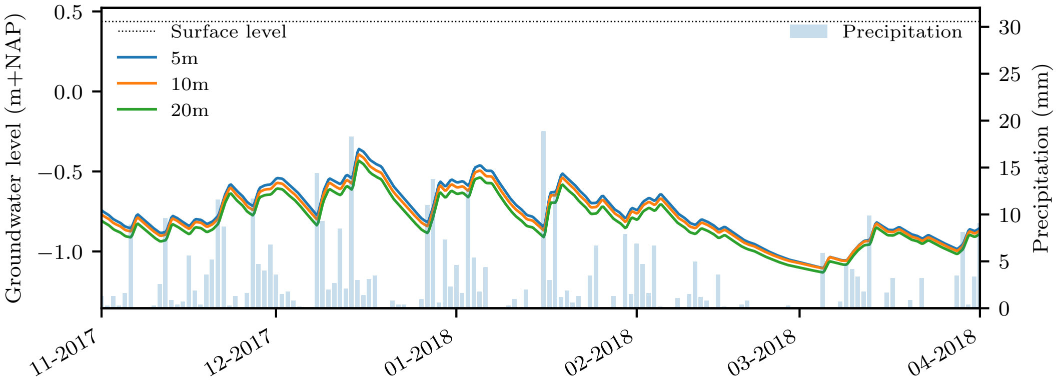
These results imply that the model is affected by its model grid size. When the model grid is too coarse the upward curvature in groundwater levels might be underestimated. It is likely that the calibrated values for hydraulic conductivity correct for these errors. Therefore, when the model grid is not chosen appropriately the model might need to be calibrated again when another grid size is used. This does not form any major problems but needs to be taken into account when modelling, in the 3Di hydrodynamic model. It must be noted that the need for recalibration after a change in grid or mesh is also needed when using other groundwater models.

Table 7: Changes in mean and standard deviation of simulated groundwater level for different calculation grid sizes compared to the calibrated model with a grid 20 m by 20 m.

	10 m x 10 m		5 m x 5 m	
	ΔMean (m)	ΔStd (m)	ΔMean (m)	ΔStd (m)
B09B0555	0.12	0.03	0.11	0.03
B09B0556	0.03	0.01	0.05	0.01



(a) B09B0555



(b) B09B0556

Figure 17: Effects of changes in grid size on groundwater levels for measuring wells (a) B09B0555 and (b) B09B0556

5 Discussion

This chapter will discuss the results of this research in order to evaluate the applicability of the 3Di groundwater model on a polder area. Firstly, the relevance and implications of the results are discussed in section 5.1. Subsequently, the assumptions, simplifications and uncertainties involved in the research process will be evaluated in section 5.2. Finally, section 5.3 will discuss the generalisability of this research.

5.1 Potential

This work is a first application of the 3Di groundwater model to a large polder area, in the Netherlands, in which the water levels are managed by weirs. It is shown that it is feasible to create a model of a polder area in 3Di by the use of a digital elevation model combined with information about the surface and groundwater system. The methods used for creation of the model of the Waalenburg polder can also be used for creating a model for other areas.

The calibration of the model of the Waalenburg polder was easily performed based on the sensitivity analysis and resulted in small RMSE values with a maximum of 11 cm. It is likely that the model is also easily calibrated for other, similar areas.

The study shows that the model can be calibrated by means of a sensitivity analysis. By the use of the Kling-Gupta Efficiency (Gupta et al., 2009) it is shown that the model performs well on all of its aspects. The simulated model results correlate well compared to the measured groundwater levels, little deviation is shown in the mean results of the model and measurements, and the variability of the model results is in accordance with the measurements. The model performance for computing groundwater levels provides confidence in the ability of the model to simulate the groundwater flows, especially so for the winter period.

The 3Di Hydrodynamic model resolves both the groundwater and surface water system simultaneously. Other groundwater models such as MODFLOW (Langevin et al., 2017) focus on only groundwater. These models are however often combined with a one-dimensional surface water model as is the case in the Netherlands Hydrological Instrument (De Lange et al., 2014) or simply regard the surface water domain as a boundary condition. The simulation of both the surface water and groundwater in two dimensions as done in this research provides an additional insight into the relation of and the interaction between these two domains.

5.2 Limitations

This research aimed at evaluating the applicability of the 3Di groundwater model. The available data used to set up the model, calibrate and validate have some limitations. The methodology used in 3Di to simulate the groundwater system knows limitations as well, due to the assumptions made This section will discuss the most important choices and assumptions which influence the results.

5.2.1 Calibration and Validation

The calibration was done using about half of the available time series and uses all measuring wells due to the spatial scarcity in usable measurements. This leaves insufficient data for a sufficient validation of the model. Therefore, it cannot be verified whether or not the model might be over-fitted to its data and its use in predictive studies can, therefore, be questioned.

Furthermore, the unavailability of inflow discharges over several weirs made it not possible to validate the model by the use of a water balance. A possible solution to this is modelling a larger area to estimate the flow over the weirs at the edges of the model. This would, however, increase the complexity of the model and introduces more uncertainty.

5.2.2 Model Design

The simplifications made in 3Di model design can be attributed to its development history. As it was originally designed short term precipitation events where processes such as evaporation do not have to be simulated in great detail (Nelen & Schuurmans, 2019).

A particular point of interest in the 3Di groundwater model is the exclusion of the vadose zone. Processes in the vadose zone determine the evapotranspiration and lag of precipitation towards the groundwater. Other groundwater models have varying strategies to deal with the vadose zone. Models such as MODFLOW (Langevin et al., 2017) and the Netherlands Hydrologic Instrument (De Lange et al., 2014) groundwater recharge is calculated from the precipitation and evaporation by taking among others soil type, land cover and vegetation into account.

Within 3Di the vadose zone is essentially modelled by the infiltration capacity. This infiltration capacity can only decrease over time using the Horton infiltration function. For use in a longer simulation such as the Waalenburg model in this study, this is not sufficient as the infiltration capacity varies over time. This variation is both due to saturation of the vadose zone during a precipitation event but also dependent on other conditions. Such as a decrease in infiltration capacity of grounds after dry periods. Dry ground can have a lower infiltration capacity as described in Burch et al. (1989). The results show that the model performs poorly for June through October 2017. The groundwater recharge in 3Di is likely overestimated as the infiltration rate is too high and the vadose zone is excluded.

The interaction with deeper groundwater layers is not taken into account. Fluxes from other groundwater layers are provided as a boundary condition to the system. Variation in the interaction between these layers cannot be taken into consideration. For use in the model of the Waalenburg, a constant leakage of 0.5 mm/day was assumed. In reality, this leakage flux varies over time based on the differences in hydro-static pressure of the confined and unconfined aquifers. For this area, it is not expected that this limitation affects the results for the simulation period in a significant way. However, changes in the water system as described in section 2.1, are likely to affect the leakage fluxes as has been calculated by Royal HaskoningDHV (2018). The 3Di groundwater model will need to be coupled with another groundwater model in order to to have predictive modelling capabilities when changes interaction between the phreatic aquifer and deeper aquifers are expected to be significant.

5.2.3 Forcing Data

The model assumes actual evapotranspiration by the use of the Global Land Evaporation Amsterdam Model (GLEAM, Martens et al. 2017). GLEAM has a coarse resolution and is therefore hard to scale down. It does, however, take into account the soil moisture which is excluded by the potential evapotranspiration as calculated by the KNMI (2018). It is hard to validate whether or not this evapotranspiration is correct. Because groundwater levels in the area are hardly ever below the surface water levels of the surrounding ditches. A downward curve in the groundwater table between ditches, indicating a net loss of water, can not be found within the data nor the model.

5.3 Generalisation

In this study, the methods are only applied to one area, the Waalenburg polder. Some of the aspects of the area are site-specific, such as the prohibition of groundwater extraction, the density of the measurement network and the proximity of a nature area with high surface and groundwater levels. In other areas in the Netherlands, groundwater abstractions are more common. Nevertheless, these areas can also be modelled within 3Di as these extractions can be used as a forcing on the system.

The use of canals, pumps and weirs as boundary conditions was experimented in this study. This study showed the feasibility of using open canals as boundary conditions, especially if the water level is thoroughly measured. Other polder areas are also heavily regulated by weirs and pumps. These can provide ample data for the use as boundary conditions in models of their respective areas.

The calculation of both the surface and groundwater domain in two dimensions makes the model also applicable as an extension for surface water modelling. Currently, the one-dimensional surface water models in the NHI (De Lange et al., 2014) are based on a bucket-model. A two-dimensional approach of the 3Di Hydrodynamic model makes it so spatial variation in parameters for both surface and groundwater can better be taken into account. Interaction between the surface and phreatic groundwater domain is resolved simultaneously relieving the need for iterative runs of multiple models, which often result in high computation times. The model runs done in this research only took around two and a half hours each.

Further research can be done for other water systems other than a polder. Because, based on the calibration results, the Waalenburg polder has little variability in hydraulic conductivity and storativity. It is not known if similar model results can be achieved for areas where the ground is more complex and the hydraulic conductivity and storativity are not as invariable. An example of another type of water system is an area with peat where variations in hydraulic conductivity and storativity are present. An area such as this can be used to investigate whether it is possible to calibrate the 3Di groundwater model. Results of this can be used to evaluate the applicability of the 3Di groundwater model in other areas.

6 Conclusions and Recommendations

This chapter will start with providing answers the research questions in section 6.1. This is followed by a general conclusion based on the research objective in section 6.2. Finally, section 6.3 provides recommendations to further expand on this research and the development of the 3Di model.

6.1 Answers to the Research Questions

1. *How sensitive are simulated groundwater levels for changes in hydraulic conductivity and storativity, the time-independent model parameters?*

The simulated groundwater levels are sensitive to changes in hydraulic conductivity and storativity in different ways. The means of the simulated groundwater levels are most sensitive for changes in hydraulic conductivity. Increases in hydraulic conductivity result in lower mean groundwater levels. In the maximum case, an increase of 0.25 m/d in hydraulic conductivity leads to a change of up to 20 cm in mean groundwater level within ranges where the ground does not become saturated. Changes in storativity do not significantly affect the mean groundwater levels of the model. These changes in storativity, however, do affect the deviation from the mean groundwater level significantly. Changes in storativity of 2.5% can cause an increase in the standard deviation of up to 10 cm.

2. *How accurate are the modelled time series of groundwater levels compared to the observed time series?*

Groundwater levels can be simulated with high Kling-Gupta Efficiency scores, ranging from 0.68 to 0.86, and good values for its parts when considering the period from 1 November 2017 through 6 July 2018. The mean values of the calibrated model generally only differ up to 5% in comparison with the measurements. The simulated model results correlate well to the measured groundwater levels with correlation coefficients that are generally over 0.7. Therefore, it can be concluded that increases and decreases of modelled groundwater levels are in accordance with the measurements. Additionally, the variability ratio of the model results ranges from 0.88 to 1.18. This indicates that the standard deviation that the standard deviations in the modelled groundwater levels are similar to the standard deviations found in the measurements.

3. *What is the effect of the model design choices on the modelled groundwater levels?*

The model provides good results using daily time series for precipitation and evapotranspiration. It was shown that refining the resolution of the precipitation time series to 5 minutes did not affect the results in a significant way.

Boundary conditions along the model edges that are not in direct connection with ditches along modelled areas do not have a significant impact on groundwater levels within the area. They do however have an impact on the discharges through ditches in the surface water domain.

It was shown that a well-performing model could be created using a grid of 20 m by 20 m for the majority of the area of interest. The grid size is mostly dictated by the surface water system as a calculation cell cannot include multiple surface water levels. It was shown that grid size does affect the groundwater levels. A finer grid may lead to an increase in groundwater levels of up to 30 cm. Due to this fact, changes in grid size may lead to the need for re-calibration of the model.

6.2 General Conclusion

The objective of this research was as follows:

> *Evaluate the applicability of the 3Di groundwater model for a polder area on its accuracy and its sensitivity for changes in time-independent model parameters and model design choices, by creating a model of the Waalenburg polder and comparing the results with observed time series.*

It can be concluded that with the 3Di groundwater model it is possible to simulate groundwater levels within a polder with good accuracy, especially for winter periods. The modelled mean groundwater level is sensitive for the hydraulic conductivity and the modelled variability in groundwater levels is sensitive to the storativity. These sensitivities can be used to calibrate a model of a particular area.

The model design is adequate for the simulation of groundwater levels during wet periods. The current state of the 3Di groundwater model may lack the ability to simulate the groundwater recharge of high precipitation events after a dry period as depicted by the overestimation of in the period July 2017 through November 2017.

It can be concluded that the model is, most likely, applicable to polders and other areas bounded by well-measured canals. The two-dimensional approach of the 3Di Hydrodynamic model makes it so spatial variation in parameters for both surface and groundwater can better be taken into account. Interaction between the surface and phreatic groundwater domain is resolved simultaneously relieving the need for iterative runs of multiple models, which often result in high computation times.

6.3 Recommendations

The applied methods and results synthesised from this research have been discussed in chapter 5 and conclusions were provided in the previous sections. For further research on the 3Di groundwater model that extends from where this research this section will provide several recommendations. Additionally, recommendations will be done for Nelen & Schuurmans for further development of the 3Di Hydrodynamic model.

The discussion describes the fact that it was not possible to validate the model using a water balance. The ability to accurately simulate groundwater levels provides confidence in the ability of the 3Di groundwater model to simulate groundwater flows but is insufficient for model validation. It is recommended that a study is done in order to validate the water balance. For use in this further study, it is important that a case study is selected based on the availability of data. The data must include a complete water balance. Preferably this case study is either limited in size or easily modelled with large calculation cells in order to keep the simulation time low.

The Waalenburg polder has experienced various adaptation. This limited the use-able period of the measurements of groundwater and surface water levels. The groundwater and surface water levels, however, are continuously being monitored. The water levels in the nature area are slowly increased. The adaptation in the water system and the increase in water levels of the nature area offer the to include these adaptations in the model. Thereby investigating the model's ability to simulate the effects of changes in the water system of the Waalenburg polder.

The usability of the 3Di groundwater model might be improved by the inclusion of a time-dependent leakage and seepage input. This term could be used to model the evaporation and seepage or leakage in a more suitable way than the use of net precipitation. Other improvements can be made in the way the groundwater model deals with infiltration. The current Horton infiltration function within 3Di is not suitable for long term calculation as the infiltration capacity can never increase. It is recommended to make this function able to do so.

The final change within the 3Di model that is recommended is to include a vadose zone in the model. This would likely take away the need for an externally calculated net evapotranspiration and the information about soil moisture might be useful for other water management cases such as irrigation advice. An approach for including this zone might be based on the MetaSWAP model (van Walsum et al., 2010) as included in the Netherlands Hydrological Instrument.

References

Anderson, M. P., Woessner, W. W., and Hunt, R. J. (2015). *Applied Groundwater Modeling: Simulation of Flow and Advective Transport.* Elsevier Science & Technology, 2nd edition.

Bear, J. and Cheng, A. H.-D. (2010). *Modeling Groundwater Flow and Contaminant Transport.* Number 5 in Theory and Applications of Transport in Porous Media. Springer Netherlands, Dordrecht.

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

de Berg, M., Cheong, O., van Kreveld, M., and Overmars, M. (2008). *Computational geometry: Algorithms and applications.* Springer Berlin Heidelberg, Berlin, Heidelberg.

Burch, G. J., Moore, I. D., and Burns, J. (1989). Soil hydrophobic effects on infiltration and catchment runoff. *Hydrological Processes*, 3(3):211–222.

Casulli, V. and Stelling, G. S. (2011). Semi-implicit subgrid modelling of three-dimensional free-surface flows. *International Journal for Numerical Methods in Fluids*, 67(4):441–449.

Courant, R., Friedrichs, K., and Lewy, H. (1928). Über die partiellen Differenzengleichungen der mathematischen Physik. *Mathematische Annalen.*

De Lange, W. J., Prinsen, G. F., Hoogewoud, J. C., Veldhuizen, A. A., Verkaik, J., Oude Essink, G. H., Van Walsum, P. E., Delsman, J. R., Hunink, J. C., Massop, H. T. L., and Kroon, T. (2014). An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands Hydrological Instrument. *Environmental Modelling and Software*, 59:98–108.

Delsman, J. and Prinsen, G. (2008). Oppervlaktewater in het Nationaal Hydrologisch Instrumentarium. *Stromingen*, 14(4).

Delsman, J. R., Veldhuizen, A., and Snepvangers, J. (2008). Netherlands Hydrological Modeling Instrument. *Proc. of Modflow and More: Ground Water and Public Policy*, (April).

Diersch, H.-J. G. (2014). *FEFLOW: Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media.* Springer Berlin Heidelberg, Berlin, Heidelberg.

DINOloket (2019). Grondwatermonitoring. `https://www.dinoloket.nl/ondergrondgegevens`. Last accessed on 25-09-2019.

Gupta, H. V., Kling, H., Yilmaz, K. K., and Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, 377(1-2):80–91.

Hooghoudt, S. (1940). Bijdragen tot de kennis van eenige natuurkundige grootheden van den grond: Algemeene beschouwing van het probleem van de detailontwatering en de infiltratie door middel van parallel loopende drains, greppels, slooten en kanalen. Technical Report 7, Algemeene Landsdrukkerij, 's-Gravenhage.

Horton, R. E. (1933). The Role of Infiltration in the Hydrologic Cycle. *Transactions, American Geophysical Union*, 14(1):446.

Hunt, R. J. and Zheng, C. (2012). The Current State of Modeling. *Ground Water*, 50(3):330–333.

Kampf, S. K. and Burges, S. J. (2007). A framework for classifying and comparing distributed hillslope and catchment hydrologic models. *Water Resources Research*, 43, W05423.

KNMI (1988). Van Penman naar Makkink: een nieuwe berekeningswijze voor de klimatologische verdampingsgetallen. Technical report, Commissie voor Hydrologish Onderzoek TNO, Den Haag.

KNMI (2018). Dagwaarden neerslagstations. `https://www.knmi.nl/nederland-nu/klimatologie/monv/reeksen`. Last accessed on 20-11-2019.

Knoben, W. J. M., Freer, J. E., and Woods, R. A. (2019). Technical note: Inherent benchmark or not? Comparing Nash-Sutcliffe and Kling-Gupta efficiency scores. *Hydrology and Earth System Sciences Discussions*, (July):1–7.

Kollet, S., Sulis, M., Maxwell, R. M., Paniconi, C., Putti, M., Bertoldi, G., Coon, E. T., Cordano, E., Endrizzi, S., Kikinzon, E., Mouche, E., Mügler, C., Park, Y.-J., Refsgaard, J. C., Stisen, S., and Sudicky, E. (2017). The integrated hydrologic model intercomparison project, IH-MIP2: A second set of benchmark results to diagnose integrated hydrology and feedbacks. *Water Resources Research*, 53(1):867–890.

Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., and Provost, A. M. (2017). Documentation for the MODFLOW 6 Groundwater Flow Model. Technical report, U.S. Geological Survey.

Martens, B., Miralles, D. G., Lievens, H., Van Der Schalie, R., De Jeu, R. A., Fernández-Prieto, D., Beck, H. E., Dorigo, W. A., and Verhoest, N. E. (2017). GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. *Geoscientific Model Development*, 10(5):1903–1925.

Miralles, D. G., Holmes, T. R., De Jeu, R. A., Gash, J. H., Meesters, A. G., and Dolman, A. J. (2011). Global land-surface evaporation estimated from satellite-based observations. *Hydrology and Earth System Sciences*, 15(2):453–469.

Nash, J. and Sutcliffe, J. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*.

Nelen & Schuurmans (2018). Kennisrapportage: Modeling Down Under - "Serious simulations" van de klimaatadaptieve stad. Technical report, Kennis- en Innovatieontwikkeling Bodem en Ondergrond, Utrecht.

Nelen & Schuurmans (2019). 3Di Documentation. `https://docs.3di.lizard.net/`. Last accessed on 20-11-2019.

OECD (2014). *Water Governance in the Netherlands: Fit For the Future?* OECD Studies on Water. OECD.

Provincie Noord Holland (2016). Watergebiedsplan natuurontwikkeling Waalenburg. Technical report, Provincie Noord-Holland, Haarlem.

Publieke Dienstverlening op de Kaart (2014). Dataset: Actueel Hoogtebestand Nederland (AHN3). `https://www.pdok.nl/nl/introductie/-/article/actueel-hoogtebestand-nederland-ahn3-`. Last accessed on 01-11-2019.

Royal HaskoningDHV (2015). Geohydrologisch onderzoek peilopzet Waalenburg. Technical report, RoyalHaskoningDHV, Amsterdam.

Royal HaskoningDHV (2018). Analyse nulmeting Waalenburg. Technical report, Royal HaskoningDHV, Amsterdam.

Royal HaskoningDHV; Nelen & Schuurmans (2013). Nationale Regenradar Toelichting operationele neerslagproducten. Technical report, Nationale Regenradar.

Schwanenberg, D., Becker, B. P., and Xu, M. (2015). The open real-time control (RTC)-Tools software framework for modeling RTC in water resources sytems. *Journal of Hydroinformatics*, 17(1):130–148.

Stelling, G. S. (2012). Quadtree flood simulations with sub-grid digital elevation models. *Proceedings of the Institution of Civil Engineers - Water Management*, 165(10):567–580.

Stiboka (1951). Texel doorlaatfactoren kaart. map, Scale 1:20000, T.52130, the Netherlands.

Vernes, R. and van Doorn, T. (2005). Van Gidslaag naar Hydrogeologische Eenheid, Toelichting op de totstandkoming van de dataset REGIS II. Technical report, TNO, Utrecht.

Volp, N. D., van Prooijen, B. C., and Stelling, G. S. (2013). A finite volume approach for shallow water flow accounting for high-resolution bathymetry and roughness data. *Water Resources Research*, 49(7):4126–4135.

de Vries, J. J. (2007). Groundwater. In Wong, T. E., Batjes, D. A., and de Jager, J., editors, *Geology of the Netherlands*, pages 295–315. Royal Netherlands Academy of Arts and Sciences.

van Walsum, P., Veldhuizen, A., and Groenendijk, P. (2010). SIMGRO 7.1.0 Theory and model implementation. Technical report, Alterra, Wageningen.

Werkgroep Herziening Cultuurtechnisch Vademecum (1988). Cultuur technisch vademecum; deel III water. Technical report, Cultuurtechnische vereniging, Utrecht.

Witteveen+Bos (2000). Groot Geohydrologisch Onderzoek Texel. Technical report, Witteveen+Bos, Almere.

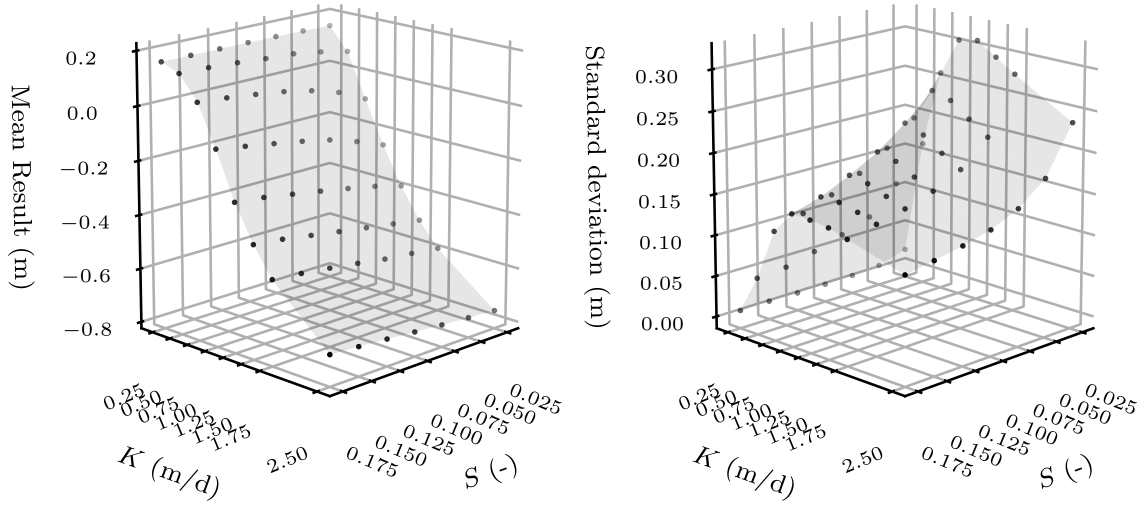
Appendix

A Crest Levels of Weirs

Table 8: Crest levels of weirs in the model for the summer and winter periods.

Weir ID	Code	Crest level		
		06-06-17 to 15-09-17 (m+NAP)	16-09-17 to 18-03-18 (m+NAP)	18-03-18 to 06-06-18 (m+NAP)
1	KST-Q-23857	-1.44	-1.42	-1.44
2	KST-Q-24065	-1.17	-1.16	-1.17
3	KST-Q-24099	-1.33	-1.32	-1.33
4	KST-Q-23924	-1.01	-0.89	-1.01
5	KST-Q-23739	-0.65	-0.65	-0.65
6	KST-S-2022	-0.62	-0.62	-0.62
7	KST-Q-24062	-0.46	-0.45	-0.46
8	KST-Q-24122	-0.89	-0.71	-0.89
9	KST-Q-24054	-1.24	-1.41	-1.24
10	KST-Q-24146	-1.22	-1.21	-1.22
11	KST-S-2049	-0.80	-0.73	-0.80
12	KST-AL-8	-0.80	-0.81	-0.80
13	KST-S-2038	-0.95	-0.98	-0.95
14	KST-S-2040	-1.46	-1.46	-1.46
15	KST-AL-3	-1.32	-1.24	-1.40
16	KST-AL-4	-1.20	-1.20	-1.23
17	KST-S-2044	-1.45	-1.45	-1.50
18	KST-JL-2586	-1.14	-1.15	-1.14
19	KST-Q-23770	-1.58	-1.60	-1.58
20	KST-AL-10	-1.20	-1.19	-1.20
21	KST-Q-23426	-1.58	-1.58	-1.16
22	KST-S-2037	-1.51	-1.53	-1.51
23	KST-JL-2587	-0.97	-0.88	-0.97
24	KST-M-6331	-1.51	-1.51	-1.51
25	KST-Q-23233	-1.11	-1.14	-1.11
26	KST-AL-06	-1.08	-1.10	-1.08
27	KST-JL-2596	-1.04	-1.04	-1.03
28	KST-A-1420	-0.85	-0.93	-0.83
29	KST-S-2136	-1.02	-1.02	-1.02
30	KST-JL-2597	-0.65	-0.58	-0.65
31	KST-Q-24012	-1.15	-1.17	-1.15
32	KST-S-2164	-1.18	-1.18	-1.18
33	KST-S-2159	-1.17	-1.15	-1.17
34	KST-Q-24137	-0.95	-0.93	-0.95
35	KST-JL-2573	-0.60	-0.56	closed
37	KST-Q-23668	-1.17	-1.19	-1.17
38	KST-Q-23702	-1.37	-1.44	-1.37
39	KST-Q-23860	-0.95	-0.93	-0.95

B Figures Mean and Standard Deviation of Model Results



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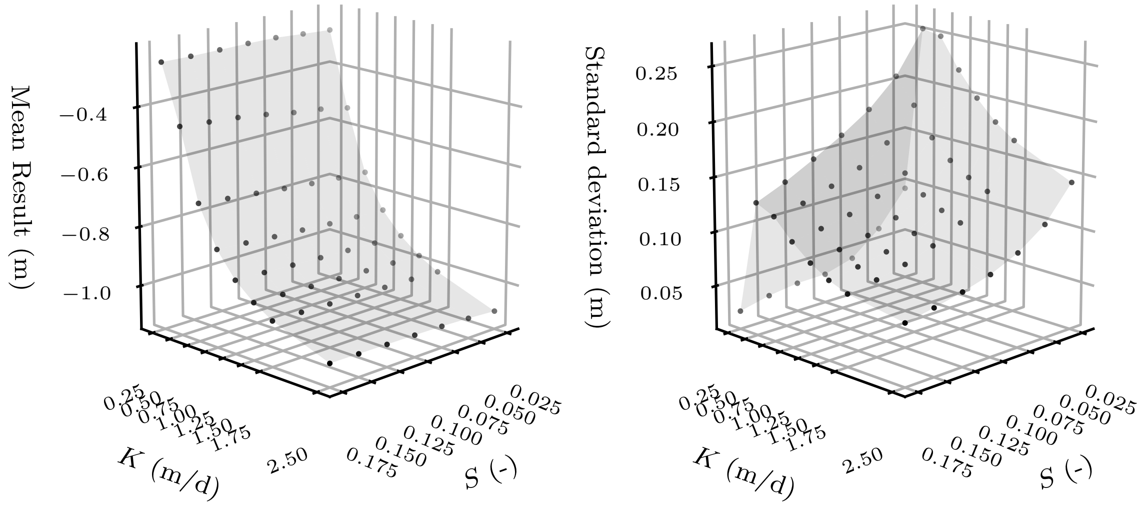

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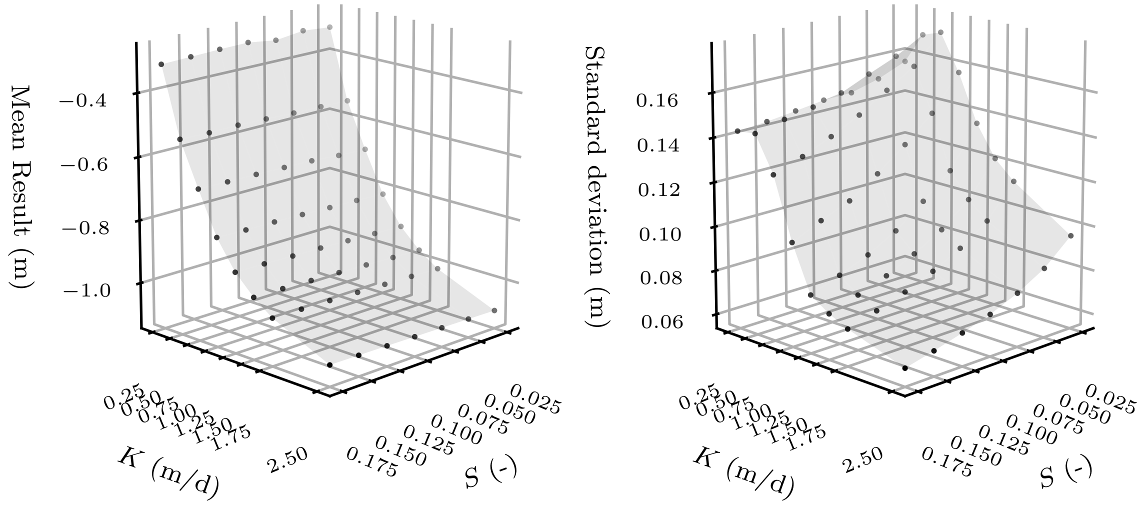
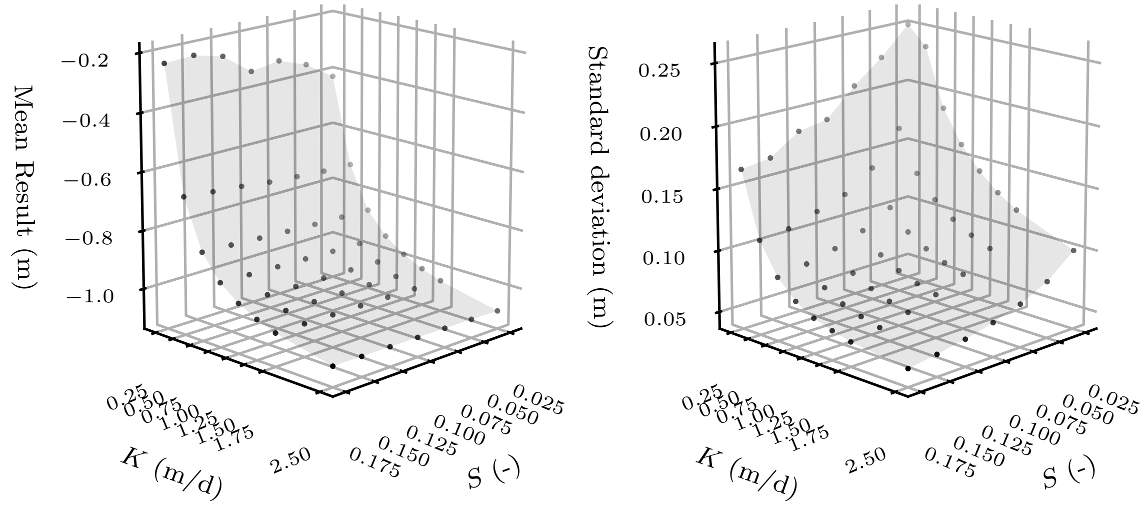
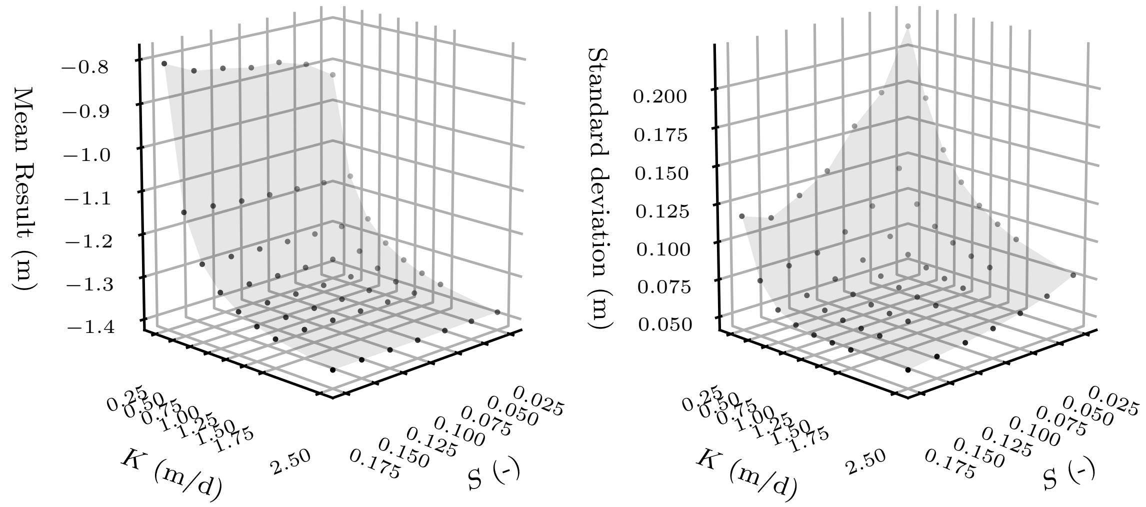


(c) B09B0542

Figure 18: Mean and standard deviation of groundwater levels for hydraulic conductivity and storativity per measuring well. *(continued on next page.)*



(d) B09B0543



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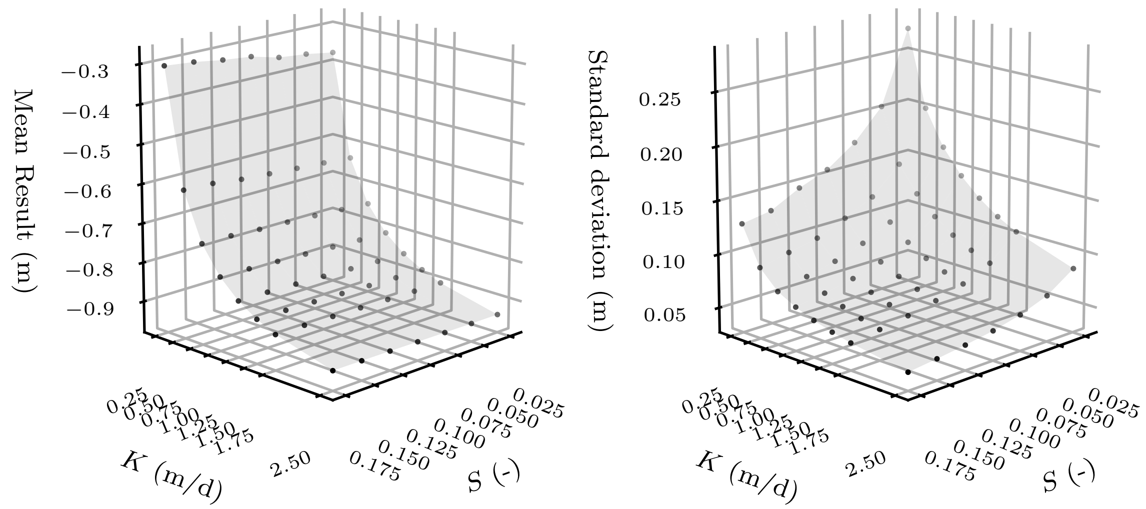
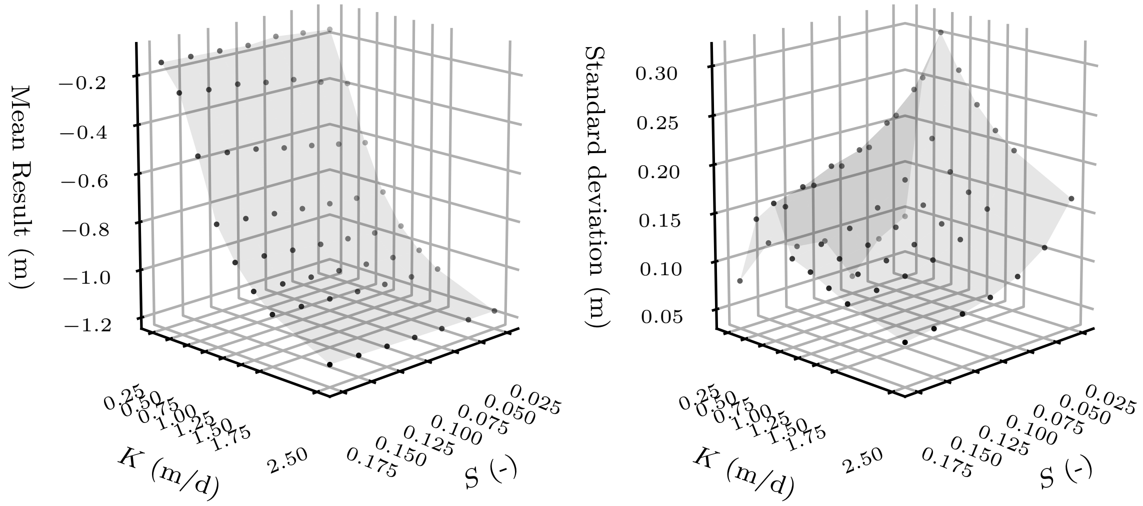


(f) B09B0555

Figure 18: Mean and standard deviation of groundwater levels for hydraulic conductivity and storativity per measuring well. *(continued on next page.)*



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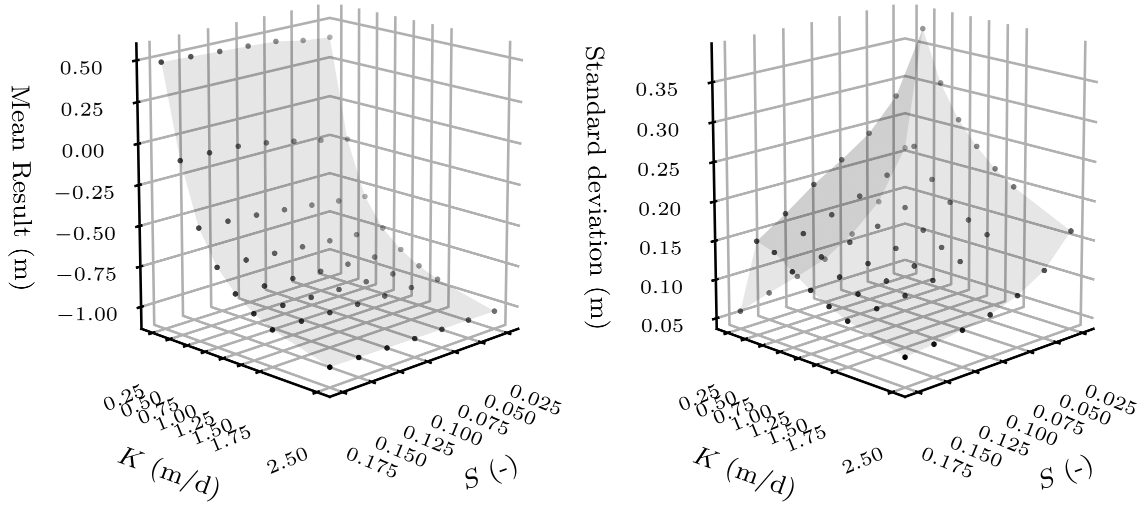
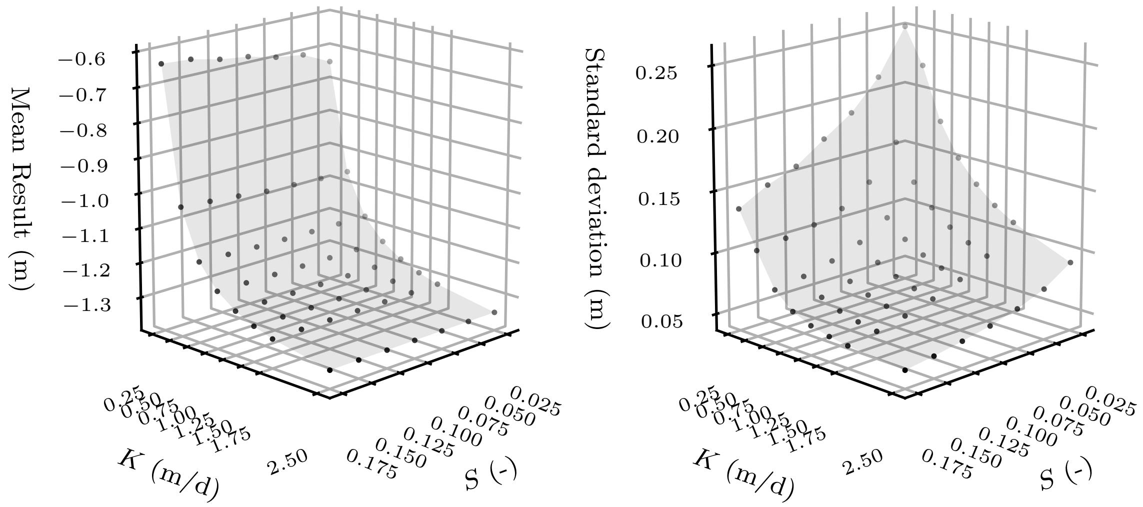
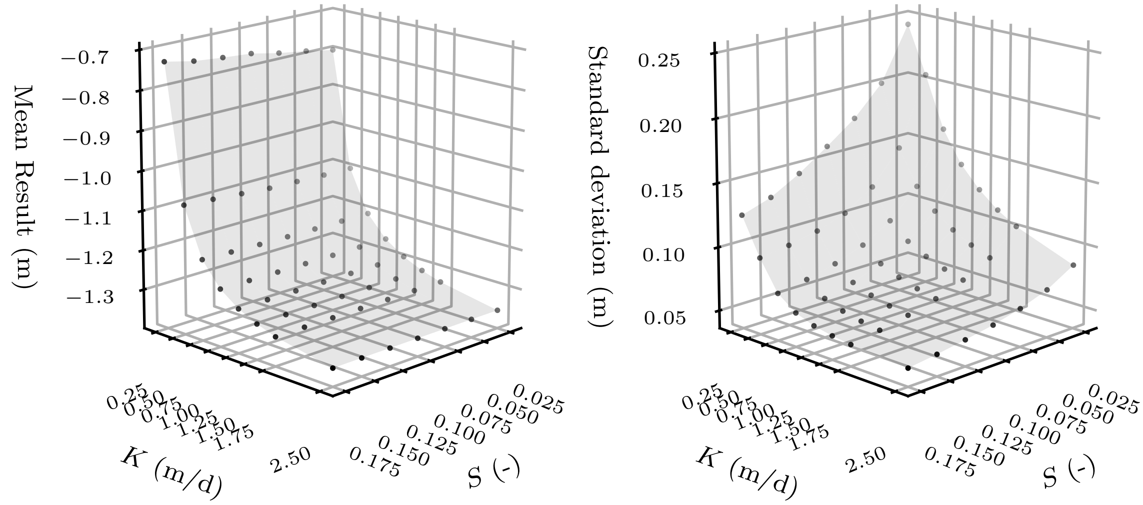


(h) B09B0557



(i) B09B0558

Figure 18: Mean and standard deviation of groundwater levels for hydraulic conductivity and storativity per measuring well. *(continued on next page.)*



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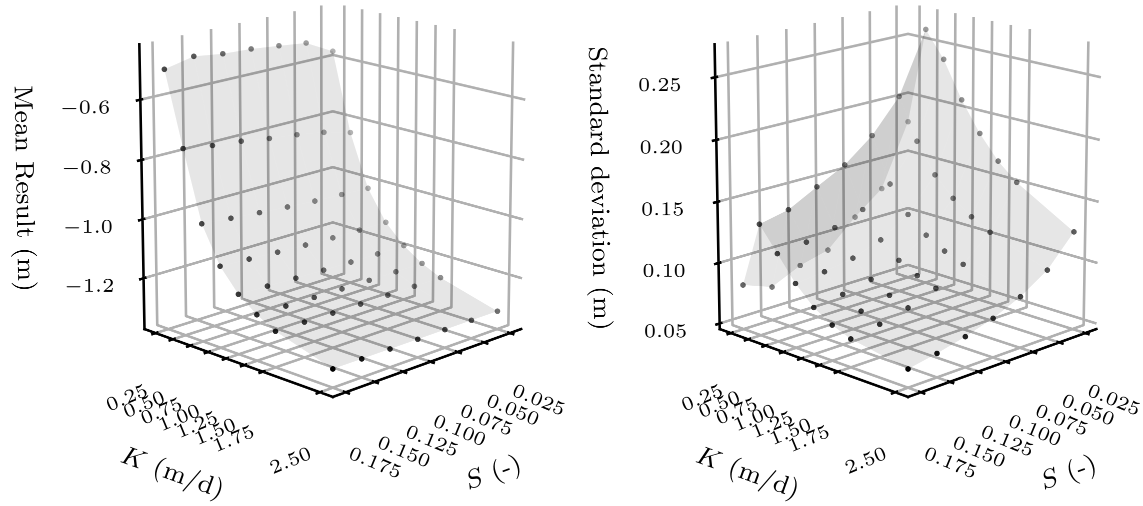
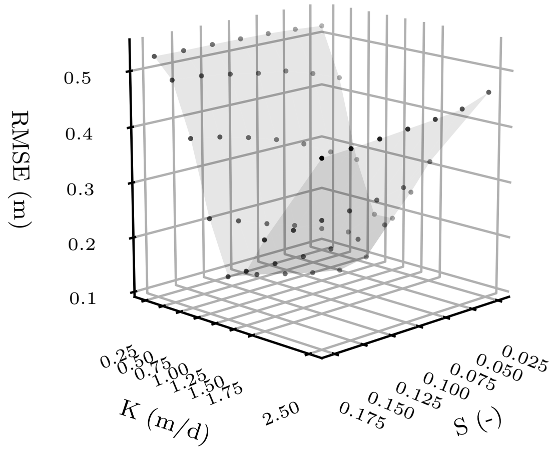


(k) B09B0560

Figure 18: Mean and standard deviation of groundwater levels for hydraulic conductivity and storativity per measuring well.

C Figures RMSE of Model Results



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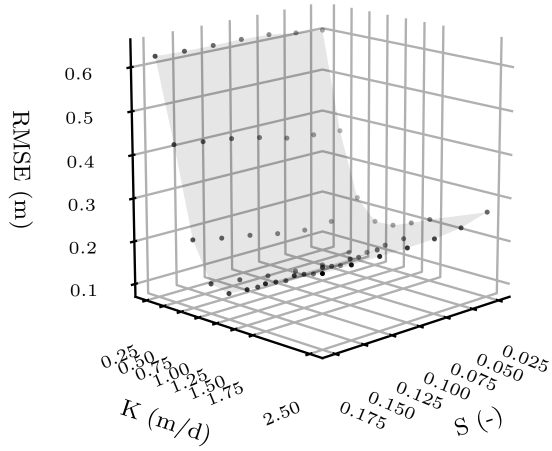

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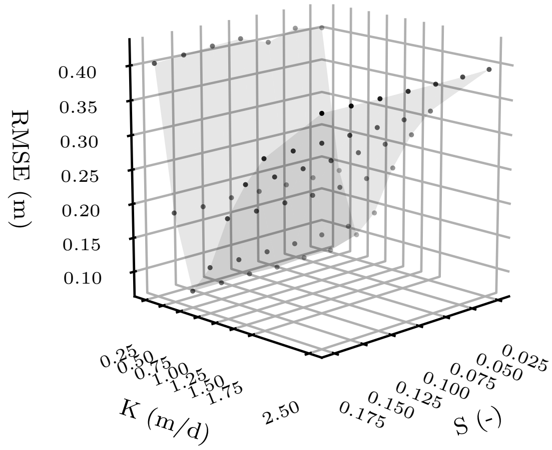

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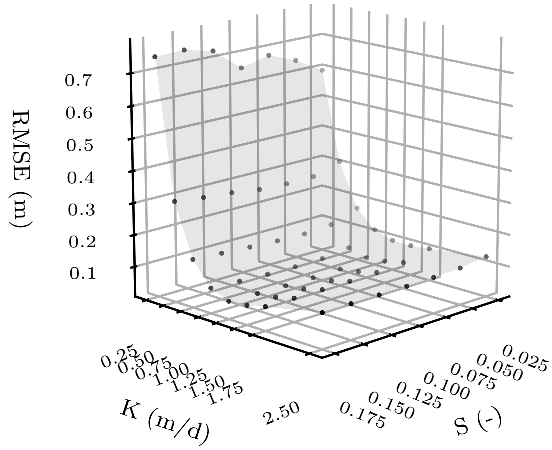

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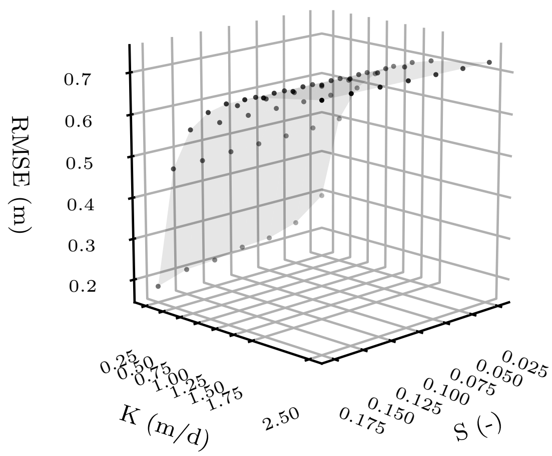

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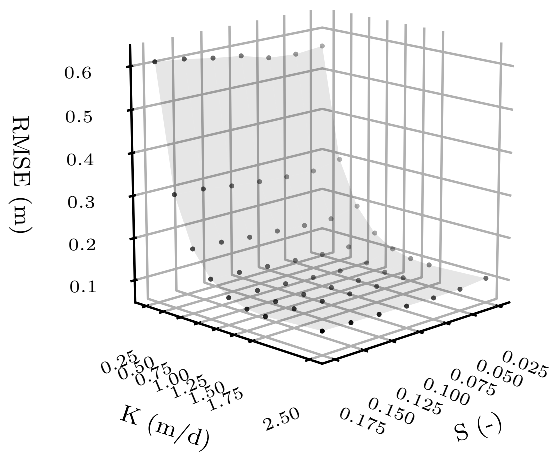

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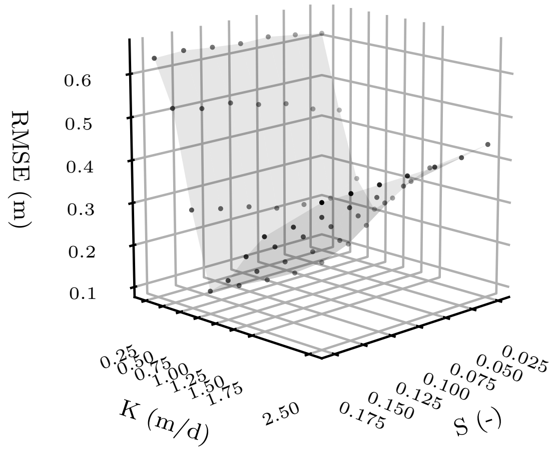
Figure 19: Sensitivity of RMSE for hydraulic conductivity and storativity per measuring well. *(continued on next page.)*



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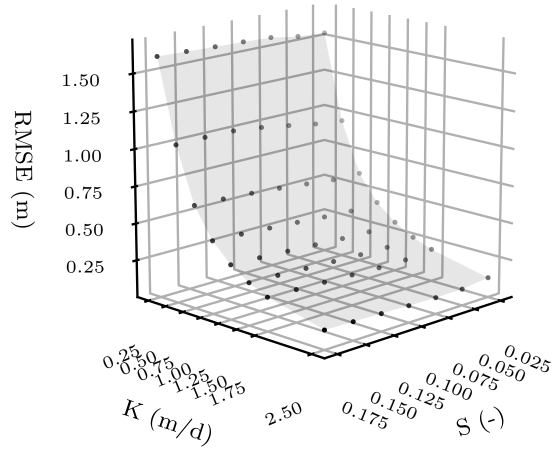

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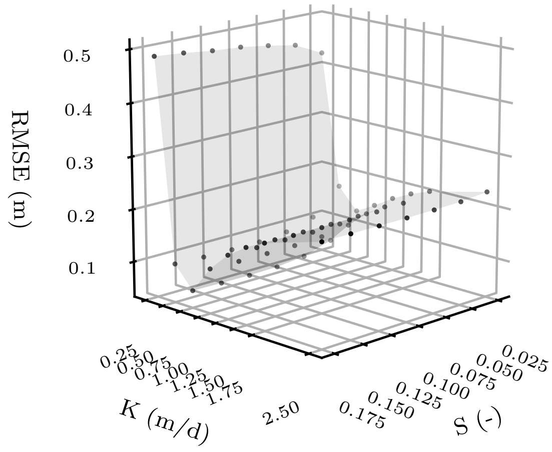
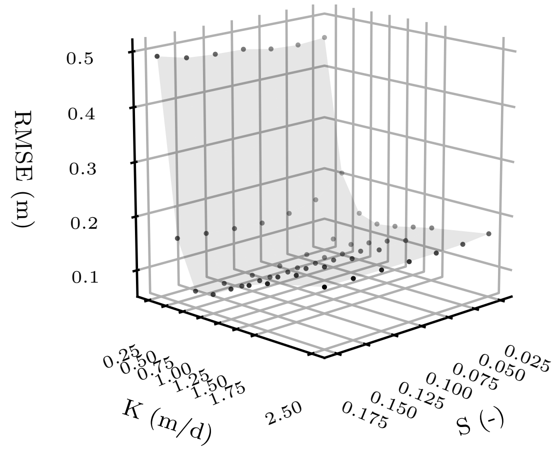


(i) B09B0558



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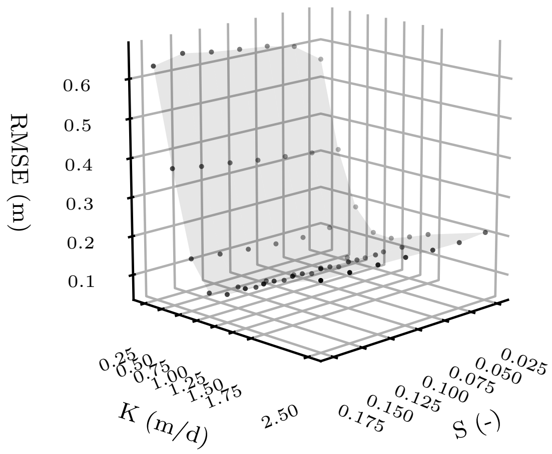


(k) B09B0560

Figure 19: Sensitivity of RMSE for hydraulic conductivity and storativity per measuring well

D Calibrated Hydraulic Conductivity

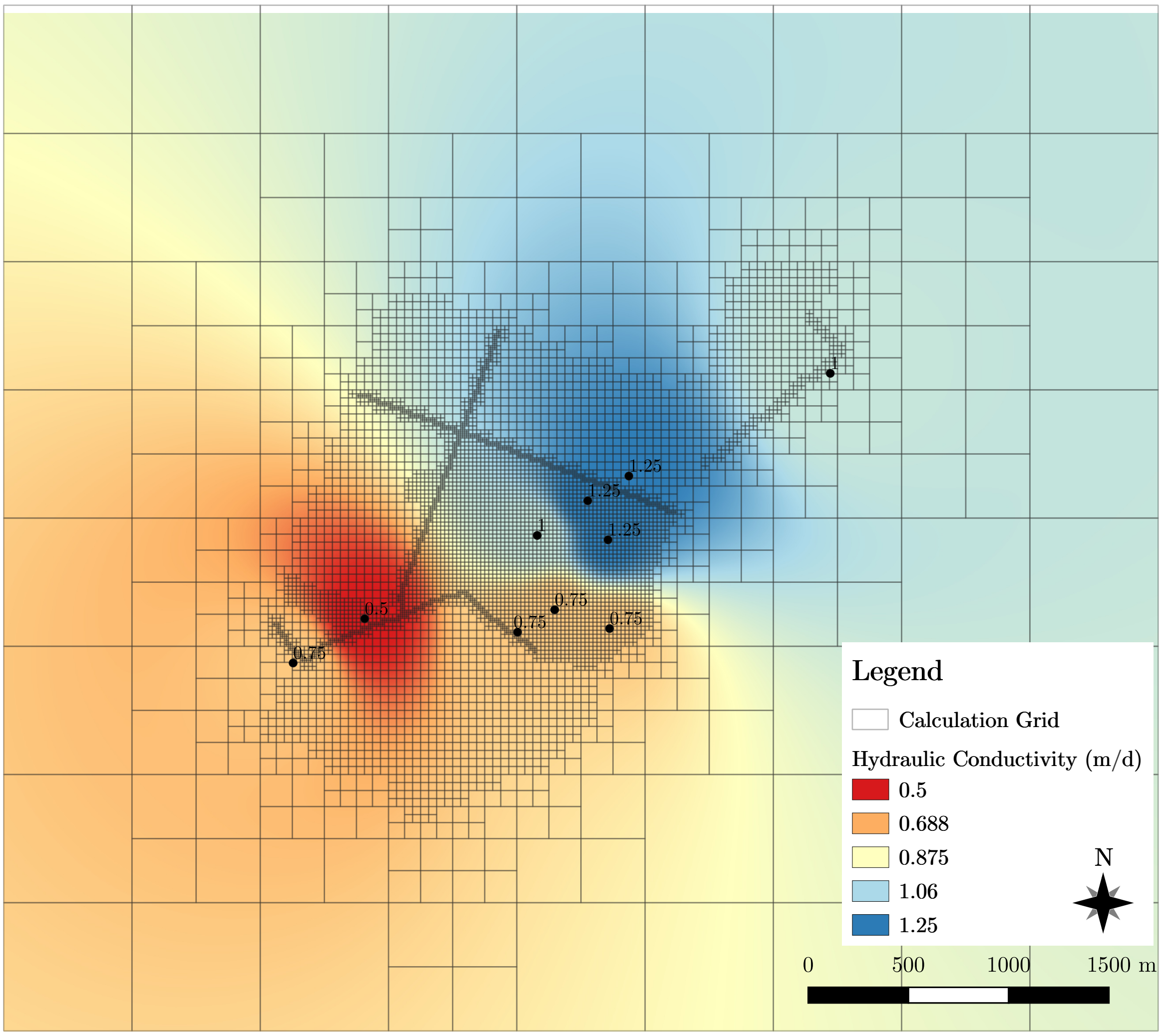
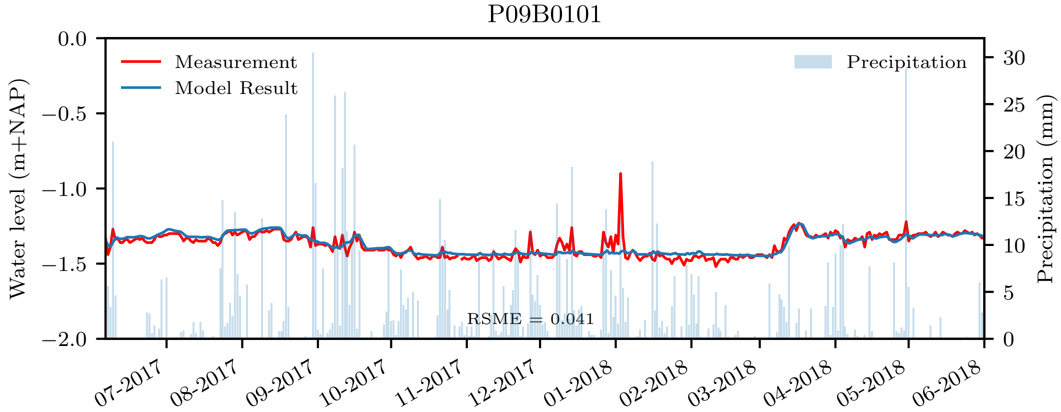
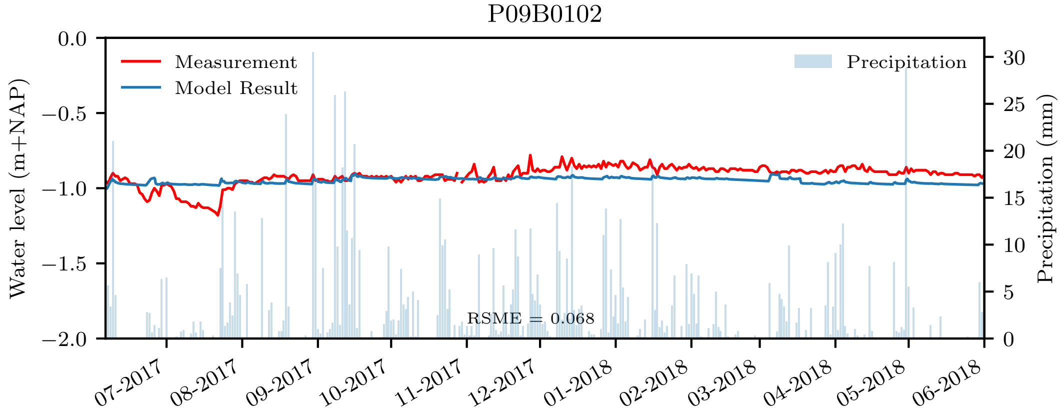


Figure 20: Calibrated hydraulic conductivity

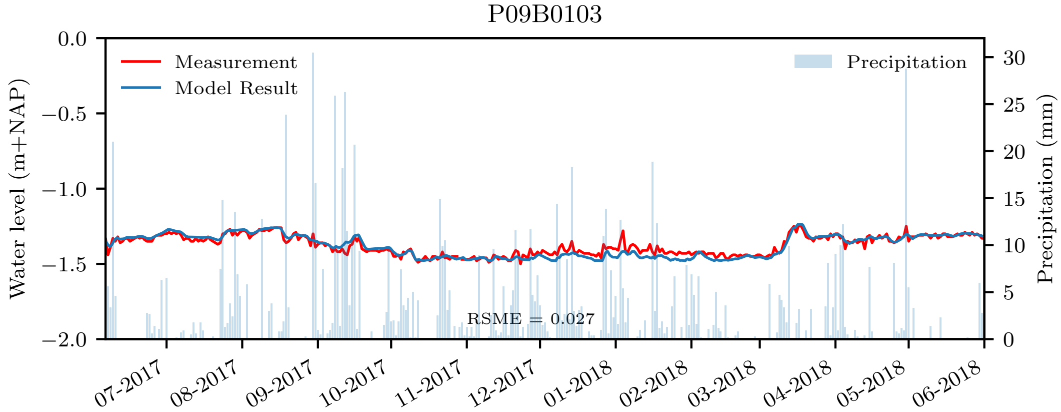
E Figures Surface Water Levels



(a)

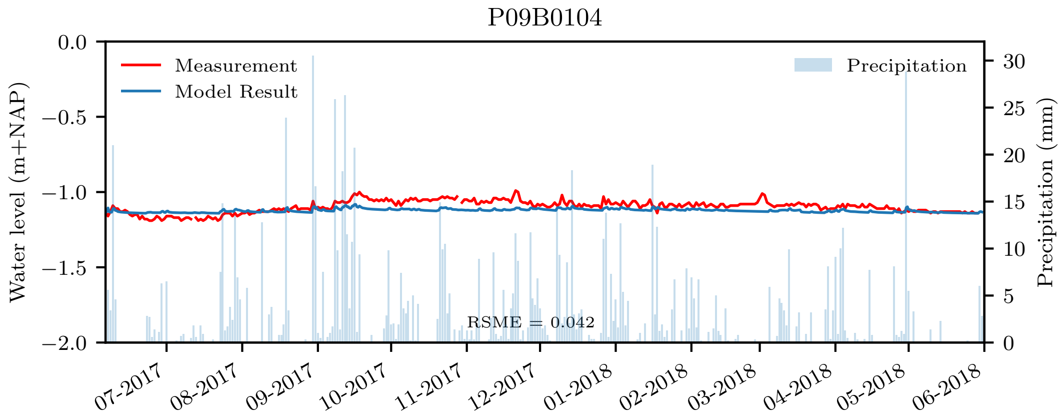


(b)



(c)

Figure 21: Measured and simulated surface water levels and RSME per measuring location.
(continued on next page.)



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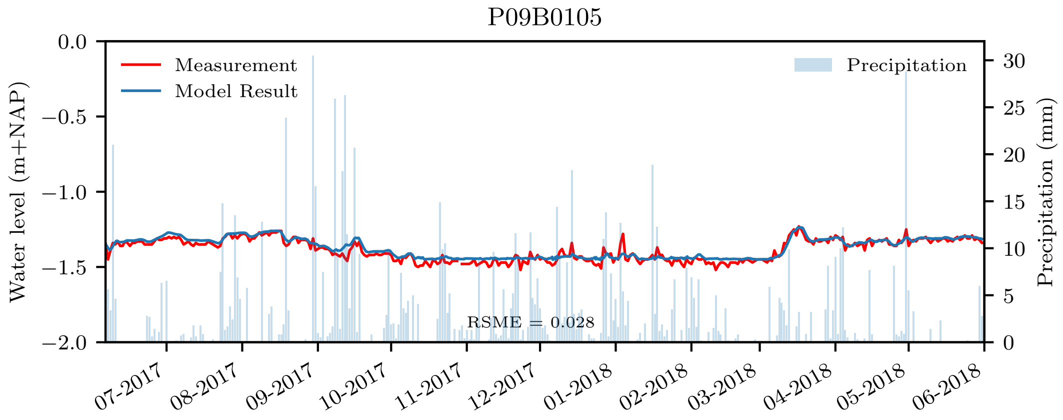

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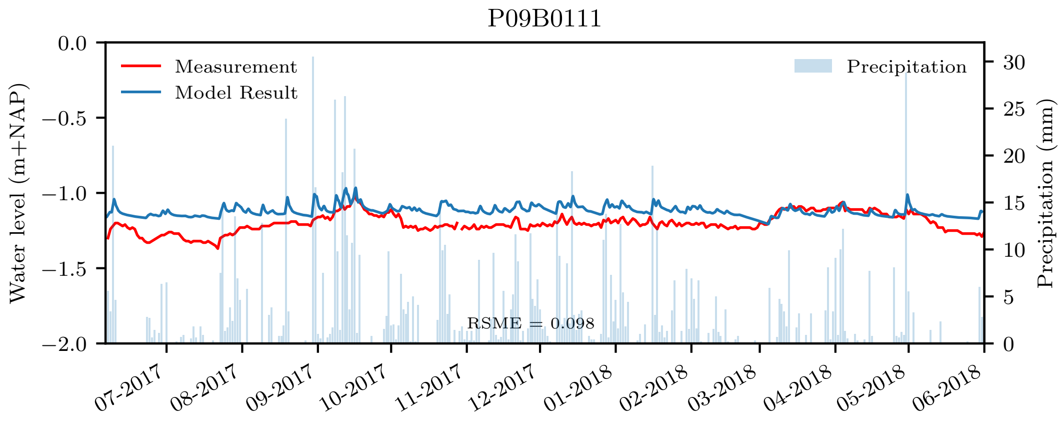

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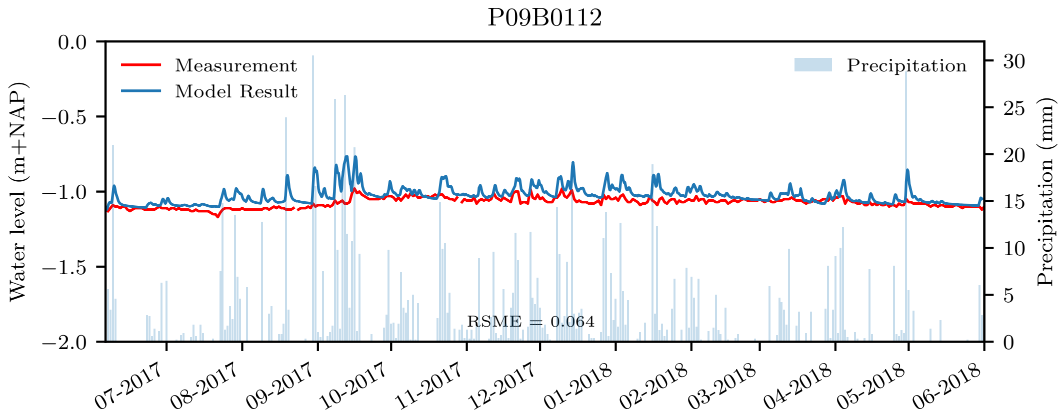
Figure 21: Measured and simulated surface water levels and RSME per measuring location.
(continued on next page.)



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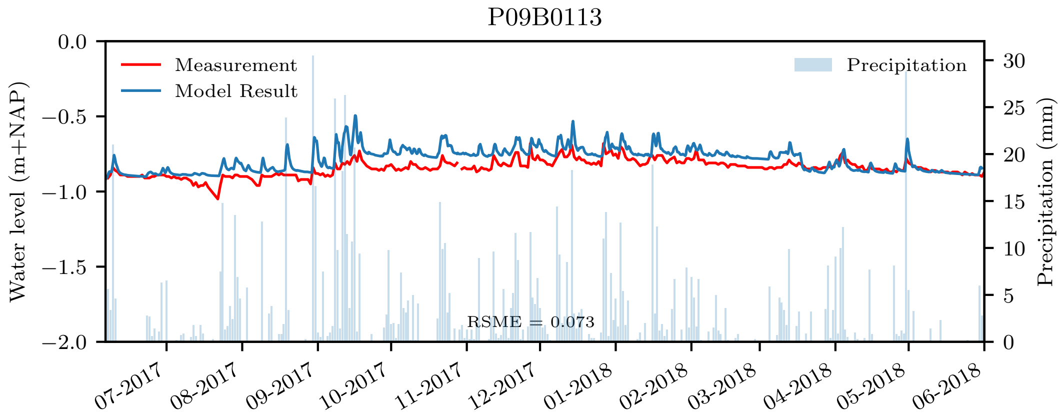

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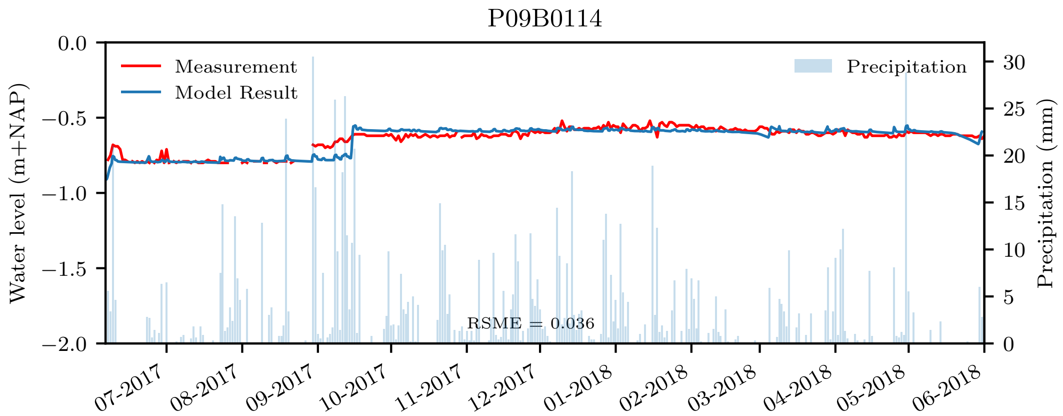
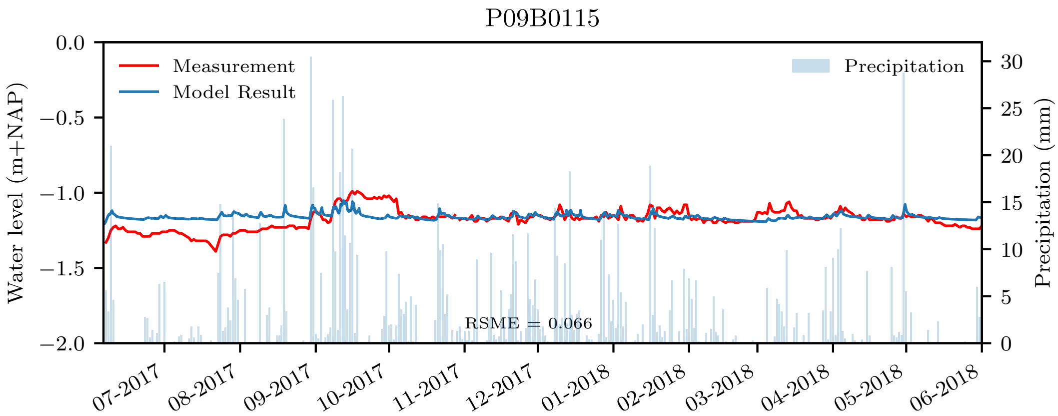


(i)

Figure 21: Measured and simulated surface water levels and RSME per measuring location.
(continued on next page.)



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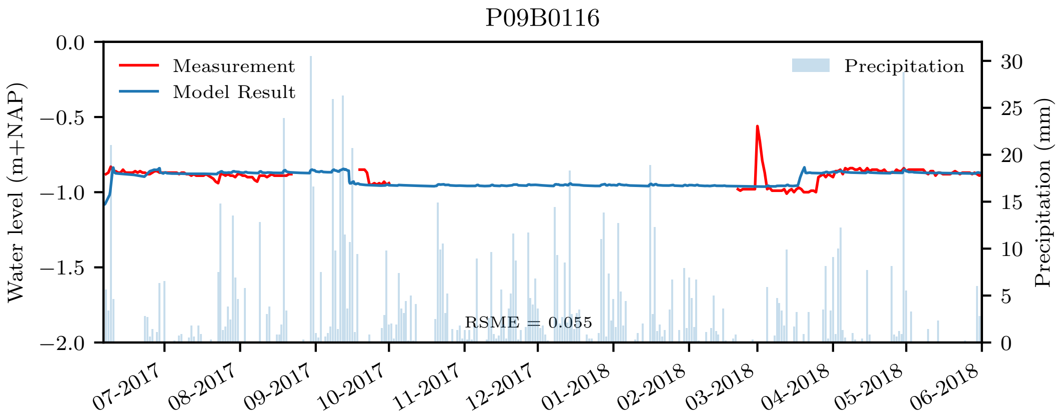
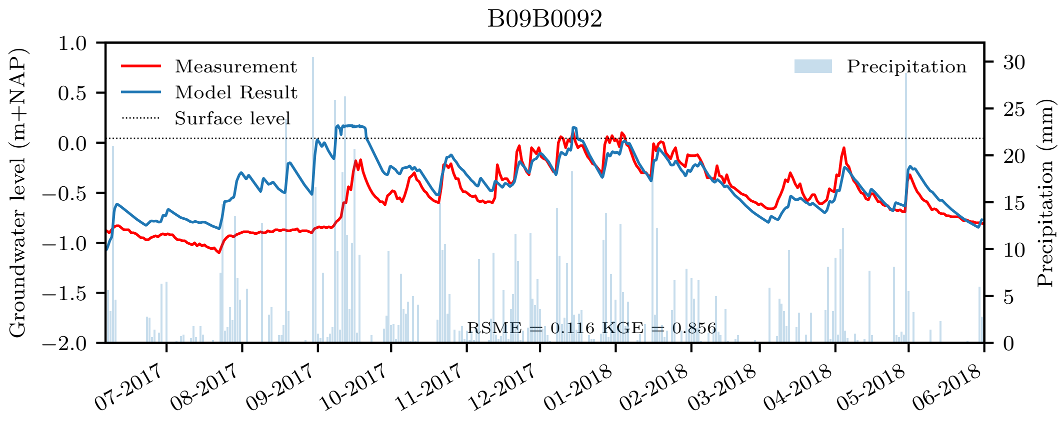


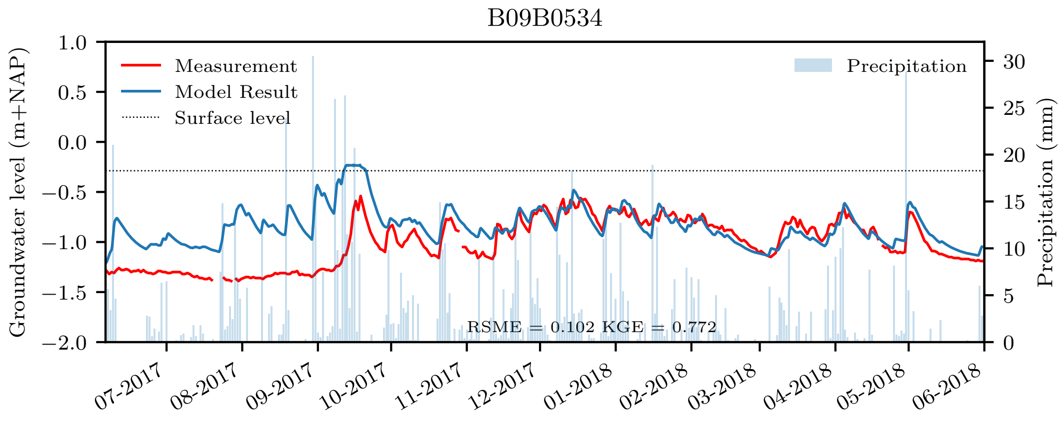
(k)

Figure 21: Measured and simulated surface water levels and RSME per measuring location.

F Figures Calibrated Groundwater Levels



(a)



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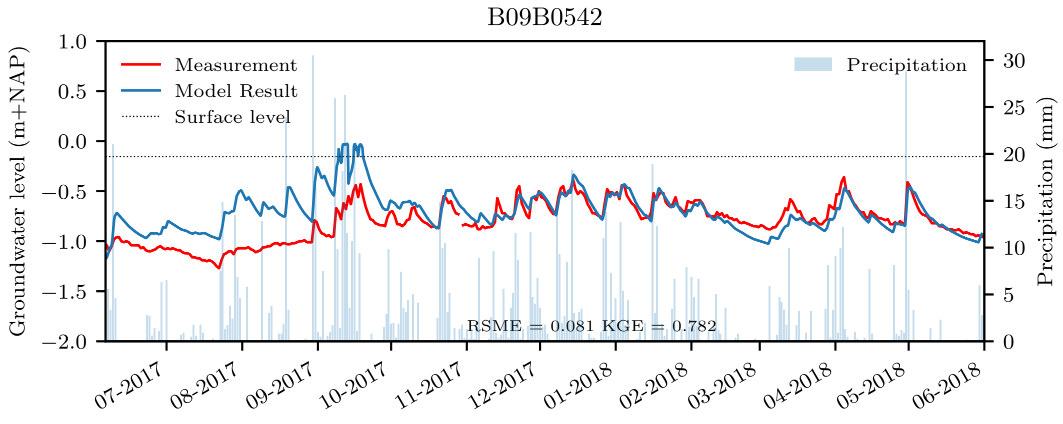
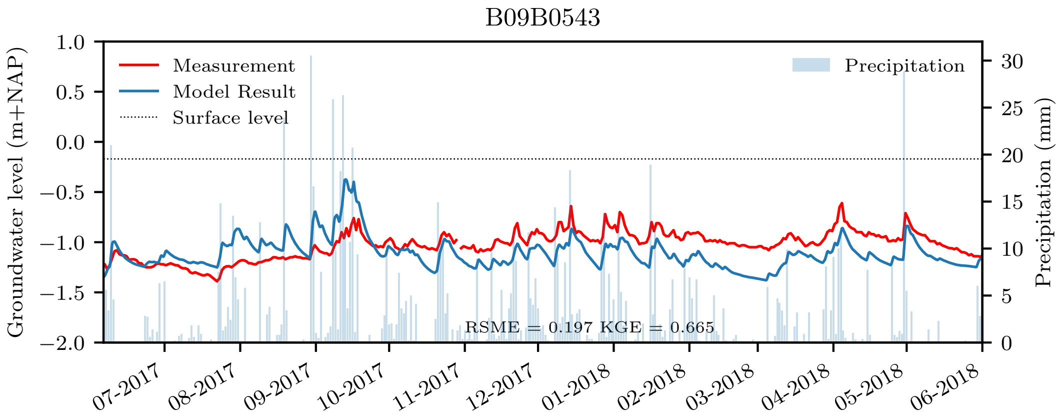


(c)

Figure 22: Measured and simulated groundwater levels and the RSME and KGE for 01-10-17 through 01-06-18 per measuring well. *(continued on next page.)*



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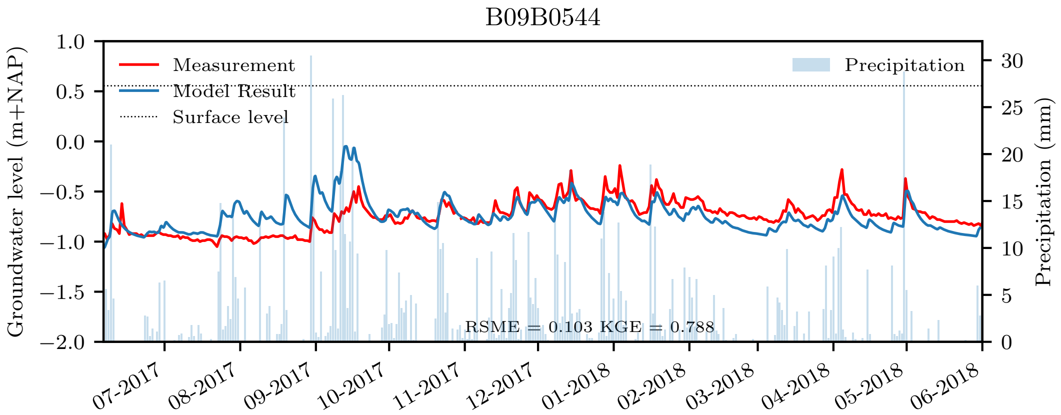

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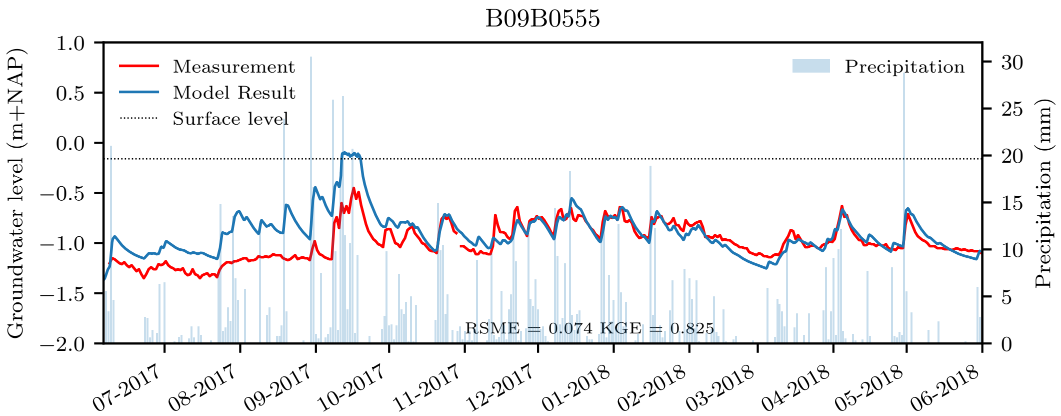
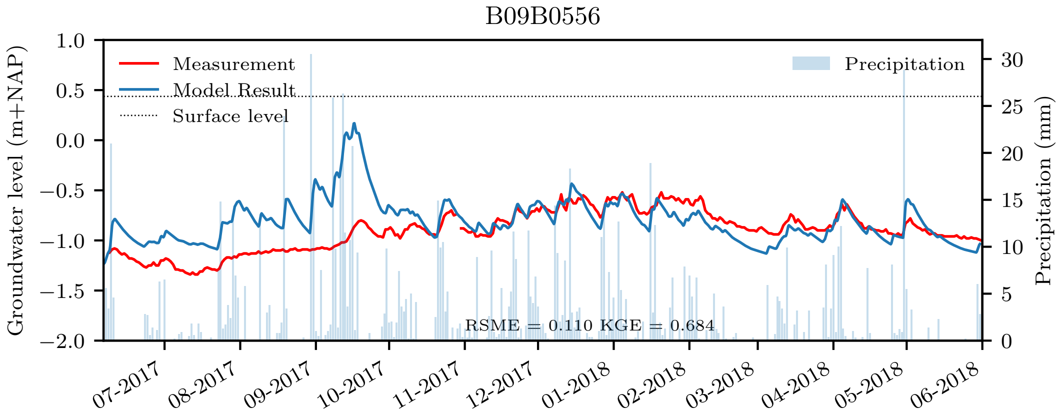


(f)

Figure 22: Measured and simulated groundwater levels and the RSME and KGE for 01-10-17 through 01-06-18 per measuring well. *(continued on next page.)*



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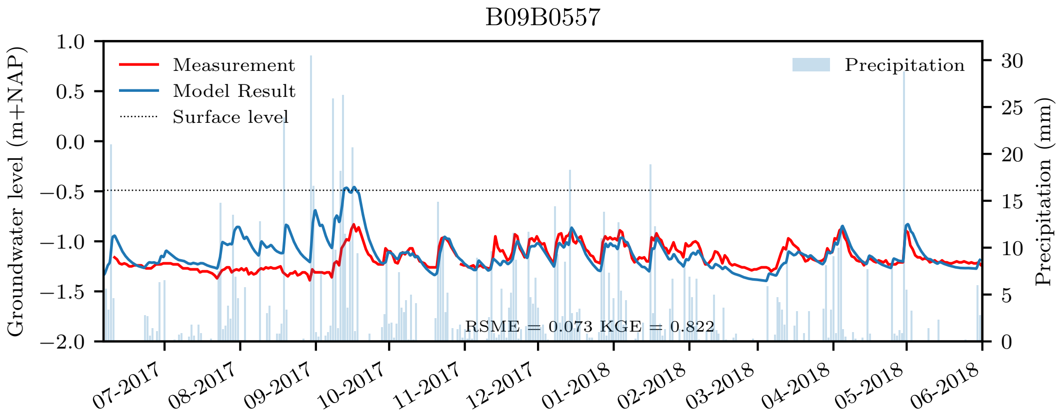

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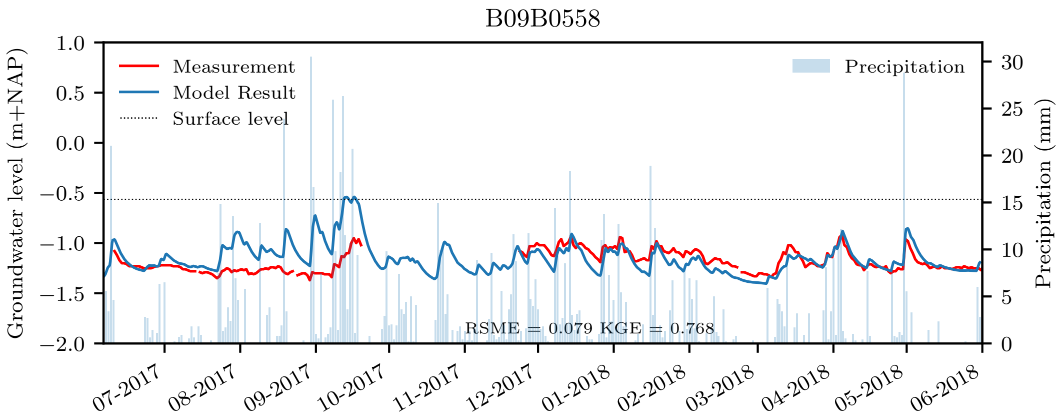
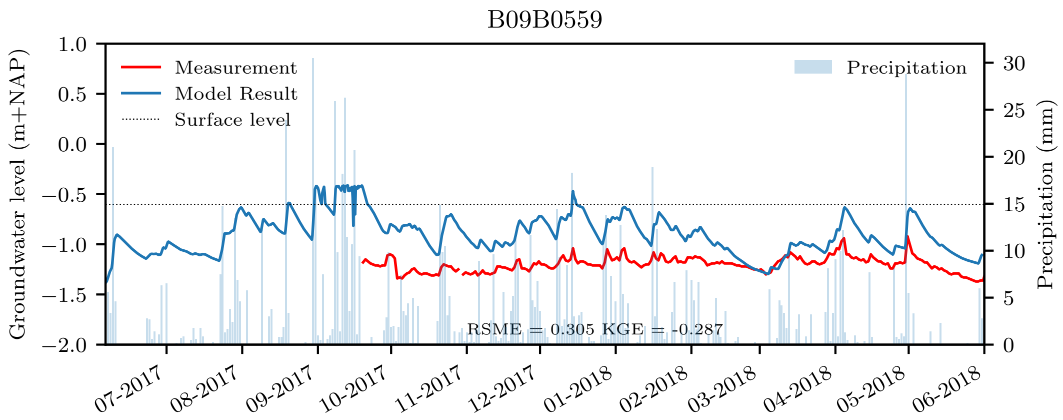


(i)

Figure 22: Measured and simulated groundwater levels and the RSME and KGE for 01-10-17 through 01-06-18 per measuring well. *(continued on next page.)*



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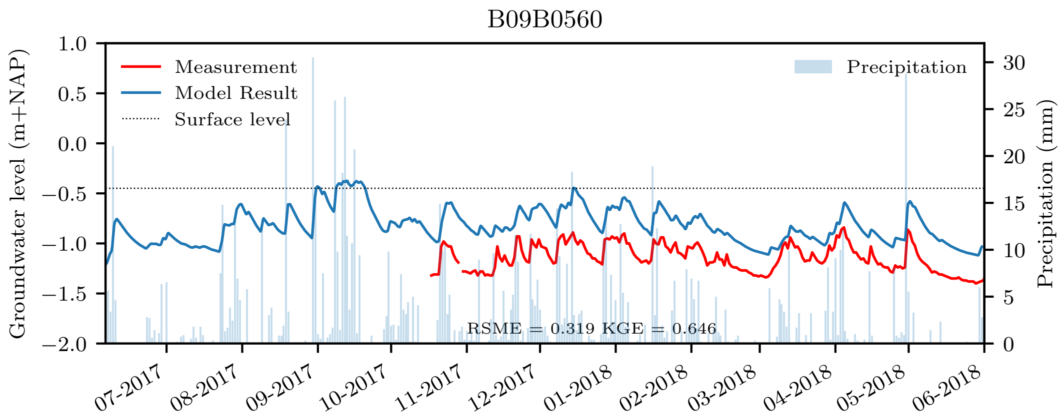

(k)

Figure 22: Measured and simulated groundwater levels and the RSME and KGE for 01-10-17 through 01-06-18 per measuring well.