Modelling surface water and groundwater interactions at the Catchment of the Beurzerbeek with a coupled Tygron and MODFLOW model

Report Bachelor Thesis Civil Engineering

Author:	Lianne Schoonderwoerd
Student number:	s2081237
Internal supervisor UT:	Vasileios Kitsikoudis
External supervisor:	Jeroen Helder
Assignment period:	April 2022 – July 2022
Publication date:	7 July 2022

Preface

In front of you lies my bachelor thesis 'Modeling surface water and groundwater interactions at the Catchment of the Beurzerbeek with a coupled Tygron and MODFLOW model', which I carried out in the water systems department of Aveco de Bondt. During this study, the coupling of TYGRON and MODFLOW is evaluated by looking at different coupling strategies and comparing them to the already existing regional groundwater model AMIGO. The research aims to contribute to a further understanding and implementation of measures against groundwater shortages in the summer, which would subsequently lead to more reliable hydrological predictions.

Looking back, I can say that I have learned a lot regarding groundwater modelling in this fleeting period of ten weeks. Next to that, I learned a lot from working on my own on a study. Fortunately, I did have guidance throughout the study. For this, I would like to thank my external supervisor Jeroen Helder (Aveco de Bondt) for his insight into the working environment and for sharing his expertise in groundwater modelling. I got the chance to speak with many of his colleagues, which he brought me in contact with during meetings and in the office, therefore, I would also like to thank his colleagues for making me feel at home at Aveco de Bondt and giving me an insight look at working at a consultancy. In addition to this, I would like to thank my internal supervisor Vasileios Kitsikoudis (University of Twente) for his guidance, confidence, and critical feedback.

Hopefully, you will enjoy reading my thesis.

Enschede, July 7, 2022

Lianne Schoonderwoerd

Abstract

Dutch

Deze studie onderzoekt of de dynamiek in grondwaterstanden accuraat gemodelleerd kan worden in een nieuwe koppeling van een grondwatermodel en een oppervlaktewatermodel. Hiervoor is een case study over vier periodes in het stroomgebied van de Beurzerbeek uitgevoerd. Daarnaast brengt dit onderzoek de sterke en zwakke punten van deze koppeling in kaart.

De klimaatverandering is in Nederland duidelijk te merken aan dat de laatste jaren de zomers telkens warmer en droger worden en de winters telkens natter. Met name op hoge zandgronden, zoals bijvoorbeeld rondom de Beurzerbeek bij Winterswijk in het oosten van Nederland, wordt het water te snel afgevoerd en kunnen beken droog komen te vallen. Dit komt onder andere door de hoge permeabiliteit van het zand, maar ook de inrichting van de gebieden, via sloten, beken en drainagebuizen wordt het regenwater snel afgevoerd. Een gedetailleerd model waarin alle hydrologische processen in opgenomen zijn, zouden de effecten van diverse maatregelen om water langer vast te houden in droge gebieden in kaart kunnen brengen.

Het onderzoek is opgedeeld in twee delen. Allereerst wordt de koppeling, een programma die het grondwatermodel en het oppervlaktewatermodel aanstuurt en koppelt geschreven in de programmeertaal Python, onderzocht en verbeterd. Hiervoor is er onderzocht wat de invloed is van neerslag en de mogelijke evapotranspiratie, de volgens literatuur twee grootste variabelen die invloed hebben op de grondwater berging, op de grondwater berging in het model dat het oppervlaktewater berekent, Tygron, is. Hieruit is geconcludeerd dat deze twee variabelen inderdaad de grondwaterberging veel beïnvloeden en dat dit voornamelijk voor de neerslag erg tijdsafhankelijk is. Zo komt de neerslag wanneer deze binnen één uur valt in plaats van verspreid over 24 uur op andere locaties terecht komt in de grondwaterberging. Dit komt doordat Tygron, in tegenstelling tot veel andere modellen, oppervlakkige afstroming kan modelleren.

Doordat het onderzoek liet zien dat de berekende grondwateraanvulling gevoelig is voor de intensiteit van weer data en doordat de rekentijden aanzienlijk toe kunnen nemen, worden de modellen gekoppeld op dag basis terwijl de uur gegevens van het KNMI worden gebruikt als invoer. Kortom, Tygron berekent na een dag de grondwateraanvulling. Deze wordt vervolgens doorgegeven aan het grondwatermodel MODFLOW die de grondwaterstanden berekent. Deze grondwaterstanden worden vervolgens weer aan Tygron teruggekoppeld.

In het tweede deel van het onderzoek zijn de oscillaties in de gemodelleerde grondwaterstanden van de koppeling vergeleken met gemeten grondwaterstanden van het drinkwaterbedrijf Vitens en met gemodelleerde grondwaterstanden in het grondwater model AMIGO van waterschap Rijn en IJssel. Het onderzoek laat zien dat AMIGO een betere benadering tot de gemeten grondwaterstanden dan de nieuwe koppeling kan modelleren. Daarnaast laten de kaarten met grondwaterstanden ook zien dat het model voor een periode onbetrouwbare resultaten geeft. Desondanks, zijn er nog veel kansen voor het gekoppelde model om in te verbeteren. Pas met meer verbeteringen en uitgebreidere testen kan er geconcludeerd worden of dit model daadwerkelijk alle hydrologische processen accuraat kan worden.

English

This study investigates whether the dynamics in groundwater levels can accurately be modelled in a new coupling of the groundwater model MODFLOW and surface water model Tygron for Tygron can model surface runoff and is fast and MODFLOW can calculate the groundwater flow through various and multiple ground layers. To this end, a case study was carried out over four periods in the catchment of the Beurzerbeek. In addition, this research maps the strengths and weaknesses of this coupling.

Climate change in the Netherlands is noticeable in recent years for the summers have become increasingly warm and dry, and the winters wetter. Particularly on high sandy soils, such as around the Beurzerbeek near Winterswijk in the east of the Netherlands, the water is drained too quickly, and streams can run dry. This is partly due to the high permeability of the sand, but also the layout of the areas, the rainwater is quickly drained via ditches, streams, and drainage pipes. A detailed model in which all hydrological processes are included could map the effects of various measures to retain water longer in dry areas.

The research is divided into two parts. First, the coupling, a program that controls and links the groundwater model and the surface water model, written in the Python programming language, is investigated and improved. For this purpose, the influence of precipitation and the possible evapotranspiration, which according to literature are the two largest variables that influence groundwater storage, are investigated on the groundwater storage in Tygron, the model that calculates the surface water. It has been concluded that these two variables do indeed have a considerable influence on groundwater storage and that this is very time-dependent, especially for precipitation. For example, when precipitation falls within one hour, instead of spreading over 24 hours at other locations, it ends up in groundwater storage. This is because Tygron can model surface runoff, unlike many other models.

The research showed that the calculated groundwater replenishment is sensitive to the intensity of weather data and because the calculation times will increase considerably, the models are linked daily while the hourly data from the KNMI are used as input. In short, Tygron calculates the groundwater replenishment after one day. This is then passed on to the MODFLOW groundwater model, which calculates the groundwater levels. These groundwater levels are then passed back to Tygron.

In the second part of the study, the oscillations in the modelled groundwater levels of the coupling were compared to measured groundwater levels from the drinking water company Vitens and modelled groundwater levels in the groundwater model AMIGO of the Rijn and IJssel waterboard. The research shows that AMIGO is able to model a closer approximation of the groundwater levels than the new coupling. In addition, the maps with groundwater levels show that the model gives unreliable results for one period. Nevertheless, there are still many opportunities for the coupled model to improve. Only with more improvements and more extensive testing can it be concluded whether this model can be accurate for all hydrological processes.

Table of contents

List of figures

List of abbreviations

NAP	Normaal Amsterdams Peil (Water level above the standard Dutch water level)
KNMI	Koninklijk Nederlands Meteorologisch Inistituut (Dutch royal meteorological institute)
GW	Groundwater
SW	Surface water
WFD	Water Framework Directive
ET	Evapotranspiration

1. Introduction

1.1. Problem context

Effects of climate change are visible in the Netherlands as each year is getting warmer and wetter on average (CBS, PBL, RIVM, WUR, 2020). Not only does this cause higher flood risks e.g., the flooding of the river Meuse in the province of Limburg in the Netherlands in the summer of 2021 (Kreienkamp, et al., 2021), but it also causes more heat and periods of extreme droughts. For this, water supply and water quality are also important aspects of water management.

Flood protection, water supply and water quality refer directly to one Sustainable Development Goals (SDG) of the United Nations (UN). Specifically, SDG 13 "take urgent action to combat climate change and its impacts" (SDGS UN, 2022). The warming of the climate system affects each country in the world unquestionably, and therefore, SDG 13 is also relevant for the Netherlands. The heated atmosphere and oceans, the amount of melted snow and ice, sea-level rise, and the concentration of greenhouse gases are evidence of climate change (Intergovernmental , 2013). Scientists expect a rise in the global average temperature between 1°C and 4°C which will lead to a greater difference in precipitation values between dry and wet periods (Pörtner, et al., 2022). In dry periods, the precipitation is expected to be lower than it would be normally which can cause water scarcity and water shortage as a large part of the precipitation is needed for agriculture, industry, and drinking water. In wet periods, there will be much precipitation that will discharge either as surface water (SW), infiltrate to the groundwater (GW) or runoff over the ground. Estimating the amount of surface water runoff is not simple as the intensity, duration, spatial extent, relief, hydrogeology, soil characteristics and vegetation play a role in the discharge (Booij, 2019).

The Water Framework Directive (WFD) was founded in 2000 to ensure that all bodies of SW and GW are in good status. The policies of the European Union aim to protect and improve the quality of aquatic environments, including their surroundings by aiming to make sustainable use of water and reduce the amount of pollution, and mitigate the effects of droughts and floods (Booij, 2019).

Water management has a long track record in the Netherlands. Responsibilities for water management are divided between ministries on the national level for the largest rivers and provinces for legislation of water management. Moreover, a large part of the executive work is the responsibility of the 21 waterboards. Waterboards are responsible for the maintenance of the water system and are initiating the projects to make water bodies WFD compliant.

To achieve a more sustainable water system, waterboards apply the principle: of hold-store-discharge which can be seen in Figure 1. With this strategy, the discharge of rainwater into streams is delayed. As surface water does have more time to infiltrate in the ground, more water is stored instead of discharged and more groundwater will be available in periods after. Moreover, this triplet is used in the restoration of streams and creeks to make them more climate-resilient. By adjusting culverts and weirs in a catchment, water levels can be heightened to prevent water shortage during dry periods in upstream areas and floods in downstream areas. To gain insight into these matters and to design measures and predict their (hydrological) effects on the use and functions of the surrounding grounds, policymakers and project teams rely on models.

One of the recent developments in hydrological modelling is fast high-resolution cloud computing models. New models are able to capture the process of surface runoff and infiltration better than conventional models as they are able to transform the rainfall height to surface runoff and estimate the associated soil infiltration amount and location better. Furthermore, the level of detail in the ground layers in groundwater models is increasing, therefore, the processes can be captured in higher detail. Instead of having one uniform ground layer, models do contain multiple soil types and layers with their corresponding characteristics like permeability. Hydrological models are used for calculations in stream restoration projects. These projects can, as a result of the more accurate models, be carried out more reliably.

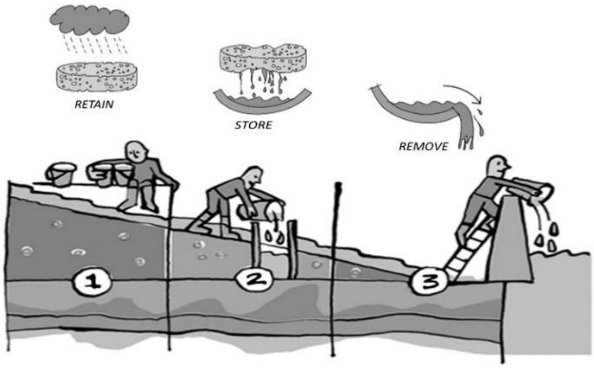


Figure 1: Retain – store - discharge principle (Ritzema, 2015)

Current practice

The main challenges of modelling hydrological dynamics are numerical instability, high modelling costs, and computational time (Diaz, Sinicyn, & Grodzka-Lukaszewska, 2020).

In models, the interaction between the GW and SW is often incorporated in diverse ways and complexity. Models are always a simplification of the actual situation but with increasing computational power and availability of high-resolution data, the complexity of the model increases as well. This allows researchers and practitioners to include more components of the hydrological system in their models. For this, there are several strategies and options. There are, for example, papers written about different single and coupled hydrological models, some of them are explained below.

Firstly, there are single models which model SW flows in detail but simplify GW flows such as TOPMODEL, HL-RMS, and SWAT. Secondly, there are detailed GW models which simplify SW flows such as MicroFEM, ZOOMQ3D, and MODFLOW. These models account for single flows, neglecting the interaction between GW and SW (Chen & Wang, 2021). There are also coupled models which model the SW and GW at the same time. Examples of such models are the catchment hydrology model, Parallel Flow model, and HydroGeoSphere. However, these models make the modelling overly complex, have minimal free code, and result in over-parametrization (Chen & Wang, 2021).

Chen and Wang (2021) conclude that loosely coupled models are models in which the components have little knowledge or make little use of each other's model components including climate, nutrients, soil temperature and properties. However, these models use a lot of free code and modules instead. These free modules are a desirable alternative as they operate simply, have good visualizations, and do not require much data. Examples of loosely coupled models are GSFLOW, MODBRANCH, and SWAT-MODFLOW.

The coupling strategy of SWAT and MODFLOW is reviewed in a paper by Chen and Wang (2021), they wrote about these models that *"the coupled surface and groundwater models have proven their great potential in hydro-biogeochemical studies and support the management of watershed ecology and environment*" (Chen & Wang, 2021). Furthermore, they pointed out things where there is room for improvement. Firstly, they wrote that coupled SW-GW model should be adopted to work on short time scales to capture hydrological dynamics under extreme climate conditions which can cause a short-term influx of nutrients (Chen, Krom, Wu, Yu, & Hong, 2018). Secondly, they concluded that model uncertainties should be reduced and that the model can be expanded for the study of hydro-biochemical processes. Lastly, they propose linking the model with other models to improve the decision-making process. Strengths of the coupling, however, include good visualization and low data requirements.

Another model which is used for GW management, thus, to model the interactions between SW and GW, is the Actual Model Instrument Gelderland Oost (AMIGO) model of the Waterboard Rijn and IJssel, province of Gelderland, and the water company Vitens. The model has a resolution of 25x25m and is based on MODFLOW for the saturated GW flows and based on Meta Soil Water Atmosphere and Plant model (MetaSWAP) for the flows in the unsaturated zones. MetaSWAP divides the unsaturated and saturated zones into thin layers to model the flow of water in between the ground layers and it is a simplified version of the SWAP model and reduces computational time. It is a one-dimensional model, and thus, does only vertical calculations.

1.2. Research objective and questions

The main goal of this research is to investigate whether a new coupled model is able to capture the hydrological dynamics under extreme climate conditions in both the saturated and unsaturated ground layers more accurately than current modelling practice. Before and while evaluating the functioning of the model, the coupling will be improved e.g., to make the model faster, more accurate and easier to deploy. This new coupling aims for a better understanding of fast changes in the hydrological groundwater dynamics. Tygron, MODFLOW and Python are used for this coupling and are presented in section 2.3.

Contrary to other models, Tygron does model surface runoff, as water does not always infiltrate on the location of the precipitation. Accumulation of rainfall and infiltration will occur in local depressions. Moreover, in urban and hilly areas, runoff over the ground can be a key factor as urban areas do have a lot of impermeable areas and hilly areas can enhance runoff due to their steep slopes. Also, rainfall does not necessarily infiltrate where it falls. This process is getting more important due to increased rainfall intensities and increased length of dry periods due to climate change.

Although Tygron has a sophisticated module for SW modelling, it contains only one ground layer and simplifies groundwater movement like some other regional groundwater models do. For this reason, Tygron is coupled to the groundwater model MODFLOW by a python script. MODFLOW can calculate the groundwater flows and recharge with high accuracy after which Tygron will use the feedback to start the next simulation step. It is expected to lead to a better representation of the dynamic behaviour of the groundwater system.

Since the coupling is relatively new, the objective of this research is:

“To map the strengths and limitations of the coupling of Tygron to MODFLOW focussing on the interactions between surface water and groundwater for the Beurzerbeek Creek.”

First, the models must be coupled correctly, making sure that the water balance is correct, as the models work with different grid cell sizes, time scales, variables, and data types. Thereafter, coupling strategies should be drawn up and assessed whereafter one should be chosen. For example, Tygron uses time steps of one minute while MODFLOW usually works with a time step of one day. This time should be assessed and possibly changed to model extreme events correctly as, for example, storms could change the watershed hydrography and create a short-term inflow of substances (Chen, Krom, Wu, Yu, & Hong, 2018). Second, the groundwater level dynamics must be investigated and compared to current modelling practice and measurements in a case study for the catchment of the Beurzerbeek Creek. This leads to the following two sub-questions:

1. How should Tygron be coupled to MODFLOW in order to capture extreme weather conditions at the Beurzerbeek?
2. Can the groundwater oscillations of the Beurzerbeek be simulated more accurately in a model where the location of infiltration is not only dependent on the location of the precipitation but also on the runoff when coupled to a detailed groundwater model?

1.3. Thesis outline

The structure of the remaining of this report is as follows. Chapter 2 describes the study area and used models. The theoretical framework is outlined in Chapter 3 . Thereafter, the methodology is described in Chapter 4 followed by the Results and Discussion in Chapter 5 and Chapter 6, respectively. Finally, the Conclusions and Recommendations for future studies are given in Chapter 7.

2. Study area, used models and data

2.1. Study area

The study area is the catchment of the Beurzerbeek, shown in Figure 2. The Beurzerbeek is located north of the village Winterswijk in the east of the Netherlands in the province of Gelderland on the East-Netherlands Platform. This specific region is interesting as the elevation in the catchment of the Beurzerbeek is varying as it used to be a meltwater channel, the height elevation map and two Figures about the geohydrology of the catchment Beurzerbeek can be found in Appendix A: Beurzerbeek geohydrology. The meltwater carved the landscape. It is expected that during heavy rainfall events, there will be runoff over the ground from hilly areas to the creeks instead of infiltrating on the location of the precipitation. Moreover, the first fifteen meters of the soil of the Beurzerbeek is an aquiferous layer mostly consisting of sand. Groundwater easily moves through such an aquiferous layer, which means that the system gets dry in the summer and wet in the winter. To deal with these fluctuations in the groundwater level, drainage pipes are present underneath several farmlands. If the soil is wet, the drainage pipes discharge groundwater allowing farmers to grow their crops also in wet periods.

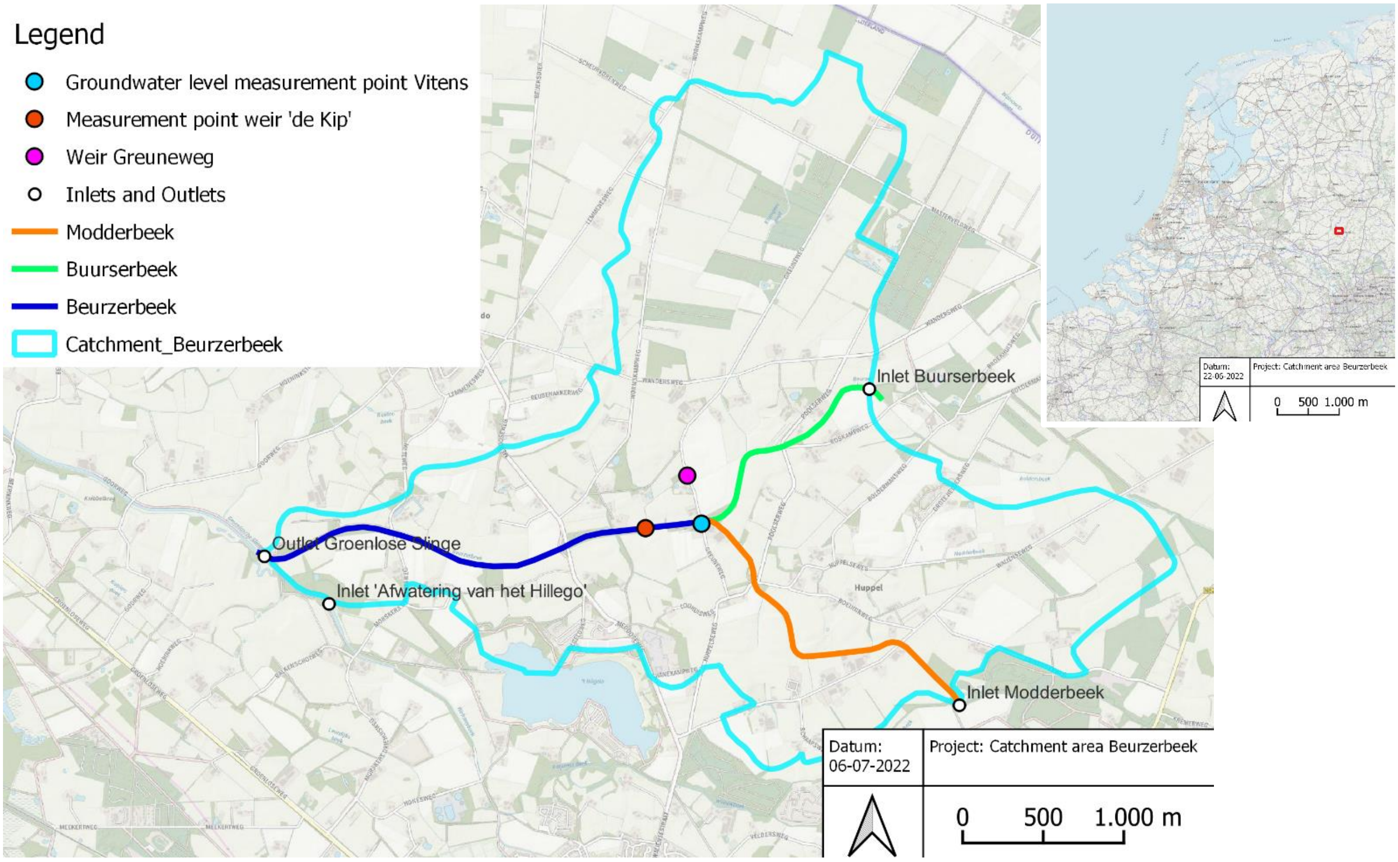


Figure 2: Beurzerbeek catchment

The waterboard Rijn and IJssel own several measurement installations for monitoring surface water levels. The weir 'Overlaat de Kip' is one of them, located in the Beurzerbeek in the middle of the catchment Beurzerbeek, and therefore, will be used to compare modelling results. Also, the drinking water company Vitens has installed a measurement well for groundwater levels at a location close to the road Greuneweg. As the groundwater measurement is located close to the Beurzerbeek, the ground is normally speaking relatively wet (Bodemberging in grafieken, 2022). These measurement locations are shown in Figure 2.

The Beurzerbeek has a rich history which can be seen in the landscape. About two hundred years ago, the Beurzerbeek did meander a lot, this can be seen in Figure 3. Between 1900 and 1950, people moved to the Beurzerbeek after which the creek was relocated to several locations probably due to allotment.

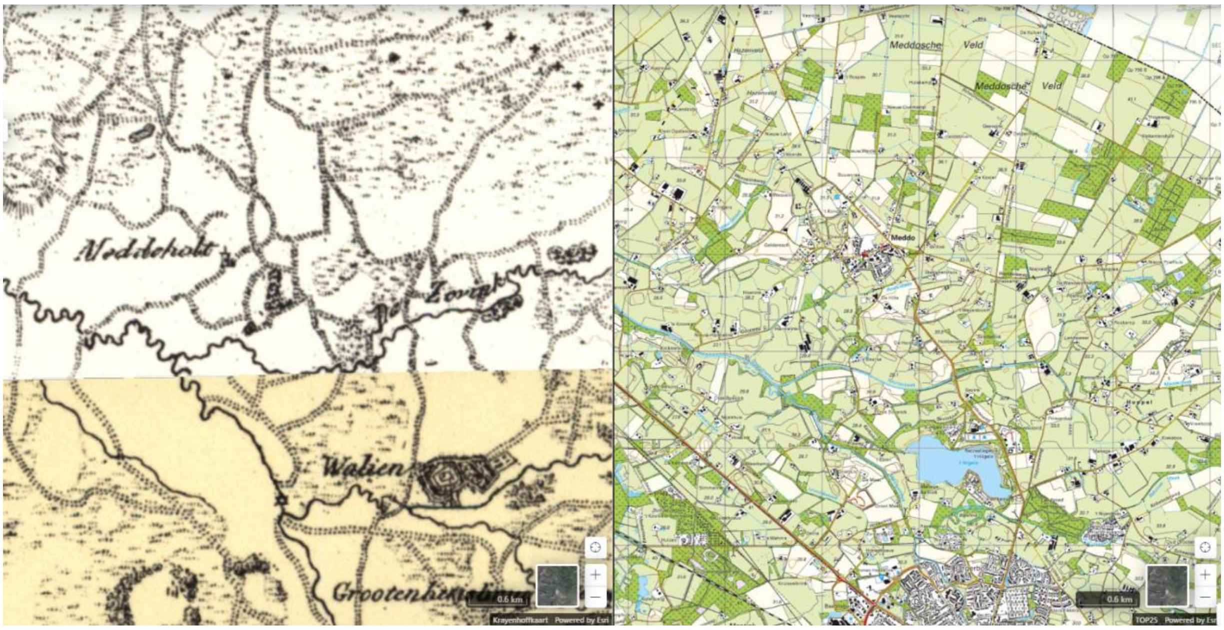


Figure 3: Map of the Beurzerbeek in 1828 (left side) and map of the Beurzerbeek in 2021 (right side) (Topotijdreis, sd)

2.2. Site observation

On 10 May 2022, the catchment of the Beurzerbeek was visited (Helder, 2022). The Buursebeek and the Modderbeek originate in the Beurzerbeek, this can be seen in Figure 2. Both creeks are throughout the reach covered with a geotextile where no sand, but water can pass through. This embedding fixates the creek to its current position. The roughness coefficient is therefore not as high as in other parts of the creek. As a result, the velocity of the water is higher at these places and less water is likely to infiltrate. To counteract this, weirs are made by piles of stones to retain water and allow more infiltration.

Furthermore, at several spots near the Beurzerbeek, orange sand is seen. Deep groundwater does not contain oxygen, however, when the iron is present in the groundwater, this will turn orange when the groundwater flows to the surface. If the groundwater containing iron comes to the unsaturated zone where there is air, Fe^{2+} turns into Fe^{3+} (from liquid to particles) and it gets an orange colour. Also, the farmlands have a rounded surface and a slight dark ground colour as a result of using manure for the fertilization of the farmland for many years.

Upstream, there is a campsite which empties its water in the Buursebeek. This could cause higher discharges in the Buursebeek at several moments. Moreover, there is no sprinkling policy and new withdrawals from the area are allowed (Drainagebeleid en beregeningsbeleid voor onttrekkingen uit grondwater, 2020). Water from irrigation can therefore end up in the water system and, at several points in the creek, drainage tubes are coming from under the fields. They are passive drainage tubes as there are no wells to be seen where the water can be regulated. These drainages ensure that the fields do not get too wet and that farmers can grow crops early in the year. These drainages will lower the groundwater levels in the field and increase discharges in wet periods.

Figure 4: Weir and measurement point 'Overlaat de Kip'

The weir before the Overlaat de Kip in Figure 4 is located at 28.55m+NAP while the weir upstream is located at 28.35m+NAP. It is remarkable that the weir upstream is lower, but the purpose is unclear. Also, the positions of weirs and culverts were checked. At a location along the Greuneweg north of the Beurzerbeek, a culvert is present while it is not in the register of the waterboard. This should be added manually to the model.

Figure 5: The banks of the Buursebeek, the creek is covered with a geotextile and stones

Stones are placed on the banks of the Buursebeek and Modderbeek as can be seen in Figure 5. These make sure that the banks of the creek do not erode or collapse. The weirs in the Beurzerbeek are not passable for fish as some weirs gap a water level height difference of more than seven centimetres and fish can only jump about seven centimetres high. The WFD aims to improve the weirs in the period 2022 to 2027 to increase the ecological quality of the Beurzerbeek. Also, the current chemical load of the Beurzerbeek should be further reduced as the waterways from Germany contain polystyrene foam and oily substances (Waterschap Rijn en IJssel; Royal Haskoning DHV, 2020).

2.3. Used models

2.3.1. Tygron Platform

The Tygron platform is a software package which is founded in 2014 and it is since then in constant development. Tygron contains many modules (About Tygron, 2022). For this research, the water module is of interest. In the water module, the hydrological dynamics in a project area can be modelled in the unsaturated zone where the soil is modelled as one layer with uniform properties in depts, but different spatial units. Moreover, examples of the dynamics modelled are infiltration, surface flow and evapotranspiration. Tygron models are run on super computers at Tygron. Therefore, the computational time is not dependent on the processor of your laptop and thus they are much faster (About Tygron, 2022).

Tygron creates a 3D world which automatically loads many public data like elevation terrain maps and land use types. Next to this, data can be manually imported, for example, information about culverts, bridges, and trees. These kinds of data sets can be downloaded from the websites of waterboards in GeoJSON formats. These data sets can be checked in QGIS, and information can be added if needed. QGIS is an Open-Source Geographic Information System (GIS) (GGIS, 2022).

2.3.2. MODFLOW

MODFLOW is a 3D groundwater flow modelling program from the USA, written in Python. A numerical representation of a groundwater model of an environment can be made using MODFLOW. MODFLOW uses the finite-difference method to solve differential equations. The project domain is first divided into a series of rows, columns, and layers after which the hydraulic head at each cell is calculated. These sets of grid blocks define hydrological properties and boundaries (What is MODFLOW?, 2012). For practical reasons, iMOD version 5.3 is used in this research. iMOD is a Graphical User Interface that aids fast and large MODFLOW modelling and has a 2D and 3D visualisation of the data (Deltares, 2021).

2.3.3. Coupler

To connect Tygron to MODFLOW, an initial python script was written in 2021 by Jeroen Helder and Ward van Laatum from Aveco de Bondt. The script accesses TYGRON via an Application Programming Interface. This enables the script amongst others to start and save a simulation run in Tygron as well as modify and extract data from Tygron. Next to this, the script uses the iMOD python packages for handling the groundwater model.

Tygron is a relatively new model, a lot of innovations happened last year therefore the coupling script did have to be improved and verified. Also, some variables of the hydrological cycle were optimized, and the coupling strategy was revised.

2.3.4. MetaSWAP

Meta Soil Water Atmosphere and Plant model (MetaSWAP) is used to model the water flows in the unsaturated zones. MetaSWAP divides the unsaturated and saturated zone into thin layers to model the flow of water in between the ground layers and it is a simplified version of the SWAP model and reduces computational time. It is a one-dimensional model thus, does only vertical calculations for the groundwater flow.

2.3.5. AMIGO

The drink water company Vitens and the waterboard of Rijn and IJssel which is the waterboard operating in the catchment of the Beurzerbeek, make frequent use of the Actual Model Instrument Gelderland East (AMIGO) to model groundwater flows regionally (Nederlands Hydrologisch Instrumentarium, 2022). AMIGO is a coupling of MODFLOW to MetaSWAP. The model has a resolution of 25x25m.

2.3.6. SOBEK

SOBEK is a modelling suite used to simulate 1D/2D surface water flow using a numerical solution algorithm (Deltares, 2022). The model is i.e., used by the waterboard Rijn and IJssel to analyse water systems including the river Ijssel and the channels in the Beurzerbeek Catchment. Therefore, data about surface water heights and discharge rates from the SOBEK model are used to develop the Tygron model of the Beurzerbeek, this will be explained in sections 4.3.2 and 4.3.3.

2.4. Data

Data from the waterboard Rijn and IJssel was needed for the construction of the Tygron and MODFLOW models, and the coupling program. The register on the website of Rijn and IJssel has for example a list of all the bridges, weirs, and culverts. Next to this, they do have validated models for surface water levels and groundwater levels. The results of those models are used to compare the outcome of the coupling. Next to this, weather data from the KNMI is used, the data used can be found in Appendix B: Rainfall events of interest.

3. Theoretical framework

Different hydrological processes are important when looking at the SW and GW interactions in the catchment of the Beurzerbeek. Precipitation is the most key factor in determining the infiltration as precipitation will either infiltrate, evaporate, or runoff (Booij, 2019). This depends on the temperature, but also the soil moisture conditions: In case the soil is completely saturated, precipitation is discharged immediately or evaporated. If not, at least a portion of the precipitation infiltrates into the soil. This causes the groundwater level to rise as can be seen in Figure 6.

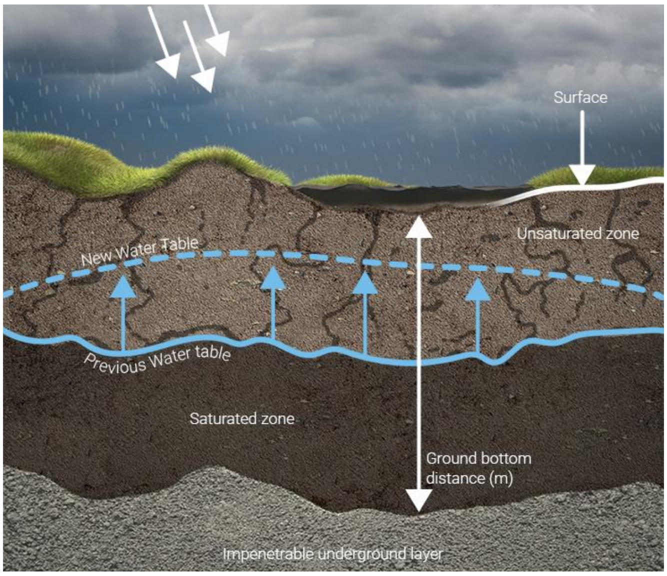


Figure 6: Schematisation ground (Underground model (Water Overlay), 2022)

Below the unsaturated zone, there is a saturated zone, in which all soil particles are saturated with water. Water can percolate from the unsaturated zone to the saturated zone, but also capillary rise can occur when groundwater travels from the saturated zone to the unsaturated zone. As water exists in many places and is exchanged between them constantly, the total sum of all hydrological fluxes in Figure 7 must be zero as no water is gained or lost.

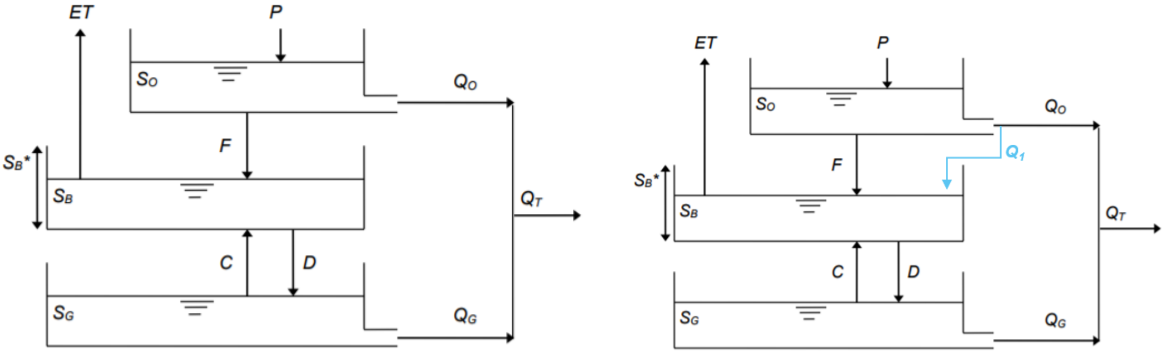


Figure 7: On the left: Schematisation of the hydrological cycle in a catchment (Booij, 2019)
On the right: Schematisation of the hydrological cycle in a catchment modelled in Tygron adapted from (Booij, 2019)

The variables in Figure 7 are:

P = Precipitation (mm/day)
F = Infiltration (mm/day)
C = Capillary rise (mm/day)
D = Percolation (mm/day)
ET = Evapotranspiration (mm/day)

Sg = Groundwater level
S_o = Surface water level
S_b = Soil moisture
S_b* = Maximum amount of soil moisture

Qo = Surface water runoff (m3/s)
Q_g = Groundwater runoff (m^3/s)
Q_t = Actual total runoff (m^3/s)
S = Nett storage(m^3)
Q_1 = Overland flow (m3/s)

3.1. Potential evapotranspiration

When water on the surface turns into water vapour, it is called evaporation. The evaporation is greater in the summer as the temperature and sun increase the evaporation (Wetzel, 2001). Literature shows that most evaporation takes place if there is daylight, as the ratio between evaporation at night and evaporation during the day is about 15% (Malek, 1992). This would mean that the groundwater levels are relatively stable during the night and may fluctuate more during the day.

Next to evaporation, water does also transpire from plants. The sum of evaporation and transpiration from vegetation is called evapotranspiration. The amount of evapotranspiration has a positive relationship with a certain number of factors, being temperature, relative humidity, wind speed, and ground saturation degree. Next to this, the type of plant also does influence the evapotranspiration, for example, the roots of a tree are nested deeper than the roots of grass and are therefore able to use groundwater from deeper layers. Together with precipitation, evapotranspiration has the biggest effect on the water balance.

3.2. Infiltration and overland flow

Precipitation is the most crucial factor in infiltration as a large part of the precipitation will infiltrate the ground surface. The other part will add to the volume of water bodies in the area. Next to this, the soil type influences the infiltration speed whereas water will infiltrate faster in coarse soils than in fine soils and pavement. Additionally, the slope of the land influences the infiltration speed as water will runoff quickly in sloped areas.

However, if the intensity of rainfall exceeds the infiltration capacity, the overland flow will occur (Soil Geography and Landscape Group, sd). This principle is called infiltration excess overland flow or Hortonian overland flow. Besides, overland flow can also occur if the soil is fully saturated during a long and wet period. This is called saturation overland flow. Once the water starts flowing over the surface it can be captured in ponds and infiltrated after the rainfall, or it can reach areas with higher infiltration capacities and infiltrate. The process of excess overland flow and saturation overland flow is shown by Q_1 in Figure 7.

3.3. Groundwater movement

To calculate groundwater flow, the conductivity, storage coefficient and effective porosity are the most important variables. Also, groundwater flow is happening slowly, but an intervention which causes differences in the head could cause more rapid groundwater flow which is visible in minutes, hours, or a few days.

Water always flows from zones where there is high potential energy per mass to a location where there is low potential energy per mass. The potential energy of water can be calculated based on weight via the following equation.

$$h = h_p + h_z \qquad \text{Equation 1}$$

Where h= hydraulic head (m)

h_z= elevation head (m)

h_p = pressure head (m)

Darcy’s law describes the flow velocity of groundwater. Groundwater flows in the direction of the gradient of the hydraulic head.

$$u = -KA\frac{\partial h}{\partial x}$$

Equation 2

Where u = flow velocity (m^3/s)

K = hydraulic conductivity (m/d)

A = surface (m^2)

∂h= difference in hydraulic head (m)

∂x = distance travelled water (m)

3.4. Capillary rise

The amount of capillary rise is hard to estimate as it is not directly measurable. However, the amount of capillary rise can be estimated using Pankow’s formula below in which the sum of percolation and capillary rise is estimated. The situation of Pankow’s formula is visualized in Figure 8.

$$N + \frac{h_d - h_x}{c} = \frac{h_1 - h_2\cos(\frac{x_1}{\lambda})}{\frac{x_2^2}{2kD}(\frac{2\lambda^2}{x_2^2}\cos\left(\frac{x_2}{\lambda}\right) - 1) - \frac{x_1^2}{2kD}(\frac{2\lambda^2}{x_1^2}\cos\left(\frac{x_1}{\lambda}\right) - 1)}$$

Equation 3

Where $h1$ = phreatic groundwater level at x=x1 (m)

$h2$ = phreatic groundwater level at x=x2 (m)

hd = groundwater level in the aquifer below the separating layer (m)

hx = average groundwater level in the plot (m)

x = distance to the centre of the plot (m)

N = precipitation (m/day)

c = resistance of the separating layer (days)

kD = permeability of the plot (m^2/day)

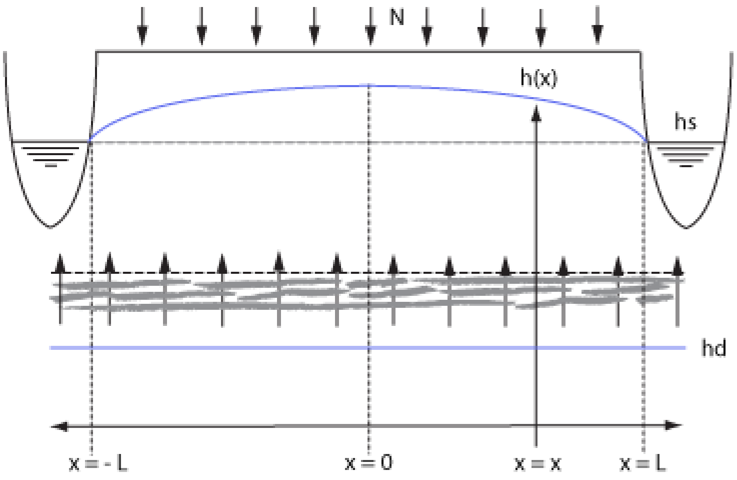


Figure 8: Visualization of Pankow’s formula of Equation 3 (Pankow & Rijtema, 2022)

3.5. Drainage

For agriculture purposes, drainage is present in the fields. There are two types of drainage. Active drainage and passive drainage. With active drainage, groundwater levels can rise and lower as water can be pumped back into the drainage pipes from e.g., the creek. Passive drainage only allows lowering groundwater levels by discharging groundwater to the creek. In wet periods, active and passive drainage control the groundwater levels ensuring that crops do not get too wet after much rainfall. In dry periods, active pipe drainage can make the ground wetter.

Maps from the Dutch Hydrological Instrument show that drainage is present in the Beurzerbeek at a depth of approximately 100cm (NHI, 2022), this matches with the corresponding advised drainage depth for the land use and soil type which is also 100cm for agriculture use on sand (Massop & Schuiling, 2015).

The drainage criterion for agriculture use is a discharge of 7mm/day and a groundwater level of 50 cm beneath the ground surface. Drainage resistance of the fields can with these values be calculated using Equation 4.

$$c_d = \frac{h_g - h_d}{q}$$

Equation 4

Where c_d = drainage resistance factor (days)

h_g= groundwater level (m w.r.t ground surface)

h_d= drainage depth (m w.r.t. ground surface)

q = drainage discharge (m/day)

3.6. Manning coefficient

The Manning coefficient of roughness is used to calculate the velocity within an open channel by Equation 5. Smooth channels do give a low value for the Manning coefficient while rough channels do have higher values for the coefficient. As the result, smooth channels do have a higher flow velocity (Song, Schmalz, Zhang, Li, & Fohrer, 2017).

$$v = (k_n/n){R_h}^{2/3}S^{1/2}$$

Equation 5

Where v = cross-sectional mean velocity (m/s)

k_n = conversion coefficient = 1

n = Manning coefficient of roughness

R_h = hydraulic radius (m) = ratio between the cross-sectional area and the wet perimeter

S = slope (m/m)

3.7. Permeability

The coefficient for permeability indicates the average distance by which water can travel horizontally or vertically through a soil type in time. The permeability of the soil depends on the coarseness of the soil and the silt content, the coefficient is denoted by k. The permeability factor is expected to be between 1 and 10 (Bot, 2011) for the catchment Beurzerbeek as the area is roughly built out of 15 meters of sand covering clay as can be seen in Figure 22 and Figure 23. There are also loamy spots present in the Beurzerbeek, their permeability is lower than the permeability of sand meaning that the water will move slower through loamy soils.

3.8. Saturation degree ground

The saturation degree indicates the relation between the total volume of water and the total ground volume.

$$S = \frac{V_{water}}{V_{pores}} = \frac{wG_s}{e}$$

Equation 6

Where S = Saturation degree (%)

V_{water} = volume water (m^3)

V_{pores} = volume pores (m^3)

e = void ratio

G_s = specific gravity of soil solids

w = moisture content (%)

4. Methodology

The approach of this research consisted of several steps and makes use of a case study. The case study looked closely into modelled groundwater levels during four historical periods, which were chosen by the method described in section 4.1 in the catchment of the Beurzerbeek. Successively, section 4.2 and 4.3 explains how the models for the case study separately in both Tygron and MODFLOW are constructed. Section 4.4 outlines the method for the coupling which during the whole study was repeatedly improved and tested. In the end, the results of the coupling are evaluated using the method in section 4.5.

4.1. KNMI data

To compare the outcome of the coupled model, data from historical events is needed as input for model runs. Therefore, precipitation and evaporation data are gathered from the KNMI. The Beurzerbeek is located near the city of Winterswijk and there is a small precipitation weather station located thereof which daily precipitation values are available. There are no evapotranspiration values and hourly precipitation values known for Winterswijk. The nearest complete weather station is in Hupsel. As there is no other weather station nearby, no polygon approach to finding the mean of two weather stations can be done. To verify if the precipitation values of Winterswijk and Hupsel correlate well enough, several statistical tests are performed. First, over the complete data set, a z- test and a root mean square error test are performed. Secondly, over specific weeks, t-tests are performed as a t-test is more suitable than a z-test if there are less than 30 measurements (McClave & Sincich, 2018).

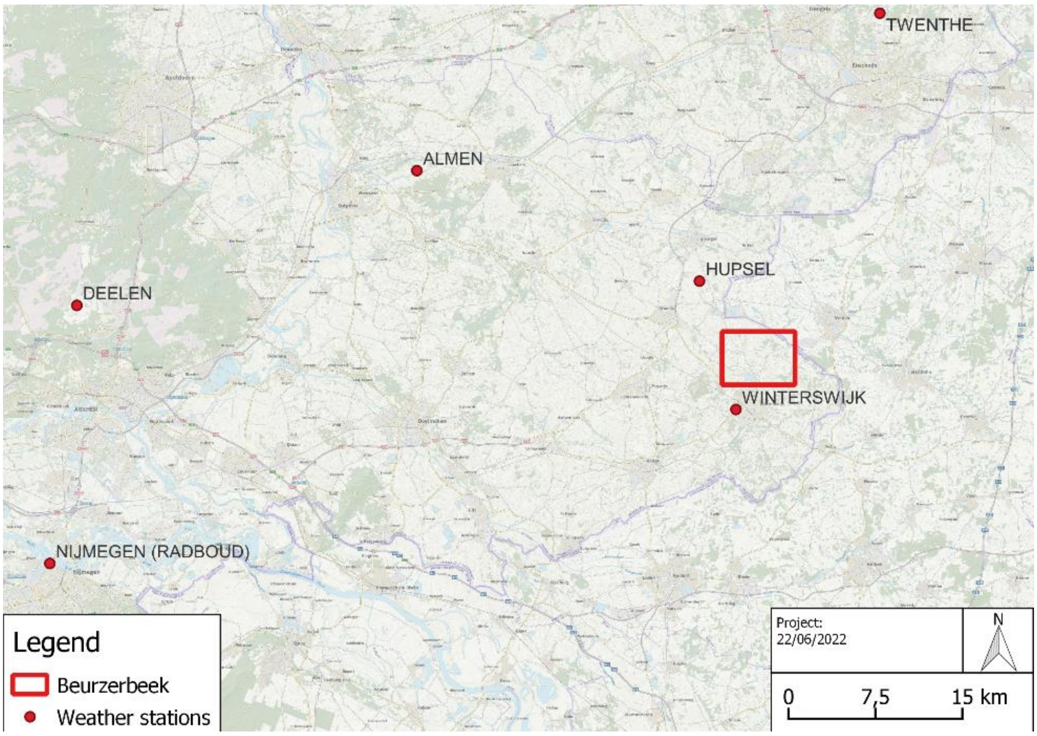


Figure 9: Weather stations

Null hypothesis: Precipitation data of Hupsel and Winterswijk are equal.

Alternative hypothesis: Precipitation data of Hupsel and Winterswijk are different.

If the p-value is greater than 0.95, we accept the null hypothesis, which means that the precipitation data of Hupsel and Winterswijk are equal and then the weather data from Hupsel can be used. In the case that not all periods accept the null hypothesis, the precipitation data are different, only periods where the data accept the null hypothesis for the t-test will be used.

Secondly, evapotranspiration numbers are imported from the KNMI. In the beginning of July, the evapotranspiration reaches 3mm/day while 1.5mm/day is representative for days in April (Koninklijk Nederlands Meteorologisch Instituut, 2022). As the height of the evapotranspiration fluctuates throughout the day as explained in section 3.1, a sensitivity for the evaporation parameter is executed. The differences between the influence of constant evaporation and fluctuating evaporation on groundwater storage are examined.

4.2. MODFLOW model

AMIGO is the coupled MetaSWAP to MODFLOW model. For this study, the MODFLOW part of the AMIGO model from the waterboard was for coupling for the case study in the Beurzerbeek. First, the AMIGO run file was stripped from the lines of code about MetaSWAP. Thereafter, a module, the groundwater recharge flux was added to the run file for MODFLOW. In conclusion, there is no difference between the MODFLOW model from AMIGO and the MODFLOW model from the new coupling to Tygron.

4.3. Tygron model

The Tygron platform automatically loads much geo data to create an initial 3D model for a project area. Information like elevation maps, construction heights, and land use are a few examples of things that are loaded. However, it lacks specific information about for example culverts and weirs. Therefore, the TYGRON model is constructed using the following steps.

4.3.1. Gathering data

First, data sets from the waterboard Rijn and IJssel were downloaded from their data portal. The area of the catchment which is 10,14 km^2 is used as a calculation area in Tygron. Information about culverts and weirs was then imported into Tygron and checked for their functioning. As a result of the study site, a rectangular culvert was added along the Greuneweg, north of the Beurzerbeek, where the Beurzerbeek was positioned over one hundred years ago. The location can be seen in Figure 2.

Also, drainage pipes are present in the catchment of the Beurzerbeek. The waterboard does unfortunately not have information about the location and dimensions of them, therefore, the drainage pipes are not included in the model. However, a standard drainage depth for agriculture use with sand soils is known to be 100 cm with respect to ground level. Nevertheless, due to technical problems, no standard drainages could be implemented in the Tygron model.

4.3.2. Determine inlets and outlets

The inlets and outlets of the Tygron model are determined based on the standard summer situation modelled in the validated SOBEK model made by the waterboard. The standard summer situation is denoted by 0.05Q. Moreover, 1Q does represent a discharge which happens once a year and 1.5Q a discharge which happens every 10 years and 2Q a discharge which happens every one hundred years.

When looking at the SOBEK model and the catchment area, one outlet and three inlets are assigned to Tygron. The outlet is located downstream of the Beurzerbeek where the creek joins the Groenlose Slinge. The inlets are located upstream. The positions of the inlets and outlets can be seen in Figure 2. The site visit showed that the Modderbeek does have a discharge dissimilar to the SOBEK model. Therefore, the inlet of the Modderbeek is set to 0.010 m^3/s. Discharges corresponding to their positions can be seen in Table 1.

Table 1: SOBEK History at reach segments

Position inlets and outlets	5%Q Discharge SOBEK (m^3/s)	Discharge TYGRON (m^3/s)
Outlet Groenlose Slinge	0,189	0,189
Inlet Buursebeek	0,133	0,133
Inlet Modderbeek	0,000	0,010
Inlet Afwatering van het Hillego	0,005	0,005

Moreover, the discharges on the locations of the inlets should be based on a water height relation. Unfortunately, this is not an option in Tygron, and therefore, the inlets are constant instead of varying depending on the weather and water levels upstream. Next to this, in Tygron, inlets and outlets are point-based structures, but to make sure that all the water could be extracted from the system, a buffer of two-meter was assigned to the outlet downstream. This means that all the water in a range of two-meter from the point outlet will leave the catchment if the water level is lower than the height of the weir. The weir upstream has a height of 26.6 m+NAP and the bottom of the Groenlose Slinge is 24.2 m+NAP. Therefore, the outlet of the catchment is set at 25.9m+NAP.

4.3.3. Initiate water levels

Unlike other data sets, Tygron does not load nor create water heights in the streams, the waterways are empty. The water levels for the Beurzerbeek are only provided for a few locations on the data portal of the Waterboard. Therefore, the initial water level must be estimated. First, the inlets and outlets are imported into the Tygron model.

Thereafter, the model was run for a week with several discharges and rain periods to determine the initial water levels by trial and error. When next to the inlets, no additional rainwater comes into the system, parts of the catchment are still dry while when too much rainwater falls on the catchment, water tends to accumulate on the surface and parking lots. Also, as it takes time for the water to propagate downstream, the run time should be longer than one day. After combining several precipitation intensities, lengths and run times, it was concluded that 60mm precipitation in one day followed by one dry week would fill up the Beurzerbeek. The water levels resulting from this are compared to the water levels in SOBEK and the classification from the waterboard in Table 2. The waterboard classified water levels in the Beurzerbeek in Table 2, a normal water level at the upstream location of 'Overlaat de Kip' is a water level between 28.50m+NAP and 28.875 m+NAP (Hydronet, 2022).

Table 2: Classification of water levels - Overlaat de Kip – Upstream (Hydronet, 2022)

Water level	Classification
>30.125m+NAP	High water with flooding
29.875m+NAP – 30.125m+NAP	High water with limited flooding
28.875m+NAP – 29.875m+NAP	High water within banks
28.5m+NAP – 28.875m+NAP	Normal water level
28.125m+NAP – 28.5m+NAP	Water levels of more than 5cm under the normal water level
<28.125m+NAP	Water levels of more than 40cm under the normal water level

4.3.4. Manning values

The Manning value indicates the roughness of a surface. They relate very strongly to the infiltration speed as explained in section 3.6. The Manning value is different for various locations of the catchment in Tygron. However, a Manning coefficient of 0.02 is used for the entire length of the creeks. This Manning coefficient corresponds with the values for sand, loam, and fine gravel. However, when visiting the location, it was noticed that the type of embedding along the creek was different for upstream parts of the creek. Bricks are placed there to prevent erosion. Bricks do have a higher Manning coefficient; however, this was not adjusted in the Tygron model. As the Manning roughness coefficient is also lower than in reality, the modelled flow rate is lower, and water has less time to infiltrate in the ground.

4.3.5. Initial groundwater levels

The groundwater throughout the year is characterized using the mean highest groundwater level (GHG), mean spring level (GvG) and mean lowest groundwater level (GLG). The GHG is the mean of the HG3 over 30 years. The HG3 is the mean of the three highest groundwater values in a hydrological year with a measurement frequency of twice per month. A hydrological year is from the 1st of April till the 31st of March. The GLG is the mean of the LG3 measured over 30 years. The LG3 is the mean of the three lowest groundwater levels in a hydrological year with a measurement frequency of twice per month. The GVG is the mean of the VG3 over 30 years. The VG3 is the mean of the groundwater levels on the 14th of March, 28th of March and 14th of April as these dates represent the groundwater level during spring, at the start of the growing season (Basiskaarten, 2022).

As the study focuses on heavy rainfall events which usually take place during the summer, the GLG is used as input for the models. The GLG models from the regional GW model AMGIO are used.

4.3.6. Initial unsaturated groundwater fraction

Initial unsaturated groundwater storage of 30% was chosen. This means that 30% of the ground is not fully saturated yet. When it rains, the groundwater will be recharged, and the unsaturated groundwater fraction will decrease. When it is dry, the unsaturated groundwater fraction is likely to increase. Changes in the initial unsaturated groundwater fraction will occur locally.

4.4. Coupling

In 2021, an initial python script was written which calls both Tygron and the groundwater model MODFLOW. As this is a new coupling and innovations on the Tygron platform took place last year, the python script was improved and constantly checked during this study. In Figure 10, a flow chart of the processes in the coupling is displayed. The most important parameter, therefore, is the groundwater recharge. This is calculated by subtracting the ground last storage at the end of a day from the ground last storage at the beginning of that day as modelled in Tygron. This value is via the coupling script passed onto MODFLOW which runs for one simulation time step and passes the calculated groundwater heads back to Tygron to start the next calculation day.

The abovementioned coupling can be applied to Tygron and MODFLOW models of different grid sizes, project sizes and simulation run lengths. Next to this, the python structure can be adjusted. For the python structure, two coupling strategies were assessed. They are explained below.

A) Couple the models every day, use daily weather data and calculate the groundwater recharge with Tygron after one day will be passed on to MODFLOW to calculate the groundwater head of one day. Subsequently, these groundwater heads will be used as input for the second simulation day in Tygron.
B) Couple the models every day, use weather data per hour and calculate the groundwater recharge with Tygron after one day will be passed on to MODFLOW to calculate the groundwater head of one day. Subsequently, these groundwater heads will be used as input for the second simulation day in Tygron.

Before choosing the coupling strategy, the sensitivity of the precipitation and potential evapotranspiration on the groundwater last storage should be determined as the change in groundwater last storage in Tygron is used as input in MODFLOW. Moreover, the groundwater's last storage shows the effective amount of water in both the saturated and unsaturated soil zone already accounting for amongst others the porosity of the soil.

4.5. Compare hydrological dynamics in the groundwater levels

To evaluate the performance of the modelling results, the outputs of the coupling are foremost analysed logically. The model creates for each time step a raster holding information about the amount of ground last storage, the change in the ground last storage, the surface last value, the unsaturated ground fraction, and the groundwater levels.

More importantly, the groundwater levels are compared to observed data from the groundwater measurement well of the drink water company Vitens.

Next to this, groundwater levels are for each time step compared to the results of AMIGO. The root mean square error (RMSE), Chi-Square test, z-test, standard deviations and mean absolute percent error (MAPE) can be used to conclude about the differences.

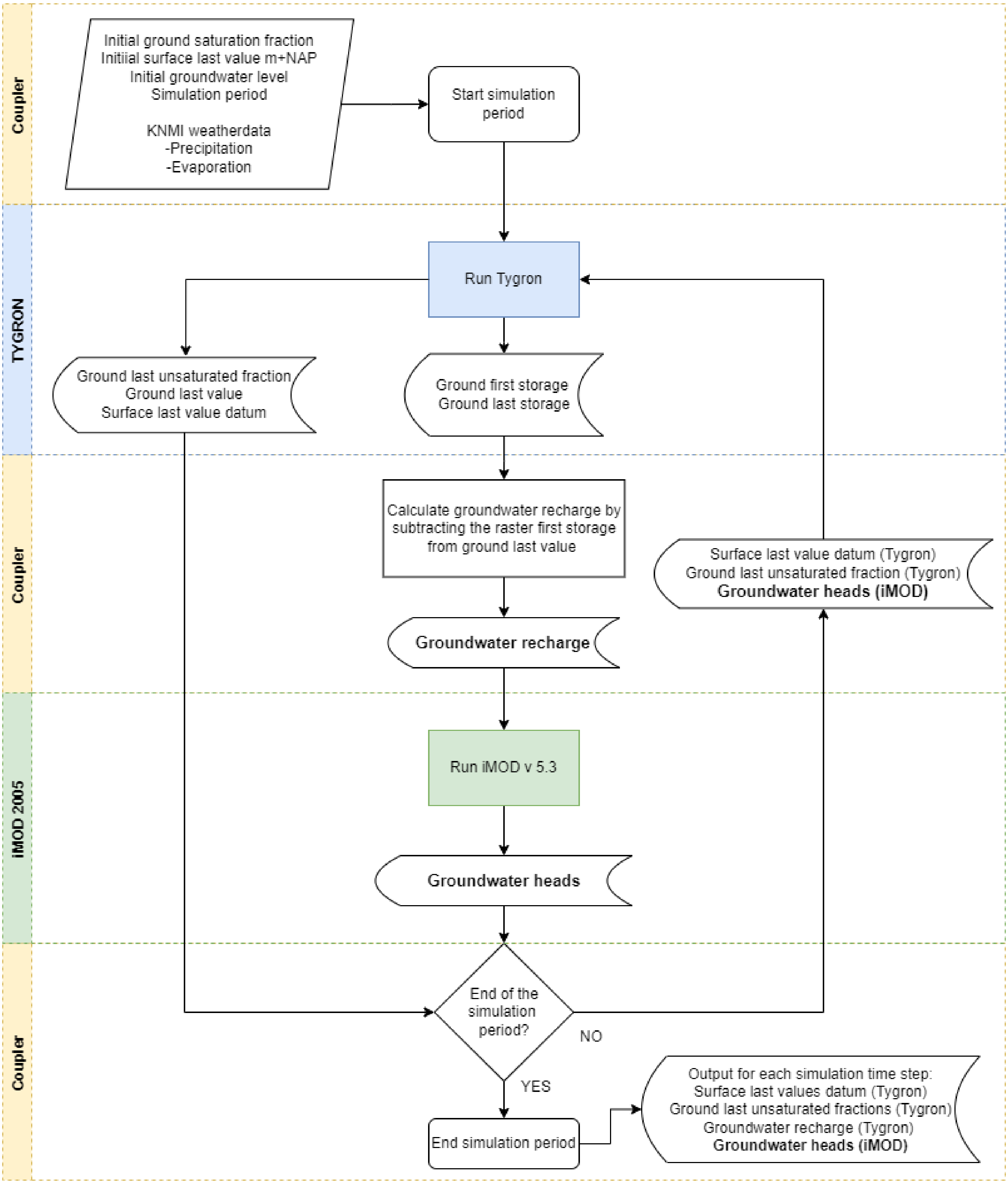


Figure 10: Flow chart simulation coupling Tygron MODFLOW

5. Results

First, the historical periods picked out for the case study are presented in section 5.1. Following the methodology for establishing the models, the initial surface water levels for Tygron can be found in section 5.2. For the development of the models, variables that may influence groundwater storage were examined through a sensitivity analysis. Lastly, the oscillations in the groundwater levels for the groundwater study in the last section of this Chapter.

5.1. KNMI data

To check for similarities between the weather data of the KNMI weather station in Hupsel and the KNMI rain station in Winterswijk, several statistical tests are performed. The statistical test of the precipitation data sets resulted in a z-value of 0.509 and a p-value of 0.611. The complete data sets are not statistically significant as the z-value is not close to zero. Furthermore, the RMSE value is 2.214 while the mean precipitation in Hupsel is 2.182mm and the mean precipitation in Winterswijk is 2.241mm. Moreover, the standard deviation of the precipitation data in Hupsel is 4.230 and the standard deviation of the precipitation data in Winterswijk is 4.490. As the RMSE is not a small percentage of the means of both data sets, the data sets differ. After this, there is looked for statistically significant periods.

For that, t-tests are performed over periods of two weeks. From these, four periods with the highest p-value in the summer months are chosen and used for the case study. Of the four periods, one is a dry period (01-07-2013 – 14-07-2013), one is a wet period (15-08-2015 - 28-08-2015), and there are two average situations (01-07-2016 – 14-07-2016) and (15-07-2017-28-07-2017). Precipitation graphs of these periods can be seen in Table 3 and Figure 24 in Appendix B: Rainfall events of interest.

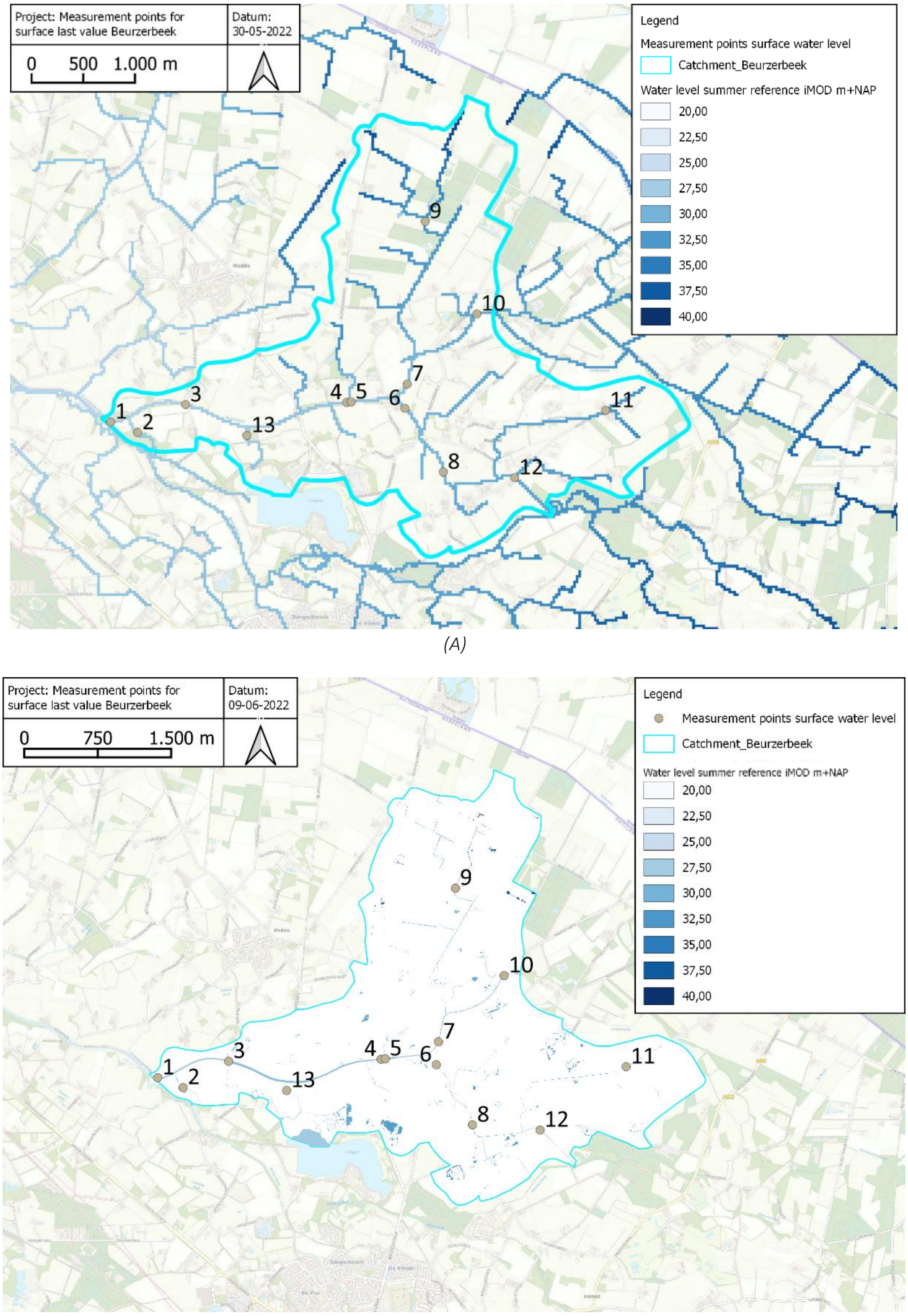
Table 3: Test periods model

Period	Total Precipitation Winterswijk (mm)	Total Precipitation Hupsel (mm)	Total ET (mm)	t-value	p-value	Mean precipitation Winterswijk (mm)	Mean precipitation Hupsel (mm)	Standard deviation precipitation Winterswijk	Standard deviation precipitation Hupsel
01-07-2013 to 14-07-2013	1.9	2.2	46.9	-0.120	0.906	0.143	0.157 mm	0.397	0.514
15-08-2015 to 28-08-2015	113.3	113.7	34	-0.006	0.995	8.092	8.121 mm	12.333	13.850
01-07-2016 to 14-07-2016	43.0	44.0	44	-0.043	0.966	5.521	3.143 mm	10.984	4.384
15-07-2017 to 28-07-2017	62.9	62.8	45.6	0.004	0.997	4.493	4.486 mm	4.640	5.181

5.2. Initial surface water level

The initial surface water level is estimated using SOBEK and several runs in Tygron. The runs each did use different weather conditions. Several combinations of durations of weather events, the intensity of weather events and the number of dry days after the weather event in which the water levels had time stabilized were applied to the model. A close approximation to the standard water level defined by the waterboard in Table 2 and the modelled water levels in AMIGO was found after an 80mm weather event on one day followed by six dry days. The initial water levels can be seen in Table 4 and Figure 11B.

The modelled water level in Tygron at the location of the Weir falls under the classification of normal water level according to Table 2. This is the same for the modelled water depths in AMIGO, and therefore, concluded to be a good fit. Next to this, a root mean square error test was performed to conclude the differences in modelled absolute water depths in AMIGO and Tygron. The RMSE for the water depths is 0.62. This number is about 50% of the mean water depths, and therefore, the absolute water depths are not a close approximation. Nevertheless, the initial surface water level depths are used in the study as water levels fluctuate and there is no data about the observed water levels in the Beurzerbeek except from one location, which was the weir 'Overlaat de Kip'.



(A)

(B)

Figure 11: Measurement points for the modelled water level in the Beurzerbeek in (A) AMIGO and (B) Tygron

Table 4: Modelled water levels at measurement points of Figure 11

	Absolute water depth AMIGO (m)	Absolute water depth Tygron (m)
1	1,15	1,72
2	0,65	0,84
3	1,56	2,74
4) Downstream weir 'Overlaat de kip'	2,19	2,59
5) Upstream weir 'Overlaat de kip'	2,52	2,71
6	0,44	0,49
7	0,52	1,02
8	0,54	0,50
9	0,89	0,30
10	0,66	1,38
11	0,10	0,48
12	0,25	0,59
13	0,51	1,81
Standard deviation	0.71	0.87
Average	0.92	1.32

5.3. Sensitivity analysis of potential evaporation influencing the groundwater storage

As rain and evapotranspiration are the biggest fluxes in the water balance, the influence of a change in the evapotranspiration parameter is verified. The results are shown in Figure 13. Also, the values in the Figures are analysed and a linear relationship is observed on all groundwater measurement points in Figure 26 and shown in Figure 12. When the evapotranspiration increases, the groundwater storages decrease as more groundwater evaporates. Also, the influence of evapotranspiration on groundwater storage is quite big as the groundwater storage decreases in most locations by a factor of 0.9. On location two, there is a water area wherefore the groundwater storage does not change. Similarly, to location two, location seven is located close to the creek for the groundwater storage does not change much. The substantial change in groundwater storage at location eleven is due to the vegetation as there are trees present based.

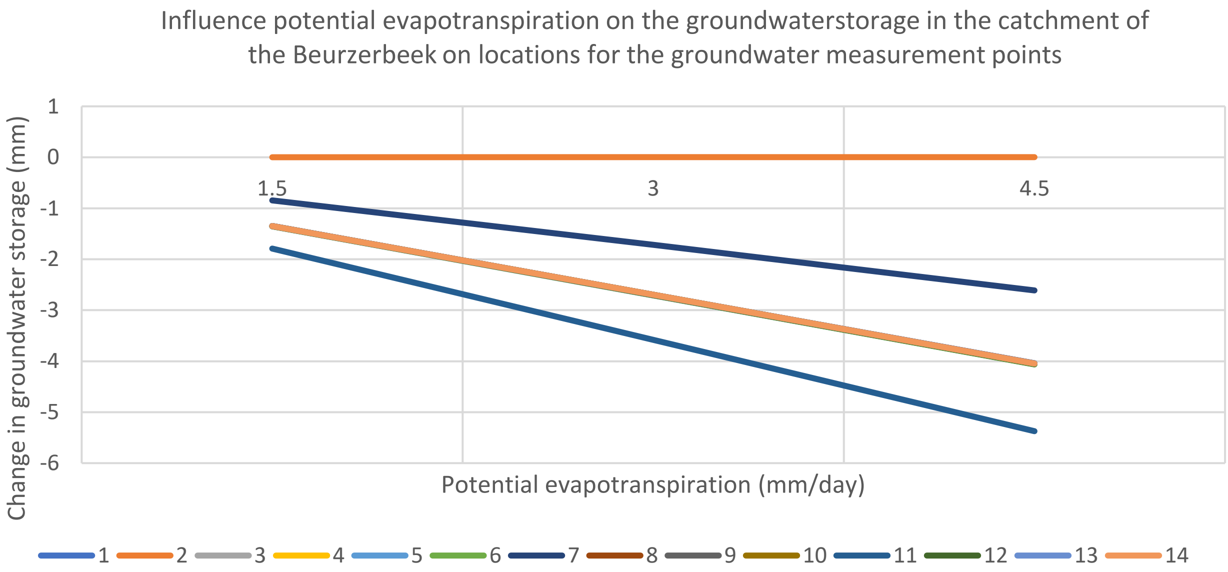
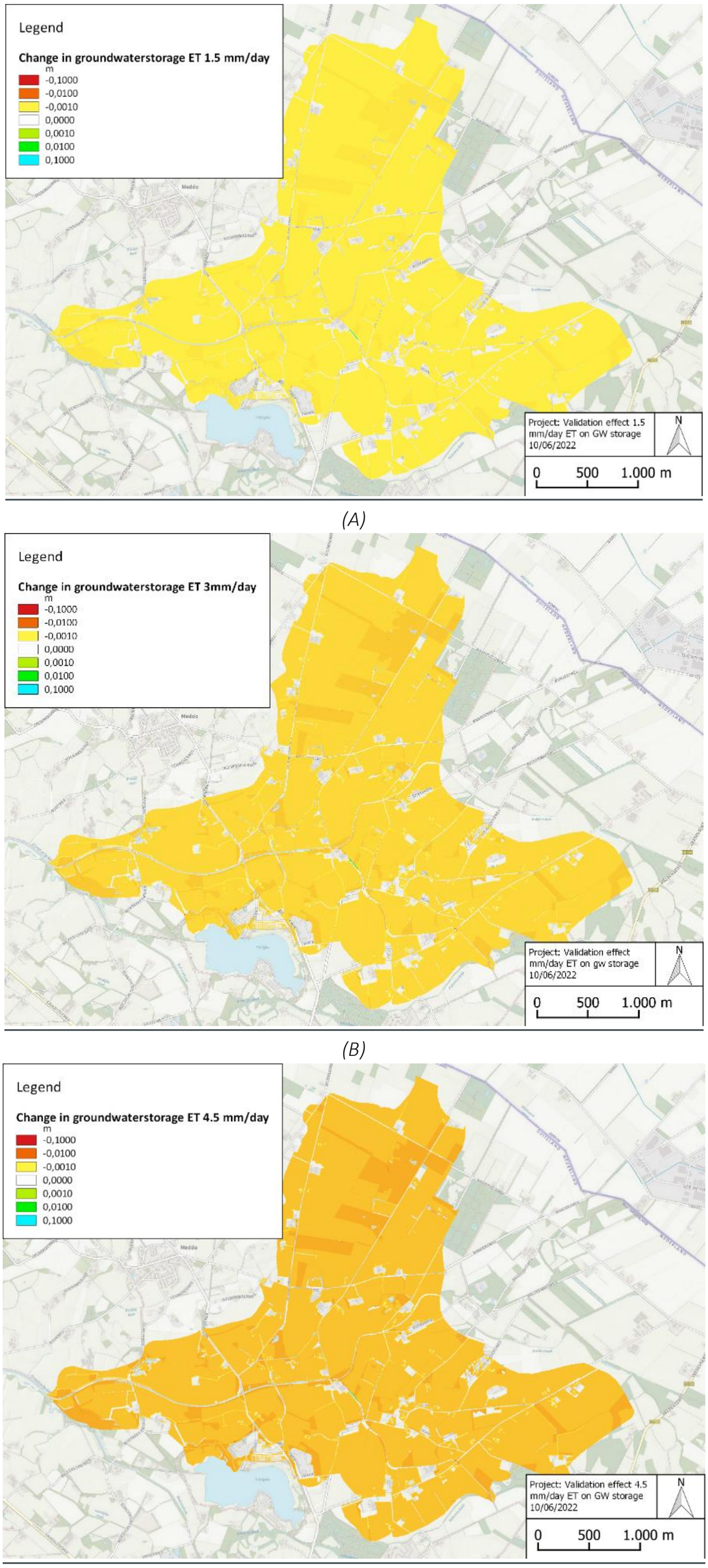


Figure 12: Graph relation of potential evapotranspiration to the change in groundwater storage in one day for the groundwater measurement points of Figure 26



(A)

(B)

(C)

Figure 13: Maps showing the change in groundwater storage after one-day simulation with potential evapotranspiration (A) 1.5mm/day (B) 3mm/day (C) 4.5mm/day

Next to this, literature in section 3.1 showed that potential evapotranspiration is not linearly distributed over 24 hours. Therefore, a modelling experiment is performed for the input parameter potential evapotranspiration as most evapotranspiration takes place during the day and the amount of evapotranspiration during an hour at night is about 1.7% of the total daily evaporation (Malek, 1992). The effect on the groundwater storage of the diverse types of ET as shown in Figure 14 is shown in Figure 15.

Figure 15 shows that time-varying evaporation input does influence groundwater storage a little throughout the day, but there are not many differences in groundwater storage at the end of the day. The difference can be seen near the waterways.

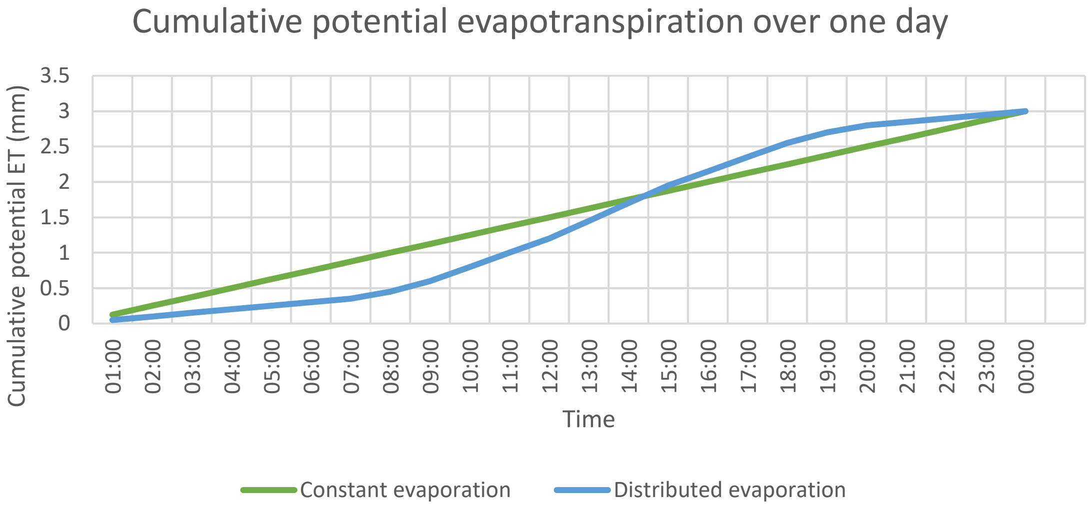
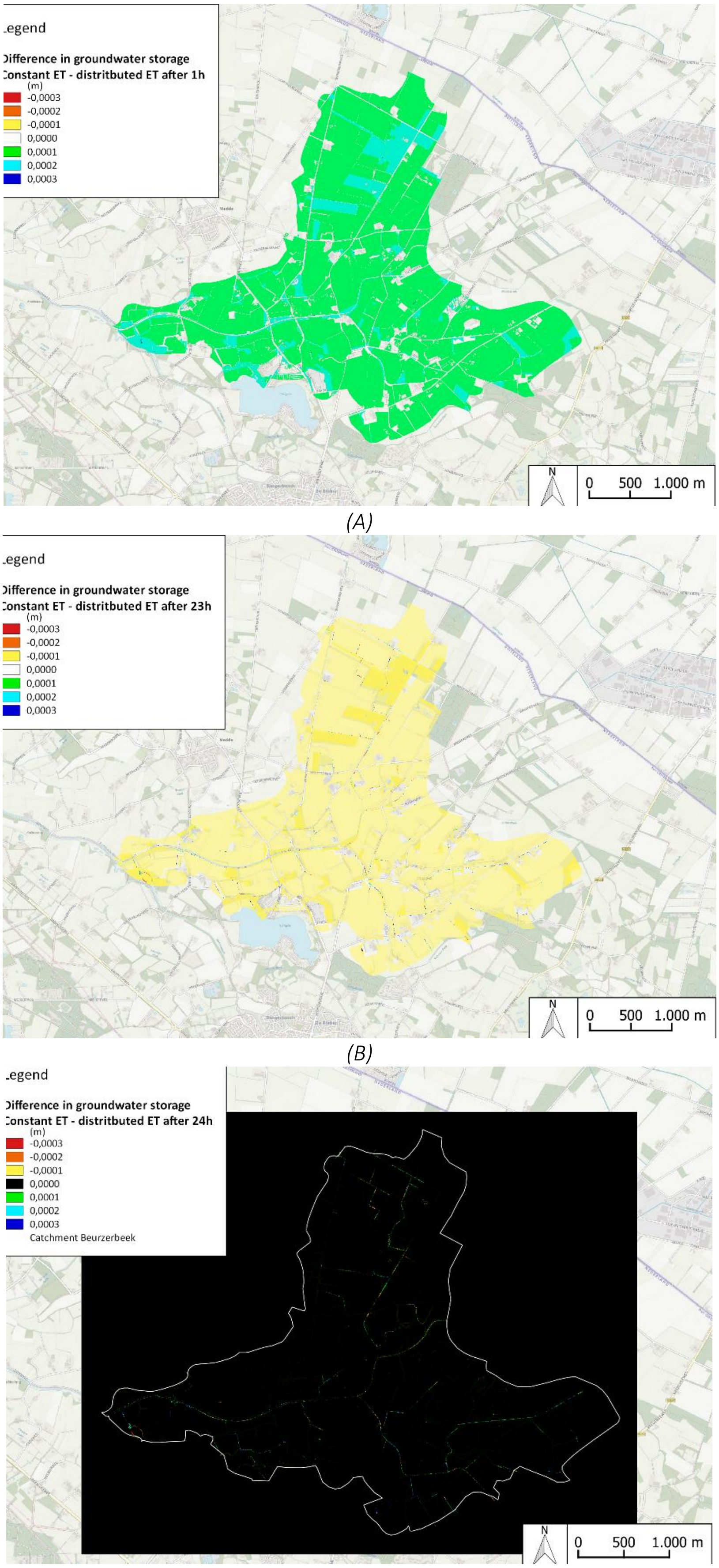


Figure 14: Graph of cumulative constant and distributed potential ET over one day



(C)

Figure 15: Difference in groundwater storage between a situation with constant ET and distributed ET as shown in Figure 14 after (A) one hour (B) 23 hours and (C) 24 hours

5.4. Sensitivity analysis of precipitation influencing the groundwater storage

To determine the sensitivity of the precipitation to the change in groundwater storage, the next four simulation runs are done in Tygron. First, an uniformly distributed weather event of 10mm rain over 24 hours is simulated. After that, a rain event of 10 mm per one hour happened followed by 23 dry hours. Thirdly, an uniformly distributed weather event of 50mm. Lastly, a weather event of 50mm happened and was followed by 23 dry hours.

Figure 16 shows that the groundwater storage after one hour is higher for the weather event where the precipitation is almost uniformly distributed. However, the groundwater recharge will be passed on after one, therefore the difference in groundwater storage after 24 hours is investigated in Figure 17 and Figure 18. They show that there is no linear relationship, this means that a part of the precipitation will runoff when heavy rainfall occurs.

Figure 18 shows the difference in groundwater storage after 24 hours for the scenarios of a 50mm weather event. The blue from the colour bar indicates the places where the groundwater recharge is higher when the weather event is spread over one day. When the rainfall event is not uniformly distributed over one day, rainwater runoffs over the ground and accumulates in lower laying areas where it infiltrates. In these locations denoted by red, the groundwater recharge will be larger.

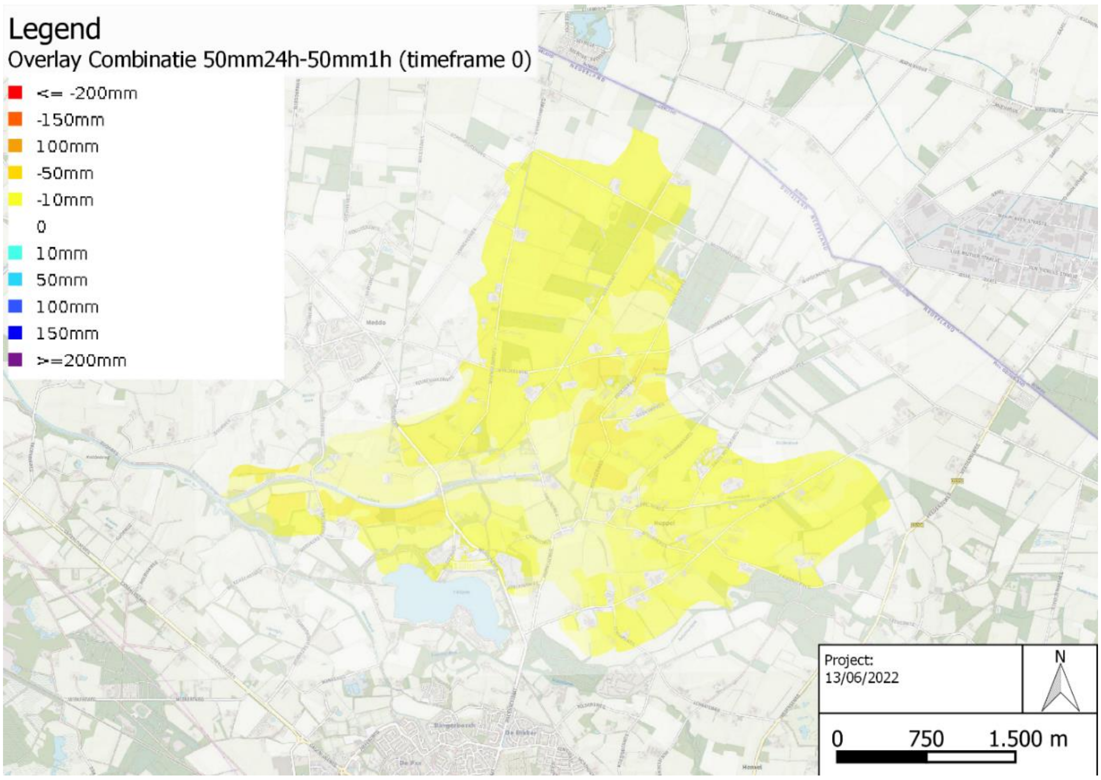


Figure 16: Difference in groundwater storage after a 50mm rainfall event over 24 hours and a 50mm rainfall event over one hour after a one-hour simulation

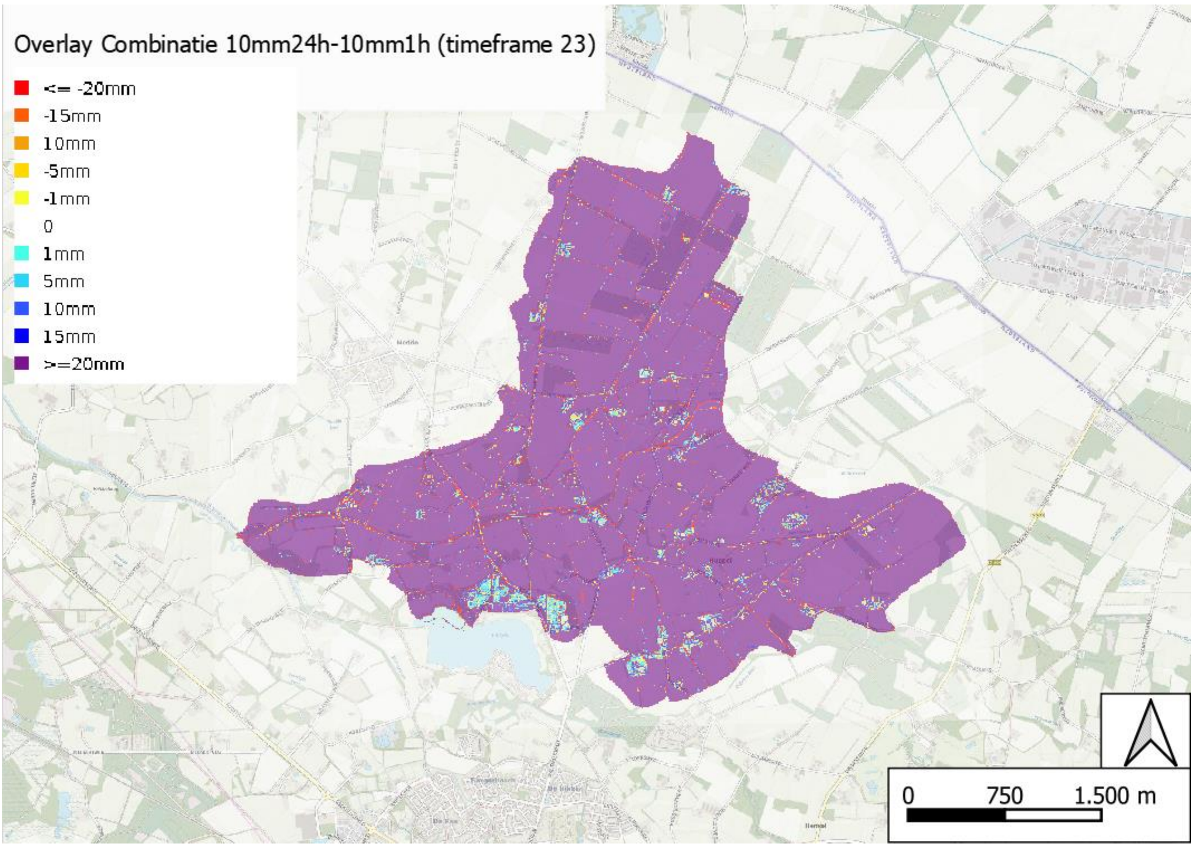


Figure 17: Difference in groundwater storage after a uniformly distributed 50mm rainfall event over 24 hours and a 50mm rainfall event over one hour after a one-day simulation

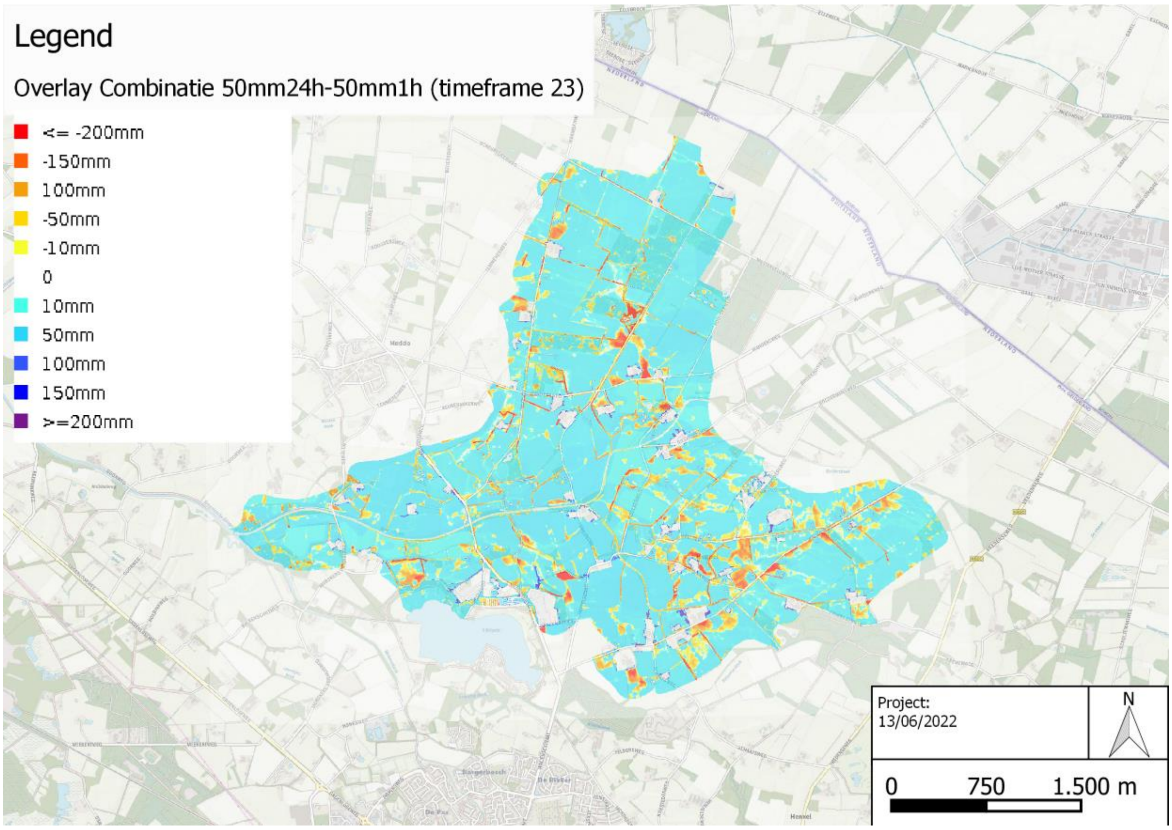


Figure 18: Difference in groundwater storage after a 50mm rainfall event over 24 hours and a 50mm rainfall event over one hour after a one-day simulation

5.5. Coupling strategy

As can be seen in Figure 10, the models are coupled by passing on the groundwater recharge from Tygron to MODFLOW. After this, MODFLOW calculates the corresponding groundwater heads which are passed back to Tygron. Other values like the unsaturated groundwater fraction and surface last value datum values are remembered in the TYGRON environment. Groundwater storage recharge is the absolute value of the storage, meaning: the groundwater storage at the end of the day minus the groundwater storage at the beginning of the day.

Figure 16 and Figure 18 show that the spread of a rain event influences the groundwater recharge in time. Coupling the groundwater recharge is most likely to be the correct way of passing the recharge on. Due to time constraints, the python script and the MODFLOW run files are not rewritten for this option. Not only would reconstructing the coupling take time, but the running of the models would as a result take approximately 24 times as much time.

This leaves two options for coupling the models. The groundwater recharge will be passed on each day, but the weather data can be loaded either daily or hourly. Figure 18 shows in which places the effect is the most visible and that there are many local differences in the groundwater recharge. However, MODFLOW uses a grid of 10x10 meters, thus these local differences might be lost again because Tygron uses a grid of 2x2 metres.

5.6. Dynamics in the groundwater levels

For the four selected periods in section 5.1, the groundwater heads are modelled in AMIGO and the coupled Tygron MODFLOW model. The Figure below shows a result from the AMIGO model at the end of the simulation of the case study for 2013.

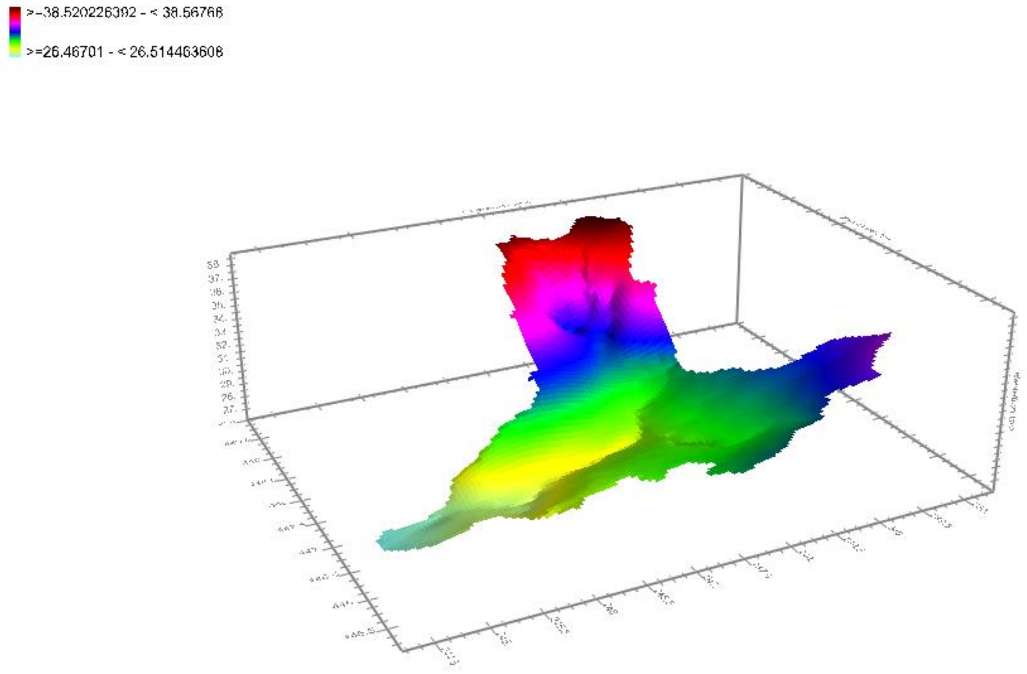


Figure 19: GW head 14-07-2013, result from AMIGO

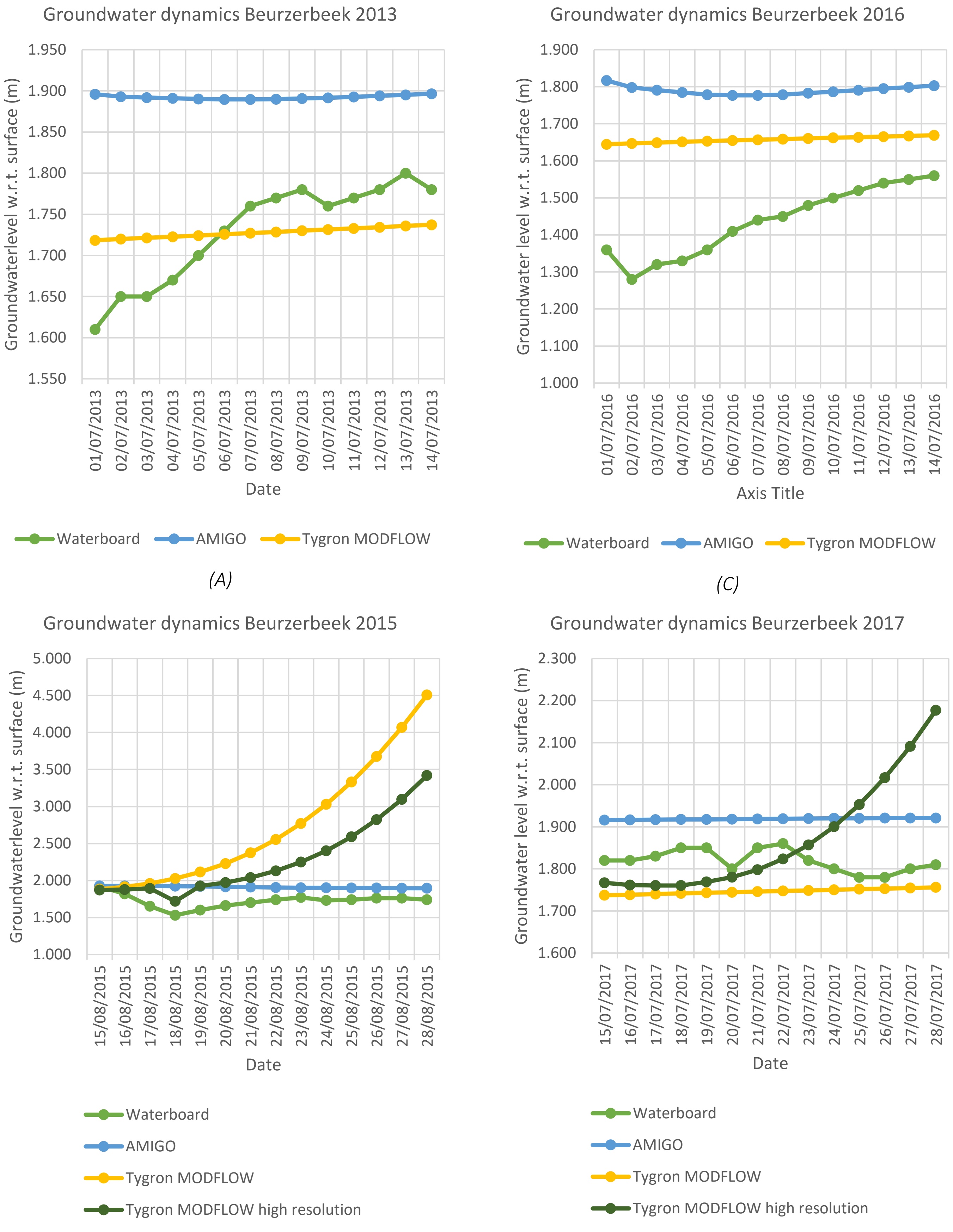
First, to results of the improved coupled Tygron MODFLOW model are for each study period compared to the measurements from Vitens and the modelled groundwater levels in AMIGO at the location of the groundwater measurement point shown in Figure 2. Figure 20 presents the dynamics in the groundwater levels at this location.

The coupling results are indicated by the yellow lines in Figure 20. The grid size of AMIGO was 25x25m while the coupled model is run using a grid 2x2m grid in Tygron and a 10x10m grid in MODFLOW. The weather events in 2015 and 2017 are also run in the coupling with a higher resolution, being 1x1m in Tygron and 5x5m in MODFLOW. This is not done for 2013 and 2016 as the computational time is quite high. More elaboration on the computational time of the models can be found in Appendix C: Calculation times on page 49.

The Figures below and Table 5 show that the modelled groundwater levels in AMIGO are still a better fit than the modelled groundwater level in the coupled MODFLOW Tygron as the root mean square error test is closer to zero. Also, both model results show that the models are not able to capture the dynamics in the groundwater levels for the location of the groundwater monitoring well of Vitens as the groundwater levels are almost constant.

Table 5: Statistics of groundwater dynamics groundwater well

	Measurement well	AMIGO	MODFLOW Tygron
Mean groundwater level to the ground (m)	2.437	2.635	2.724
Standard deviation	3.823	3.794	3.829
RMSE (with respect to the measurement well)		0.231	0.660



(A)

(C)

(B)

(D)

Figure 20: Dynamics of groundwater levels at the groundwater level measurement point from (A) 01-07-2013 till 14-07-2013 (B) 15-08-2015 to 28-08-2015 (C) 01-07-2016 to 14-07-2016 (D) 15-07-2017 to 28-07-2017

The groundwater levels are beside the location of the measurement well and also monitored at 13 distinct locations shown and elaborated on in Appendix D: Dynamics in the groundwater levels on page 51. Moreover, in that part of the Appendix, the change in groundwater heads in AMIGO and the coupled Tygron MODFLOW are shown for the four periods.

In Figure 28 on page 53, there can be seen that the groundwater levels in 2015 dropped exceptionally low where the locations are situated near the boundary. This can also be seen in Figure 32C and Figure 32E.

Furthermore, the groundwater levels are on average for 2013, 2016 and 2017 higher in the coupled MODFLOW Tygron than in AMIGO. The averages and corresponding standard deviation are shown in Table 6 below. The modelled heads in Tygron MODFLOW are on average higher as the heads from AMIGO are subtracted from the heads of the coupled MODFLOW Tygron.

Table 6: Average difference between the modelled groundwater levels in the coupled MODFLOW Tygron model and AMIGO.

2013		**2015**		**2016**		**2017**	
Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
0.358	0.020	-18.626	10.556	0.127	0.044	0.359	0.012

Coupled models that work with different resolutions are very prone to errors in the input data. The 2015 simulation on higher resolution showed incredibly low groundwater levels at the boundary of the model area. Differences in resolution caused the occurrence of no data values of -9999 in one of the high-resolution input grids. Those values are interpreted as actual values causing unrealistic values in the result. Manual correction of the data is done by loading a larger area, recommendation is to include automated checks on the input data and correction routines in the scripts that run the models.

6. Discussion

The research objective was to map the strengths and limitations of the coupling of Tygron to MODFLOW. This section discusses these and how the methodology that has been used has affected the research.

6.1. Coupling

Firstly, the coupling, the python script, will probably not keep up with the advances of individual codes. Currently, there is already the sixth version of MODFLOW and the fifth version which is used in this research will once turn outdated. Also, Tygron is rapidly developing and removing and adding several API requests. This was noted during the research as some API requests were not functioning anymore for work around had to be found.

The advantage of these rapid developments at Tygron is first the low computational times as their super computers only get faster. This gives opportunities to include more of the calculations in the Tygron environment. Currently, several results from Tygron are downloaded, including the groundwater storage. These results are locally saved via the coupling script after the groundwater recharge is calculated locally on your computer instead of in the Tygron environment. The computational time can therefore be lowered by implementing combination overlays. Combination overlays are additional spatial calculation models in Tygron. In conclusion, using combination overlays could reduce the computational time of the coupling as the supercomputers at Tygron have a high calculation capacity.

Moreover, as the study focuses on the groundwater oscillations and the ability to capture extreme weather conditions, it should have been investigated whether the models can be coupled each hour instead of every day. For this, hourly weather data should be used, and the calculated groundwater recharge is passed on to MODFLOW to calculate the heads each hour. Subsequently, these heads must be used as input for the second simulation hour in Tygron. This coupling strategy could capture hydrological dynamics under extreme climate conditions as desired by Chen, Krom, Wu, Yu & Hong (2018).

Furthermore, each iteration of the coupling creates a new overlay in Tygron. With this, information is lost. For example, the speed of the water travelling in Tygron is not kept over the iteration to the next overlay. Not only surface water velocities but also groundwater velocities are lost. Ideally, the information in an overlay for a specific timestep should be downloaded, the overlay put on pause and when new groundwater heads from MODFLOW are uploaded again, the overlay should continue to calculate.

6.2. Initial conditions

Besides, the setup of the Tygron model has influenced the results of the coupling. Equalizing data in both the MetaSWAP part of the AMIGO model and the Tygron model will make the comparison of results better. Below, several differences in the setup of the models are highlighted.

Firstly, the initial water level heights of Tygron are a good approximation to normal water levels in the catchment in the Beurzerbeek. However, the four modelled historical periods in the case study are all summer periods. For a summer period, a water level height which is lower than the normal water levels would be applicable. If the water levels in the streams are high, less groundwater will flow toward the stream. For this, the calculated groundwater storage near the creeks is higher than in reality. As a result, the groundwater levels will be higher.

Secondly, as mentioned before, there are no drainage pipes constructed in the Tygron model while a drainage system is present in the AMIGO model. Therefore, the groundwater recharge passed on to MODFLOW will be overestimated with the result that the calculated groundwater levels in MODFLOW at agriculture fields will fluctuate more in the AMIGO model than in actuality. This assumption follows the results of the groundwater levels for the case study as the groundwater heads are on average 0.3 meters higher than modelled in the AMIGO model.

Three small streams flow into the catchment of the Beurzerbeek. They are modelled as constant input water flows. In reality, these input flows will discharge more water in the Beurzerbeek if it is raining heavily and discharge less water if it has not rained for a long time. The groundwater levels close to these inlets would, therefore, fluctuate more in reality.

Fourthly, in theory, the infiltration speed is dependent on the soil saturation as water does not have a high infiltration speed when the ground is very dry or, conversely, fully saturated. As soon as the ground is fully saturated, the infiltration stops in Tygron. However, infiltration speed is constant, therefore, the modelled groundwater recharge is higher after a rain event in a dry period.

Additionally, during the site visit, it was noted that there are many different trees in the area. Every tree has its characteristics and the amount of groundwater which can evapotranspiration via trees depends on the type of the tree. The site visit showed a lot more trees than what is present in the TYGRON model, therefore, a test on the influence of trees in TYGRON can be interesting. Also, the regional AMIGO model includes several types of trees while Tygron has in a standard situation only deciduous trees (Arcadis, 2019) Groundwater can transpirate via trees and their type and size determine how much and from which depth they can extract groundwater. Therefore, the calculated groundwater recharge in Tygron can differ from MetaSWAP in locations where trees are present.

Lastly, the site visit showed that the banks of the Buursebeek and Modderbeek differed from the Beurzerbeek. As the roughness of the embankment of the Beurzerbeek is greater, it is expected that the flow velocity in the Buursebeek and Modderbeek is higher. This could result in more water downstream in the Beurzerbeek, less water infiltrating in the ground upstream, and therefore, a calculated groundwater recharge upstream along the Buursebeek and Modderbeek which are higher than in real life.

7. Conclusions and recommendations

7.1. Conclusions

In this research, the strengths and the limitations of the coupled MODFLOW Tygron model are assessed. The coupling strives to model the interactions between the surface water and groundwater for Beurzerbeek and with this aiming to contribute to a better insight into the groundwater dynamics in the catchment of the Beurzerbeek. This is done by answering two research questions.

The first sub-question was: *'How should Tygron be coupled to MODFLOW in order to capture extreme weather conditions at the Beurzerbeek?'*

The time step of MODFLOW and the coupler should be one day while Tygron should use hourly input to replicate the extreme weather events. Tygron shows a significant difference in Figure 16 in infiltration between hourly rainfall and daily average rainfall. Since no measurements of actual infiltration rates are available, validation of the outcome is limited possible. However, since infiltration can be exceeded by rainfall intensity hourly values are expected to provide better results than daily average values. Since the difference in recharge and the resulting groundwater flows show a slight improvement in dynamics this research concludes that coupling with groundwater models gives no significant improvement between hourly coupling and daily coupling. Also, the computational times would increase by at least 150% if the couples are coupled each hour.

The second sub-question was: *'Can the groundwater oscillations of the Beurzerbeek be simulated more accurately in a model where the location of infiltration is not only dependant on the location of the precipitation, but also on the runoff when coupled to a detailed groundwater model?'*

Looking at the results, the hydrological dynamics of the Beurzerbeek are not yet better simulated in the new coupling compared to the current groundwater modelling practice AMIGO for the location of the groundwater measurement point. Next to this, the modelled groundwater levels in 2013, 2016 and 2017 are a close approximation of the groundwater levels.

However, the results of the case study of 2015 which represented the wet year included many days with large negative groundwater recharges. As a result, the heads resulting from 2015 are very low. This was not expected as the precipitation values were high for 2015. The large different values can be due to the boundaries of the catchment influencing the groundwater levels a lot. If that problem is fixed, more accurate results could be obtained after which a conclusion about the second sub-question can be given. For now, this research question can not be answered as the results are not sufficient.

The answers to the sub-questions are used to reflect upon the main question of this research. In short, the coupled Tygron MODFLOW model is fast computing and captures many of the hydrological processes in very detail including surface runoff and groundwater flows. Nevertheless, the model should be further developed and amongst others more automatic checks and faster computing times are desirable.

7.2. Recommendations

Based on the outcome of the study, three recommendations are given for further implementation of the coupling. The recommendations are explained below.

First, I do recommend to further develop the coupling and testing the functioning of the coupling more extensively. As explained in the discussion, there are possibilities to decrease the calculation times of the model. Moreover, more (automated) checks on the input data should be included to improve the reliability of the model results. Next to this, in this research, the oscillations in the groundwater levels during four periods of two weeks have been extensively investigated. However, groundwater levels also fluctuate throughout the year where the groundwater levels are higher in the winter than in the summer in the Netherlands. Having low calculation times, there should be investigated how the groundwater levels oscillate throughout a year.

As stakeholders are mostly interested in three types of problems as described in the introduction; freshwater shortage, water-related hazards, and water quality, it is essential to evaluate if the coupled TYGRON and MODFLOW model can be used to investigate how effective certain measures are against flooding or droughts. There are several types of measures. For example, a measure can be adjustments to existing water management, it can be example shallowing waterways, heightening levees, or, widening floodplains or adding wadis (Hoekstra, 2018). Next to this, it can be an adjustment to the dewatering of parcels, for example adding a new GW extraction point, adding ditches, and adding drip irrigation (Schipper, et al., 2013). In general, the stakeholders would like to know what the effect of climate change or the implementation of measures or a combination of both is on the GW and SW levels, the local agriculture, and terrestrial nature. Also, stakeholders and policymakers would like to know how certain these expectations are.

Lastly, water pollution can have negative effects on health and the environment. Therefore, it is important to get insights into the quality of the groundwater and surface water, especially near sources of drinking water and bathing waters. It is meaningful to know the travel routes and times from pollutants. Therefore, I do recommend investigating how the coupled model does compare to current practice for identifying, on a parcel level, the source of water that enters the stream including travel times and routing and if it is possible to include tracers in the coupled models. There are packages in TYGRON and MODFLOW to track particles, thus I believe that it is possible to integrate such an option. That research can be a step toward models in which the use of GW and SW interactions and all hydrological processes and the transport of nutrients are modelled correctly.

8. Bibliography

(2022). Retrieved 3 13, 2022, from SDGS UN: https://sdgs.un.org/goals/goal6

About Tygron. (2022, June). Retrieved from Tygron platform: https://www.tygron.com/nl/over-tygron/

Arcadis. (2019). *Vernieuwen grondwatermodel Amigo.* Arnhem: Waterschap Rijn en Ijssel. Retrieved May 2022, from https://gelderland.maps.arcgis.com/apps/dashboards/62272f39825d403da13f50afb35bc2dc

Basiskaarten. (2022). Retrieved from Bodemdata.nl: https://bodemdata.nl/basiskaarten

Bodemberging in grafieken. (2022, May). Retrieved May 2022, from Experience arcgis: https://experience.arcgis.com/experience/a0c12ab0acb24990b11e7c7f644724c1/page/Bodembergingsindicator/

Booij, D. i. (2019). *Water Management.* University of Twente, Engineering Technology. University of Twente.

Bot, A. (2011). *doorlatendheid k.* Retrieved from grondwaterformules.nl: http://grondwaterformules.nl/index.php/vuistregels/ondergrond/doorlatendheid-per-grondsoort, www.grondwaterzakboekje.nl

CBS, PBL, RIVM, WUR. (2020, April 24). *Klimaatverandering, Jaarlijke hoeveelheid neerslag in Nederland, 1910-2019*. Retrieved March 28, 2022, from Compendium voor de Leefomgeving: https://www.clo.nl/indicatoren/nl0508-jaarlijkse-hoeveelheid-neerslag-in-nederland

Chen, N., & Wang, Y. (2021). Recent progress in coupled surface–ground water models and their potential in watershed hydro-biogeochemical studies: A review. *Watershed Ecology and the Environment, 3*. doi:https://doi.org/10.1016/j.wsee.2021.04.001

Chen, N., Krom, M., Wu, Y., Yu, D., & Hong, H. (2018, July). Storm induced estuarine turbidity maxima and controls on nutrient fluxes across river-estuary-coast continuum. *Science of the Total Environment*, 1108-1120. doi:10.1016/j.scitotenv.2018.02.060

Deltares. (2021). *Release notes iMOD v 5.3.* Retrieved from https://oss.deltares.nl/web/imod/download-imod5

Deltares. (2022). *SOBEK Suite*. Retrieved from Deltares: data from the waterboard Rijn and IJssel was needed

Diaz, M., Sinicyn, G., & Grodzka-Lukaszewska, M. (2020). Modelling of Groundwater–Surface Water Interaction. *Water*. Retrieved from https://www.mdpi.com/2073-4441/12/12/3303/pdf

Drainagebeleid en beregeningsbeleid voor onttrekkingen uit grondwater. (2020, August). Retrieved from storymaps arcgis: https://storymaps.arcgis.com/stories/28acc52ab6444424887e60b9663dc895

GGIS. (2022). *A free and open source geographic information system*. Retrieved from QGIS: https://www.qgis.org/en/site/index.html

GIS FME SERVER. (2022, May). Retrieved from Download bomen uit het Boomregister (GeoJSON): https://gisfme.vwinfra.nl/fmeserver/apps/AlgemeneToolsAdB/DownloadBoomkruineninGeoJSON

Helder, J. (2022, May 10). Site visit Beurzerbeek. (L. Schoonderwoerd, Interviewer)

Hoekstra, A. Y. (2018). *Water.* Lecture notes, University of Twente, Faculty of Engineering Technology.

Hydronet. (2022, May). *Hydronet*. Retrieved May 2022, from Waterstanden-Overlaat de Kip-Bovenstrooms: https://services.hydronet.com/hydrowatch/api/chart/project/60/theme/3117/group/1236

Intergovernmental . (2013). *Climate Change 2013 The Physical Science Basis Summary for Policymakers.* IPCC. Retrieved 3 5, 2022, from https://www.ipcc.ch/site/assets/uploads/2018/03/WGIAR5_SPM_brochure_en.pdf

Koninklijk Nederlands Meteorologisch Instituut. (2022, May). *Verdamping in Nederland*. Retrieved from KNMI: https://www.knmi.nl/kennis-en-datacentrum/achtergrond/verdamping-in-nederland

Kreienkamp, F., Philip, S., Tradowsky, J., Kew, S., Lorenz, P., Arrighi, J., . . . Wanders, N. (2021). *Rapid attribution of heavy rainfall events.* World Weather Attribution. Retrieved March 28, 2022, from https://www.worldweatherattribution.org/wp-content/uploads/Scientific-report-Western-Europe-floods-2021-attribution.pdf

Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., & Provost, A. M. (2017). Documentation for the MODFLOW 6 Groundwater Flow Model. In *Modeling Techniques* (pp. Chapter 44 of Section A, Groundwater). U.S. Geological Survey. Retrieved 2022, from https://pubs.usgs.gov/tm/06/a55/tm6a55.pdf

Malek, E. (1992). Night-time evapotranspiration vs. daytime and 24 h evapotranspiration. *Journal of Hydrology*, 119-129. doi:https://doi-org.ezproxy2.utwente.nl/10.1016/0022-1694(92)90159-S

Massop, H., & Schuiling, C. (2015). *Buisdrainagekaart.* Wageningen: Alterra Wageningen UR. Retrieved Mai 2022, from http://nhi.nu/nl/files/7314/9398/1135/actualisatie_buisdrainagekaart_2016.pdf

McClave, J., & Sincich, T. (2018). *Statistics* (13 ed.). Pearson; 13th edition (November 9, 2017). Retrieved April 2022

Ministry of Health, Welfare and Sport. (2018, 11 2). *Quality of drinking water*. Retrieved from rivm: https://www.rivm.nl/en/soil-and-water/drinking-water/quality-of-drinking-water

Nederlands Hydrologisch Instrumentarium. (2022). *AMIGO*. Retrieved March 2022, from NHI: http://www.nhi.nu/nl/index.php/modellen/amigo/

NHI. (2022). *Buisdrainage*. Retrieved from Nederlands Hydrologisch Instrumentarium: http://nhi.nu/nl/index.php/documentatie/buisdrainage/

Pankow, J., & Rijtema, P. (2022, June). *Schatten van kwel (Pankow)*. Retrieved from grondwaterformules.nl: http://grondwaterformules.nl/index.php/formules/ontwatering/kwel-berekenen-pankow

Pörtner, H.-O., Roberts, D., Poloczanska, E., Mintenbeck, K., M. Tignor, A., Alegría, M. C., . . . Okem, A. (2022). *Climate Change 2022 Impacts, Adaption and Vulnerability Summary for Policymakers.* Intergovernmental Panel of Climate Change. Retrieved from https://www.ipcc.ch/report/ar6/wg2/

Rijkwaterstaat. (2022, March 28). *Rijn-Oost*. Retrieved from helpdeskwater: https://www.helpdeskwater.nl/onderwerpen/wetgeving-beleid/kaderrichtlijn-water/grondwater/grondwater-krw/conceptuele-modellen/@178640/rijn-oost/

Rijkwaterstaat Water, Verkeer en Leefomgeving. (2020). *De staat van ons water, Rapportage over de uitvoering van het waterbeleid in 2020.* Retrieved from https://www.helpdeskwater.nl/onderwerpen/wetgeving-beleid/nationaal/staat-water/

Ritzema, H. (2015, March). Land drainage strategies to cope with climate change in the Netherlands. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science 65(1)*, 80-92. doi:10.1080/09064710.2014.994557

Schipper, P., Boogaart, P., Groot, A., Kroes, J., Mol-Dijkstra, J., Mulder, M., . . . van der Sluijs, J. (2013). *Integraal Waterbeheer - kritische zone en onzekerheden.* Alterra Wageningen UR, Wageningen. Retrieved April 2022, from http://content.alterra.wur.nl/Webdocs/PDFFiles/Alterrarapporten/AlterraRapport2443.pdf

Soil Geography and Landscape Group. (n.d.). *Overland flow*. Retrieved 2022, from Wageningen University & Research: https://www.wur.nl/en/Research-Results/Chair-groups/Environmental-Sciences/Soil-Geography-and-Landscape-Group/Research/LAPSUS-model/Modules/Overland-flow.htm

Song, S., Schmalz, B., Zhang, J., Li, G., & Fohrer, N. (2017). Application of modified Manning formula in the determination of vertical profile velocity in natural rivers. *Hydrology Research*, 133-146. doi:10.2166/nh.2016.131

TNO Geologische Dienst Nederland. (2022, 3 17). *Ondergrondmodellen*. Retrieved 2022, from DINOloket: https://www.dinoloket.nl/ondergrondmodellen

Topotijdreis. (n.d.). Retrieved 2022, from Topotijdreis: https://www.topotijdreis.nl/kaart/1848/@245793,446936,9.67

Underground model (Water Overlay). (2022, June). Retrieved from Tygron Wiki: https://support.tygron.com/wiki/Underground_model_(Water_Overlay)

Vermeulen, P., Minnema, B., & Roelofsen, F. (2021). *iMOD User Manual.* Delft: Deltares. Retrieved June 2022, from https://oss.deltares.nl/web/imod/user-manuals

Waterschap Rijn en IJssel; Royal Haskoning DHV. (2020). *Factsheets KRW Waterlichamen.* Retrieved May 2022, from https://www.bing.com/ck/a?!&&p=4290ab4e921b43b62c566215196b3346cf84f2c7320cfddee0370b0514f33dc6JmltdHM9MTY1MjM0OTMyMCZpZ3VpZD1jZWM5MTZkNC0yMjdkLTRiZjgtYjFhMy1lZWVkMGEyYTE5ODYmaW5zaWQ9NTI0MA&ptn=3&fclid=a236360a-d1d9-11ec-b9ea-5f43f21a3932&u=a1aHR0cHM6Ly93

Wetzel, R. G. (2001). Water economy. *Limnology*, 43-48. doi:https://doi.org/10.1016/B978-0-08-057439-4.50008-3

What is MODFLOW? (2012). Retrieved from Waterloo Hydrogeologic: https://www.waterloohydrogeologic.com/2012/06/22/what-is-modflow/

Appendices

Appendix A: Beurzerbeek geohydrology

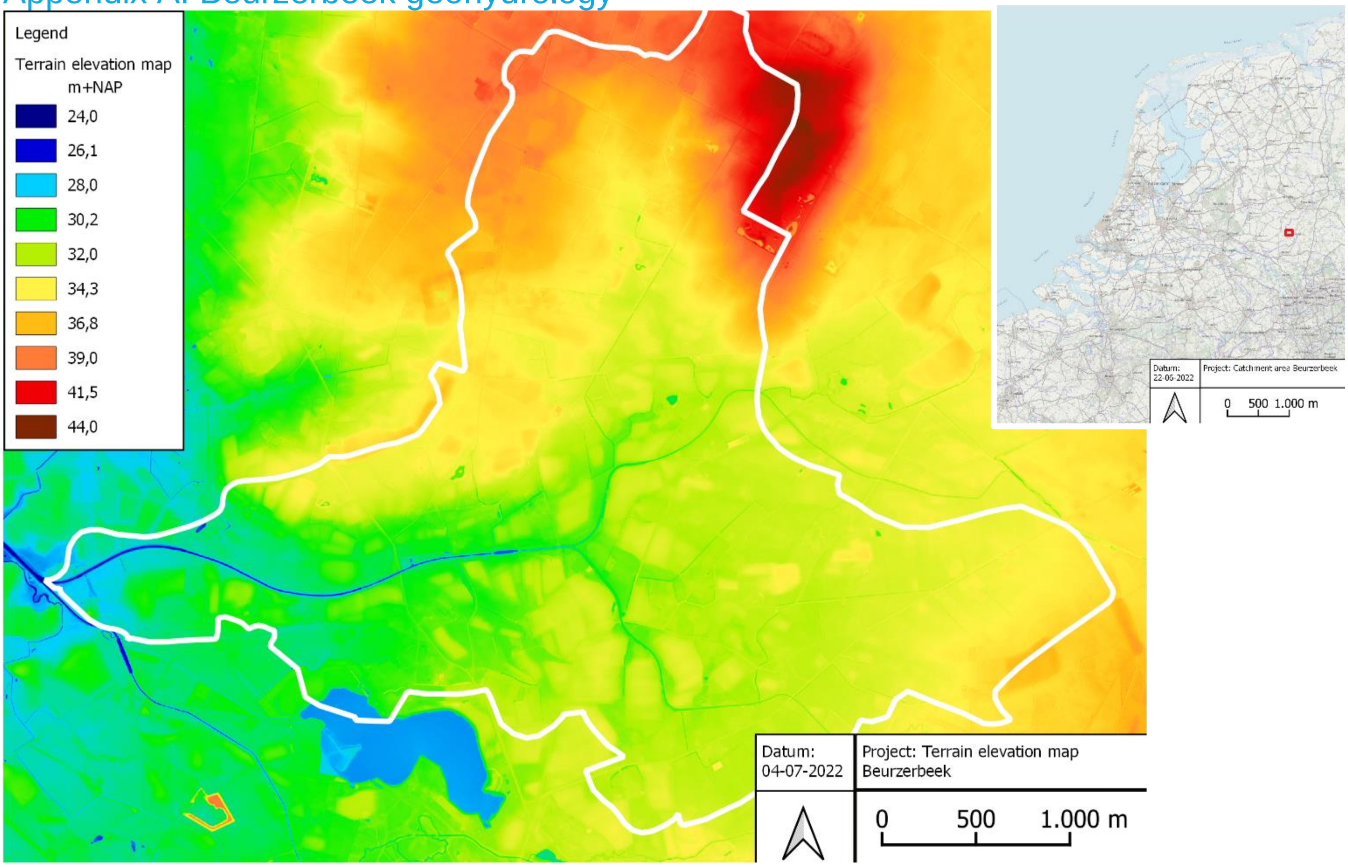


Figure 21: Terrain elevation map of the Catchment of the Beurzerbeek

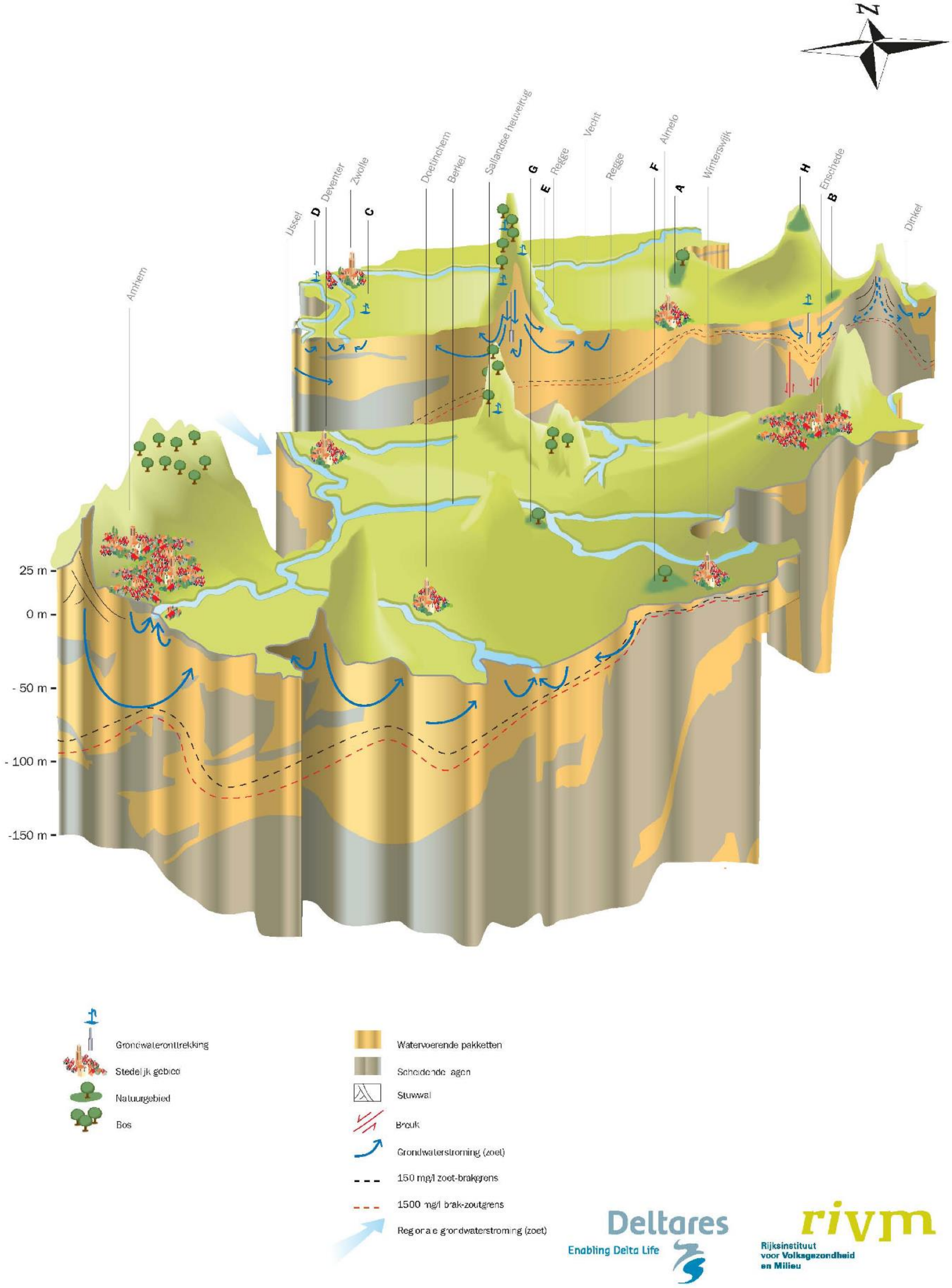


Figure 22: Conceptual model groundwater body WFD Rijn-Oost 3d Twente – Achterhoek (Rijkwaterstaat, 2022)

Appelboor BRO REGIS II v2.2

Coördinaten:	245799, 446631 (RD)
Maaiveld:	28.98 m t.o.v. NAP
Diepte t.o.v maaiveld:	0.00 m - 62.30 m

Diepte t.o.v maaiveld in meters: Tussen 0 en 62.3 m

Kies een ander model: BRO REGIS II v2.2

Hydrogeologie
HLc
BXz2
BXz3
BXz4
RUk1
DOk1

kh-waarde
0.0E0 ≤ kh < 1.0E0
1.0E0 ≤ kh < 2.5E0
2.5E0 ≤ kh < 5.0E0
5.0E0 ≤ kh < 1.0E1
1.0E1 ≤ kh < 2.5E1
2.5E1 ≤ kh < 5.0E1
5.0E1 ≤ kh < 1.0E2
1.0E2 ≤ kh < 2.0E2
2.0E2 ≤ kh < 1.0E9

kv-waarde
0.0E0 ≤ kv < 5.0E-5
5.0E-5 ≤ kv < 1.0E-4
1.0E-4 ≤ kv < 5.0E-4
5.0E-4 ≤ kv < 1.0E-3
1.0E-3 ≤ kv < 5.0E-3
5.0E-3 ≤ kv < 1.0E-2
1.0E-2 ≤ kv < 5.0E-2
5.0E-2 ≤ kv < 1.0E-1
1.0E-1 ≤ kv < 1.0E9

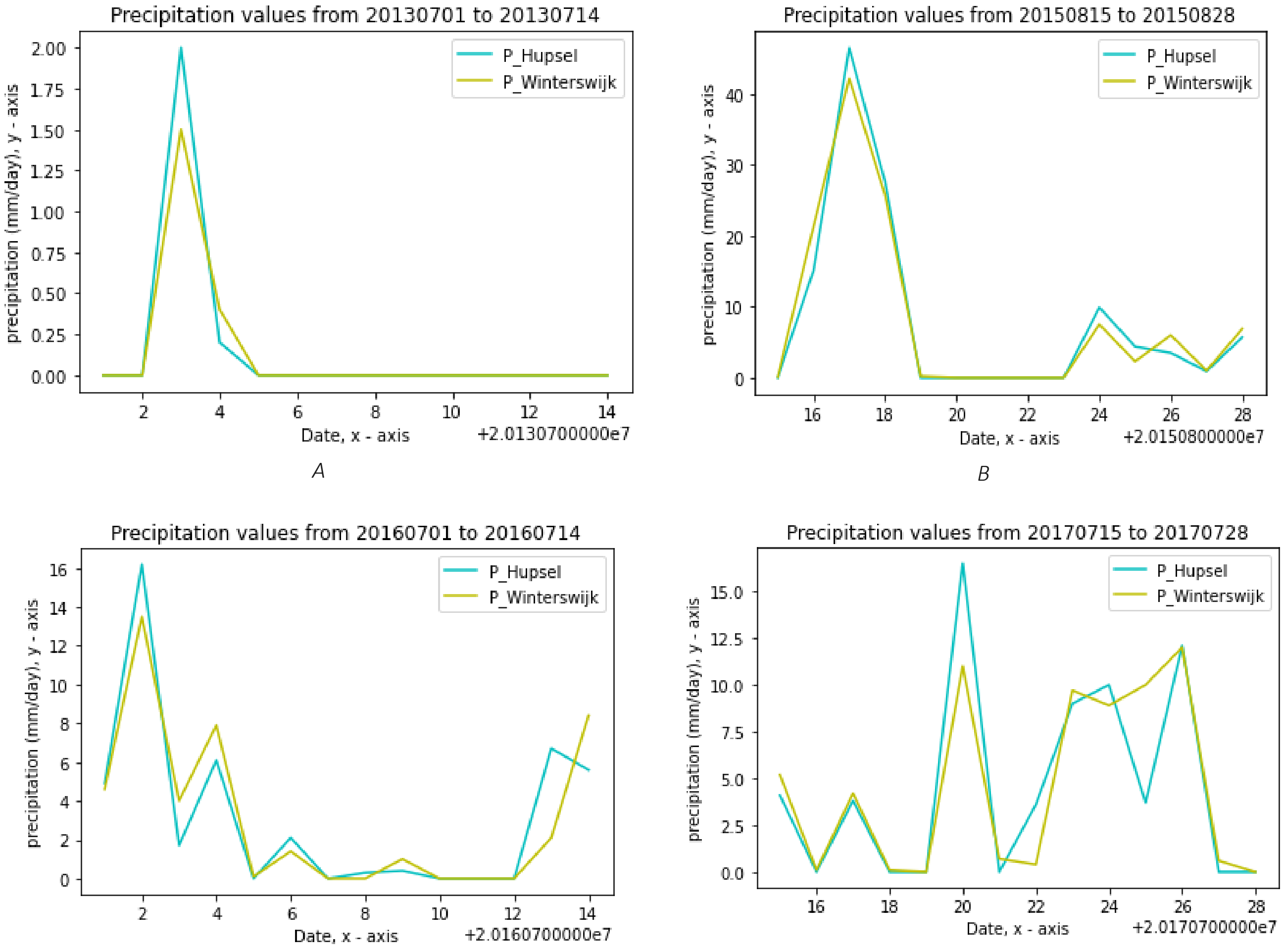
kD-waarde
0.0E0 ≤ kD < 1.0E0
1.0E0 ≤ kD < 5.0E0
5.0E0 ≤ kD < 2.5E1
2.5E1 ≤ kD < 5.0E1
5.0E1 ≤ kD < 1.0E2
1.0E2 ≤ kD < 2.5E2
2.5E2 ≤ kD < 5.0E2
5.0E2 ≤ kD < 1.0E3
1.0E3 ≤ kD < 1.0E9

c-waarde
0.0E0 ≤ c
5.0E1 ≤ c
1.0E2 ≤ c
5.0E2 ≤ c
1.0E3 ≤ c
5.0E3 ≤ c
1.0E4 ≤ c
1.0E5 ≤ c
1.0E6 ≤ c

Figure 23: Hydrogeology of soil point below the Beurzerbeek (TNO Geologische Dienst Nederland, 2022). The k-values in Figure A3 indicate the hydraulic conductivities of the soil layers.

Appendix B: Rainfall events of interest

In Figure 24, a comparison is made for the precipitation values of Hupsel and Winterswijk. Furthermore, Figure 25 show the evapotranspiration and precipitation rates of interest.



A

B

C

D

Figure 24: Graphs of the precipitation periods of interest for Hupsel and Winterswijk. (A) dry period: 01-07-2013 to 14-07-2013 (B) wet period: 15-08-2015 to 28-08-2015 (C) period 01-07-2016 to 14-07-2016 (D) Period 15-07-2017 to 28-07-2017

(A)

(B)

(C)

(D)

Figure 25: The precipitation and evapotranspiration numbers in the periods of interest (A) dry period: 01-07-2013 to 14-07-2013 (B) wet period: 15-08-2015 to 28-08-2015 (C) period 01-07-2016 to 14-07-2016 (D) Period 15-07-2017 to 28-07-2017

Appendix C: Calculation times

Aspects which impact the calculation time of the coupled model are the simulation time, grid cell size, and size of the model domain. In addition, the calculation time of Tygron also depends on the mode of the water overlay while not on the number of timeframes. A timeframe is a snapshot of a specific moment during the calculation time of Tygron.

Simulation time

A simulation can last for example 1 hour, 1 day or 1 month. As the simulation time increases, the calculation time increases linearly.

Grid cells

TYGRON can calculate with grid sizes ranging from 0.25m by 0.25 to 600m by 600m. The surface flow formula in Tygron is based on the 2D Saint Venant equations, therefore, the grid size should be smaller than the width of the creek to describe the behaviour of the flow correctly. The grid cell size influences the calculation time exponentially as does the number of grid cells.

Geographical spread

The calculation time of a simulation run increases linearly as the project gets bigger. The rectangle project around the boundaries of the Beurzerbeek is 4750mx6000m and thus the area is 28.5 km^2. If only the catchment area defined by the waterboard is used, the project is ten km^2. The calculation times are then three times smaller.

Coupling strategy

As explained, there are three strategies possible to couple the hydrological processes of Tygron to iMOD. The strategy determines, in addition to the aforementioned points, the calculation time. The strategies are discussed in section 4.4. Thirdly, the couples could have been coupled each hour. However, it was chosen not to for the reduction of computational times.

The choice of coupling strategy does not impact the calculation time of Tygron, but it does for the calculation time of the Python script and the MODFLOW model as the calculation time of MODFLOW and the python script coupler is dependent on the number of time steps and not the size of the time step.

The regional groundwater model AMIGO makes use of a MODFLOW coupler between MetaSWAP and MODFLOW 6 as does the coupling of Tygron to MODFLOW. This coupling has also computational time. Below, the components for the computational time are briefly investigated.

Table 7 shows the computational time for a simulation in AMIGO (Vermeulen, Minnema, & Roelofsen, 2021). Table 8 shows the computational time for a simulation in the coupled Tygron MODFLOW as does Table 9 for a higher resolution.

The Tables prove that iMOD, the Graphical User Interface of MODFLOW runs much faster than MODFLOW. Also, Tygron runs faster on a higher detail than MetaSWAP. However, considering that the run of Table 7 used five-time steps, the AMIGO coupler is faster than the Tygron MODFLOW coupler. Nevertheless, there is still room for improvement in the calculation time of the coupler as now there is no made use of combo overlays in Tygron for the groundwater storage overlays are downloaded, subtracted from each other and that result is uploaded to Tygron again afterwards. Data can be stored in Tygron with combo overlays, this will save computational time in the coupler.

Table 7: "Number of seconds spent in the different components of AMIGO. The test model consists of 3 layers, 1000x1000 cells, a 25x25m grid and 5-time steps. The used processor is an Intel Core i5-7200U CPU 2.50GHz" (Vermeulen, Minnema, & Roelofsen, 2021)

Component	Time (s)	Percentage (%)
MODFLOW 6	100.5	48.7
MetaSWAP	81.6	39.6
Imod_Coupler	24.1	11.6
Total	206.2	100

Table 8: Number of seconds spent in the different components of the coupling MODFLOW Tygron The test model consists of six layers, 3000x2375 cells in Tygron. Tygron grid size 2x2m, MODFLOW grid size 10x10m. The used processor is an Intel Core i7 vPRO.

Component	Time (s)	Percentage (%)
iMOD v 5.3	29.269	10.6
Tygron	230.412	82.9
Coupler	17.922	6.5
Total	277.603	100

Table 9: Number of seconds spent in the different components of the coupling for the one-time step of one. The test model consists of six layers, 6000x4750 cells in Tygron and 1-time step. Tygron grid size 1x1m, MODFLOW grid size 5x5m. The used processor is an Intel Core i7 vPRO.

Component	Time (s)	Percentage (%)
iMOD v 5.3	90.803	12.9
Tygron	550.131	78.0
Coupler	64.059	9.1
Total	704.993	100

Appendix D: Dynamics in the groundwater levels

The simulated groundwater levels from the coupling are compared to the groundwater levels in AMIGO 14 separate locations shown in Figure 26. The characteristics of these locations are elaborated on in Table 10. The modelled groundwater levels for the case study are shown in Figure 27, Figure 28, Figure 29 and Figure 30. Additionally, maps of the groundwater heads for the case study are shown in Figure 31, Figure 32, Figure 33 and Figure 34.

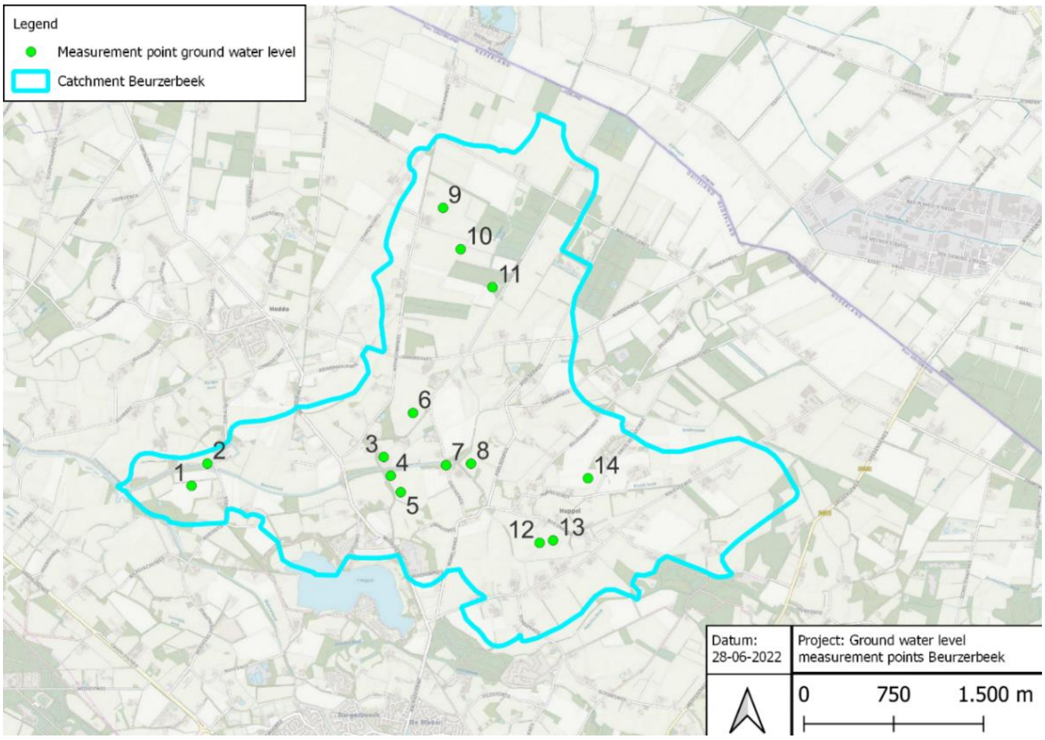
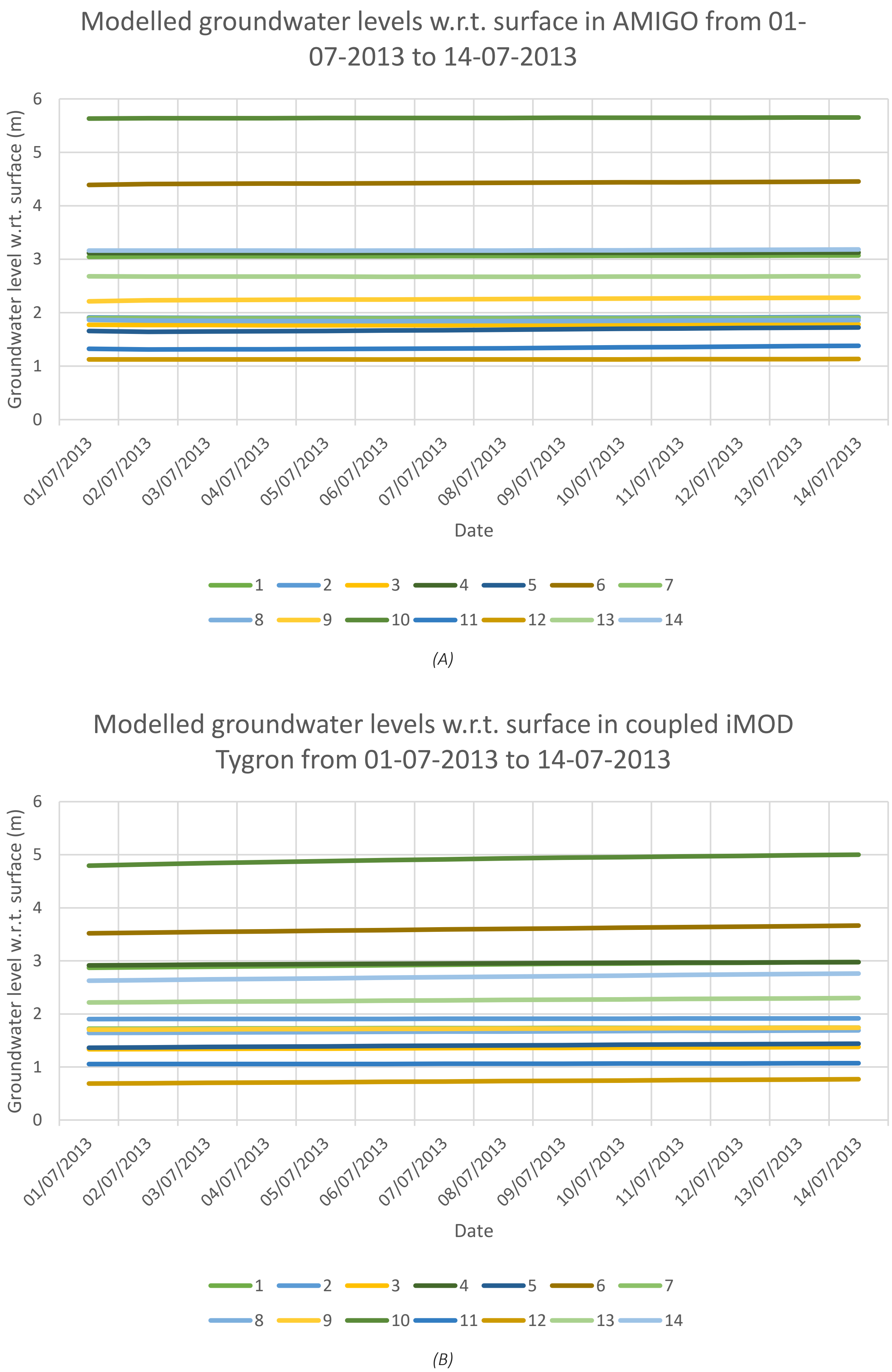


Figure 26: Groundwater level measurement locations

In addition to Table 10, all locations except for location ten consist of loam and fine sand. The soil in location ten does mainly of clay (TNO Geologische Dienst Nederland, 2022).

Table 10: Soil characteristics at the groundwater level measurement locations in Figure 26

Location ID	Infiltration speed (m/day)	Manning value	Surface classification	Terrain height m+NAP
1	0.68	0.04	Cornfield	30.147
2	0.19	0.035	Grassland	28.995
3	0.19	0.03	Regular yard	30.441
4	0.19	0.035	Grassland	31.686
5	0.26	0.035	Grassland	30.942
6	0.35	0.035	Grassland	34.934
7	0.19	0.03	Open land	31.020
8	0.19	0.035	Grassland	31.356
9	0.35	0.035	Grassland	37.964
10	0.42	0.035	Grassland	35.476
11	0	0.02	Water area	33.771
12	0	0.02	Water area	31.655
13	0.35	0.035	Grassland	33.316
14	0.4	0.35	Cornfield	34.449



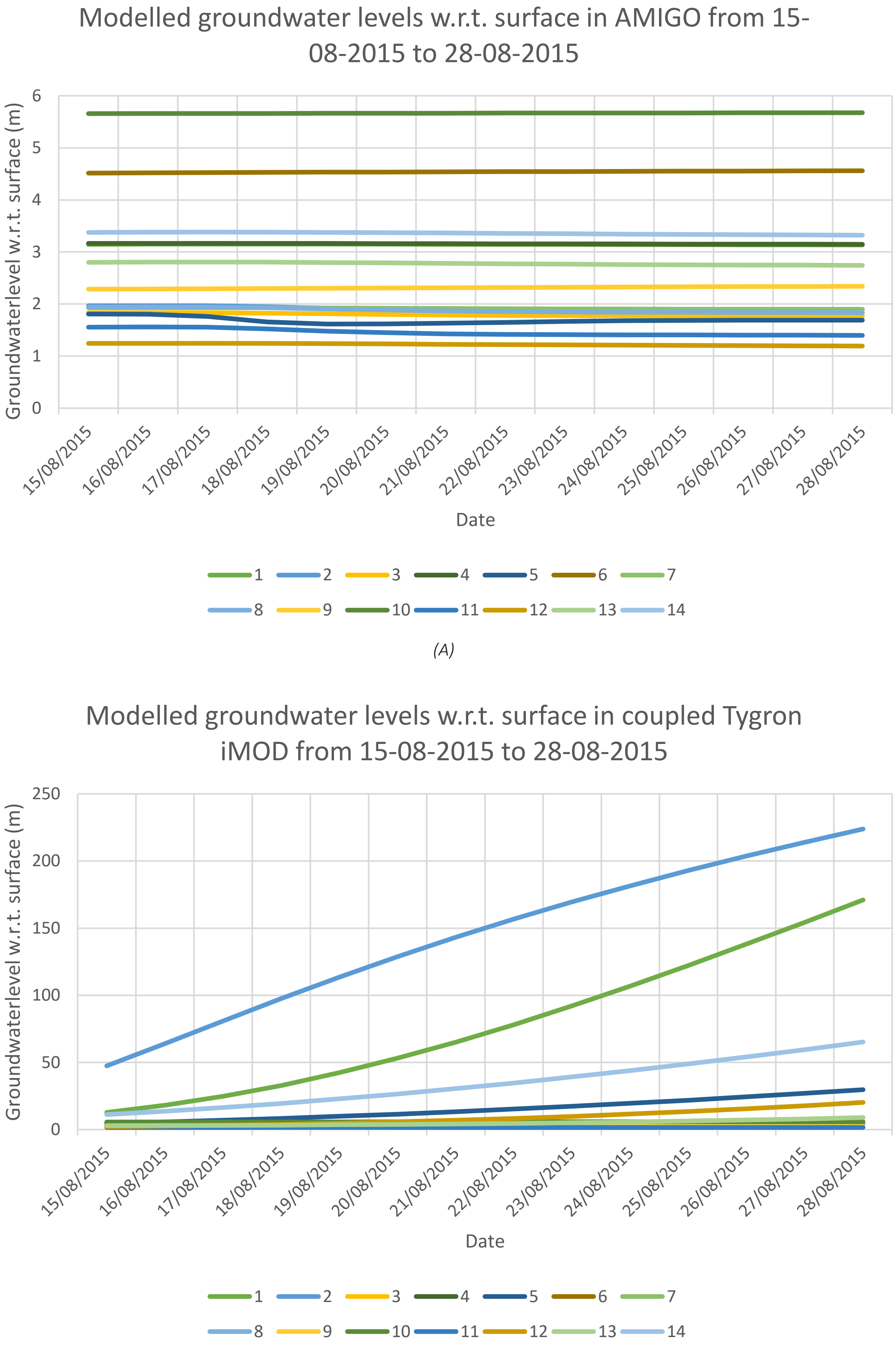
Modelled groundwater levels w.r.t. surface in AMIGO from 01-07-2013 to 14-07-2013

(A)

Modelled groundwater levels w.r.t. surface in coupled iMOD Tygron from 01-07-2013 to 14-07-2013

(B)

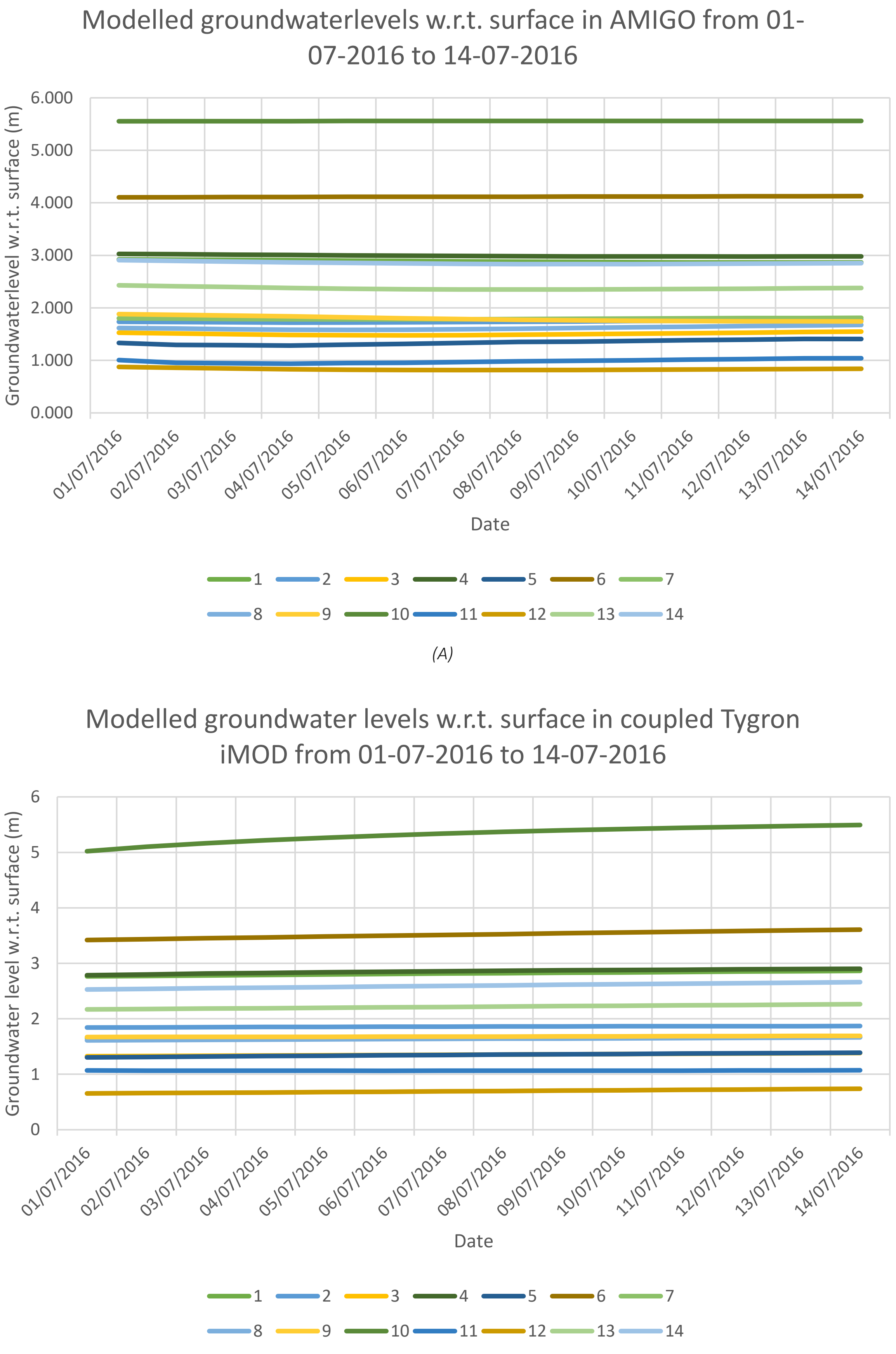
Figure 27: Modelled groundwater levels from 01-07-2013 to 15-07-2013 in (A) AMIGO and (B) coupled Tygron MODFLOW



(A)

(B)

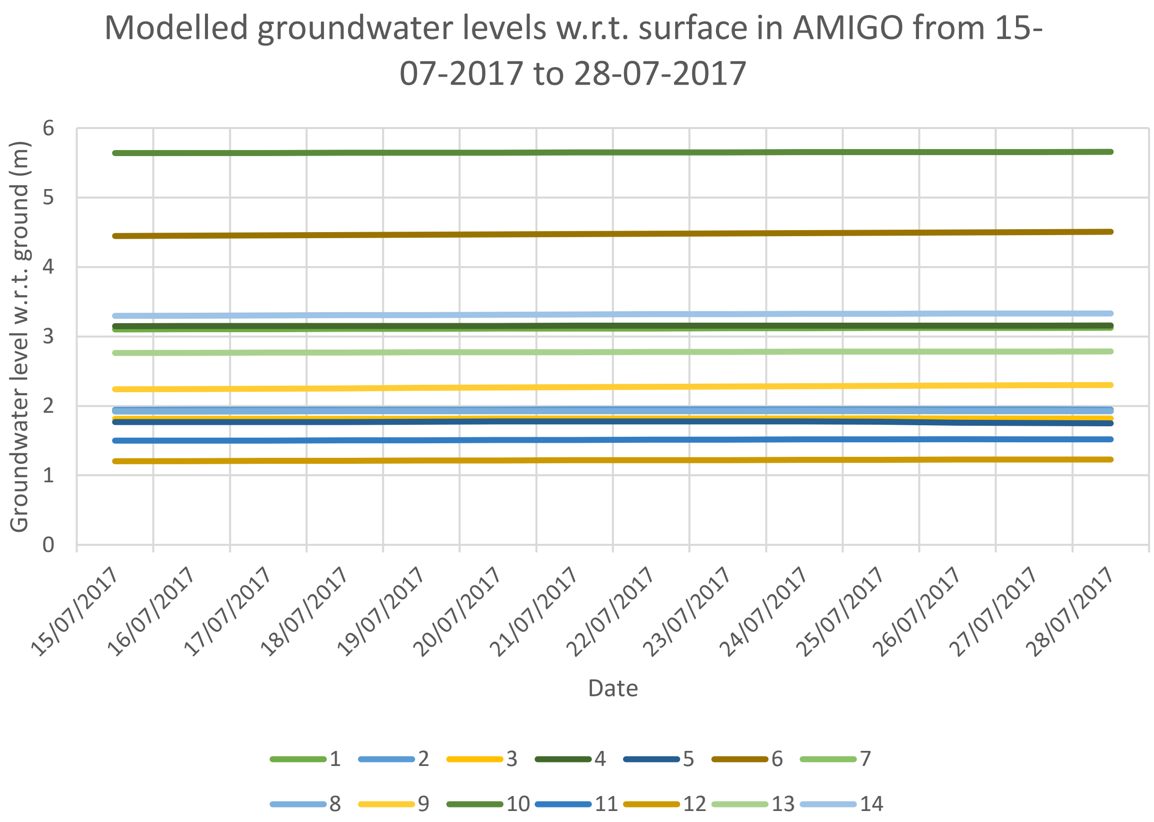
Figure 28: Modelled groundwater levels from 15-08-2015 to 28-08-2015 in (A) AMIGO and (B) coupled Tygron MODFLOW



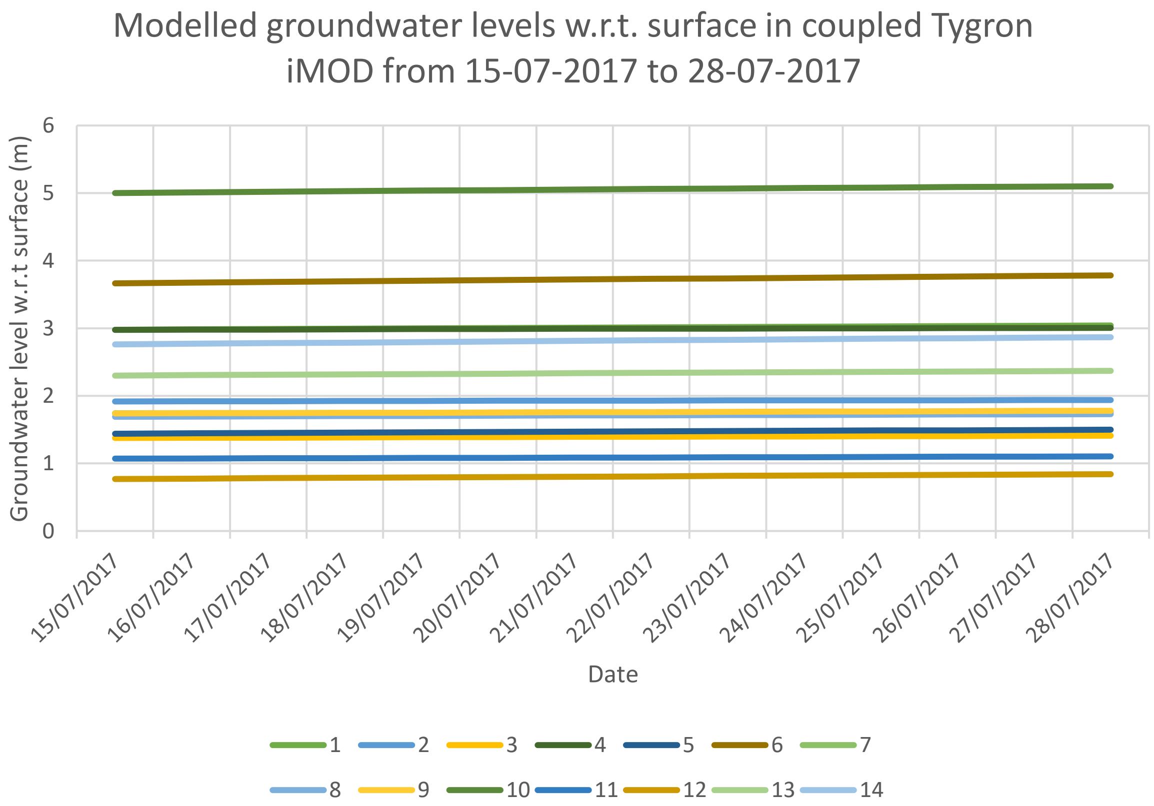
(A)

(B)

Figure 29: Modelled groundwater levels from 01-07-2016 to 14-07-2016 in (A) AMIGO and (B) coupled Tygron MODFLOW

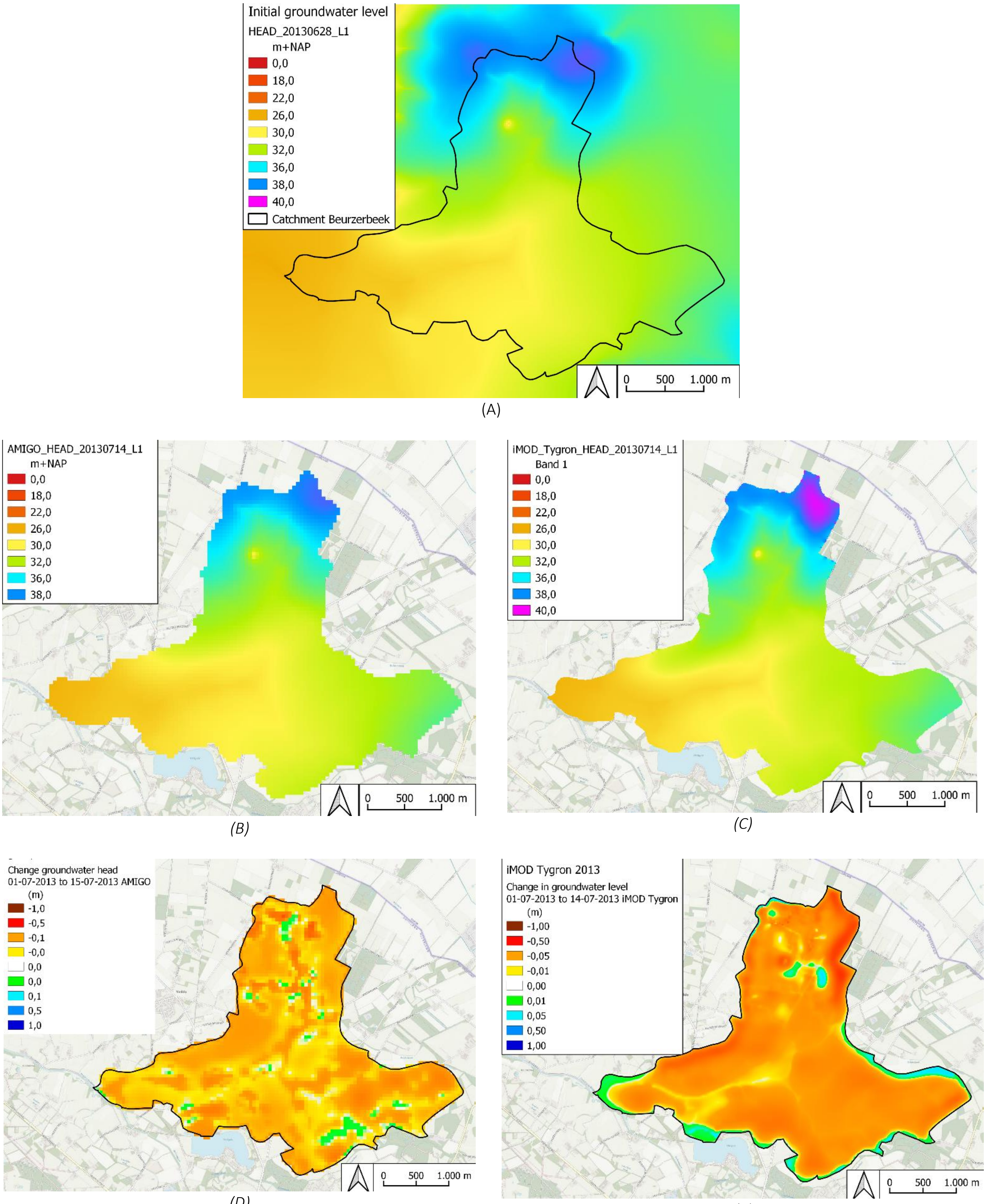


(A)



(B)

Figure 30: Modelled groundwater levels from 15-07-2017 to 28-07-2017 in (A) AMIGO and (B) coupled Tygron MODFLOW



(A)

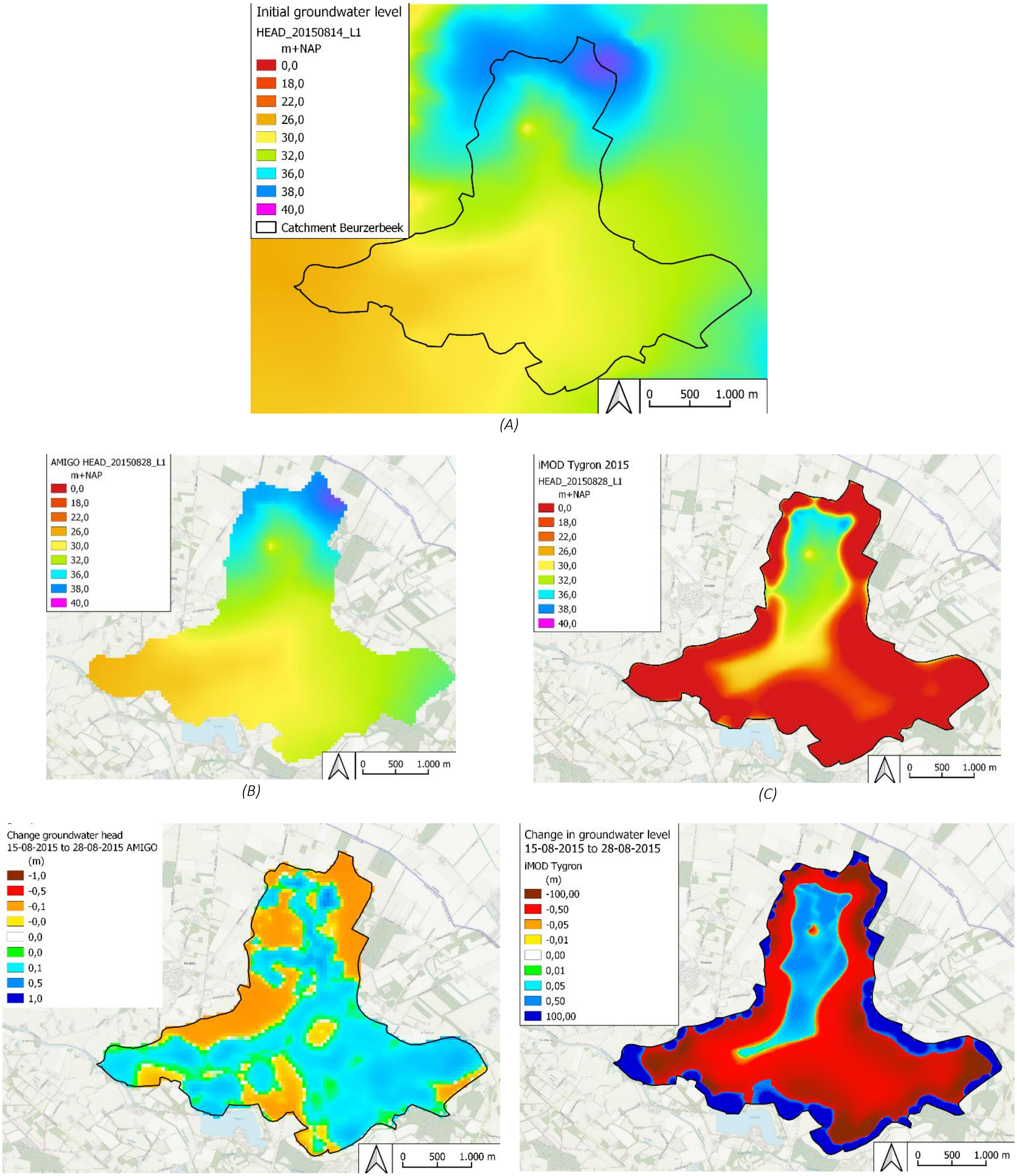
(B)

(C)

(D)

(E)

Figure 31: Maps of groundwater heads for the case study Beurzerbeek in 2013 (A) Starting heads for both AMIGO and coupled MODFLOW Tygron, (B) Final heads AMIGO, (C) Final heads MODFLOW TYGRON, (D) Change in heads AMIGO, (E) Change in heads coupled MODFLOW MODFLOW



(A)

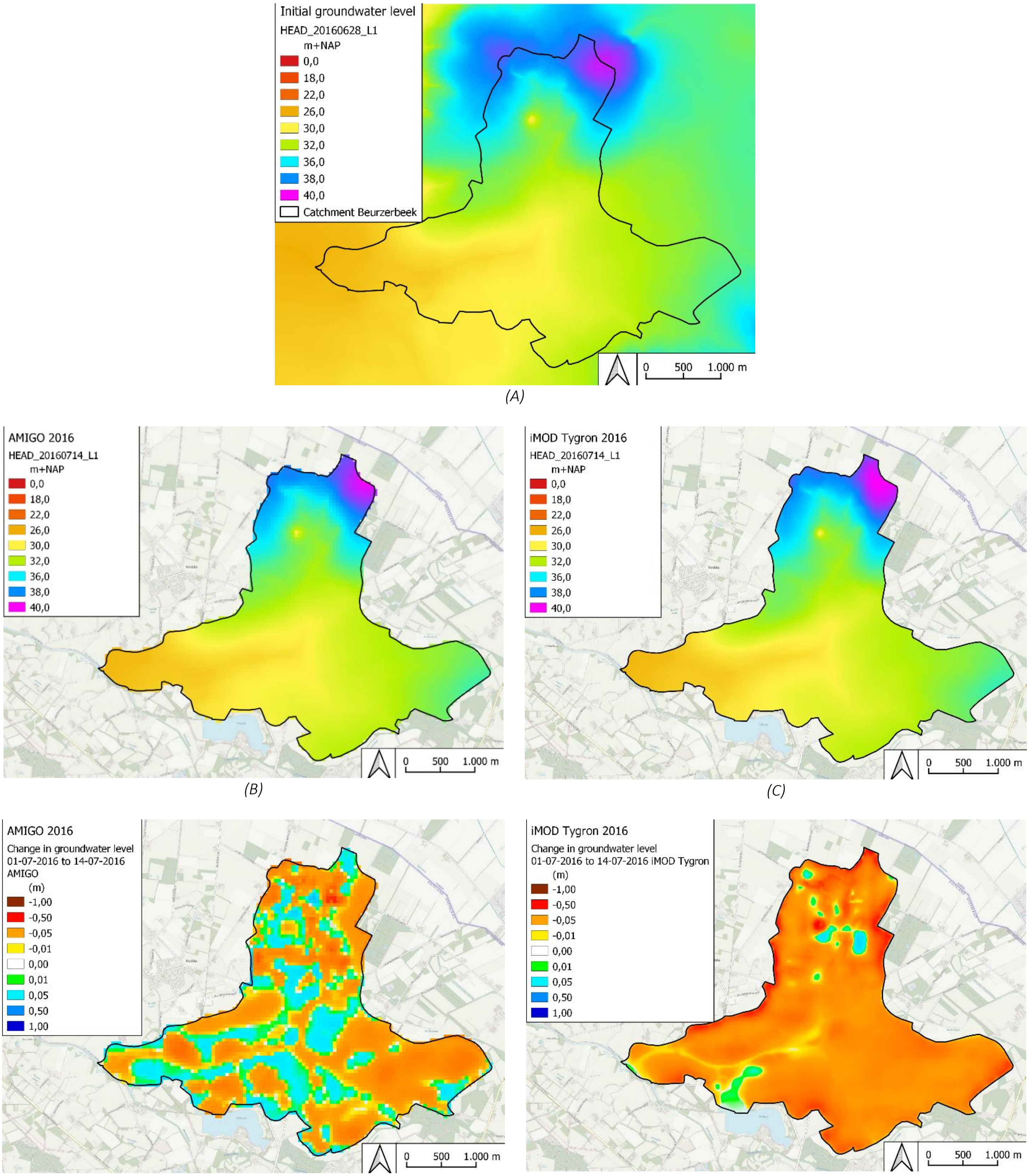
(B)

(C)

(D)

(E)

Figure 32: Maps of groundwater heads for the case study Beurzerbeek in 2015 (A) Starting heads for both AMIGO and coupled MODFLOW Tygron, (B) Final heads AMIGO, (C) Final heads MODFLOW TYGRON, (D) Change in heads AMIGO, (E) Change in heads coupled MODFLOW MODFLOW



(A)

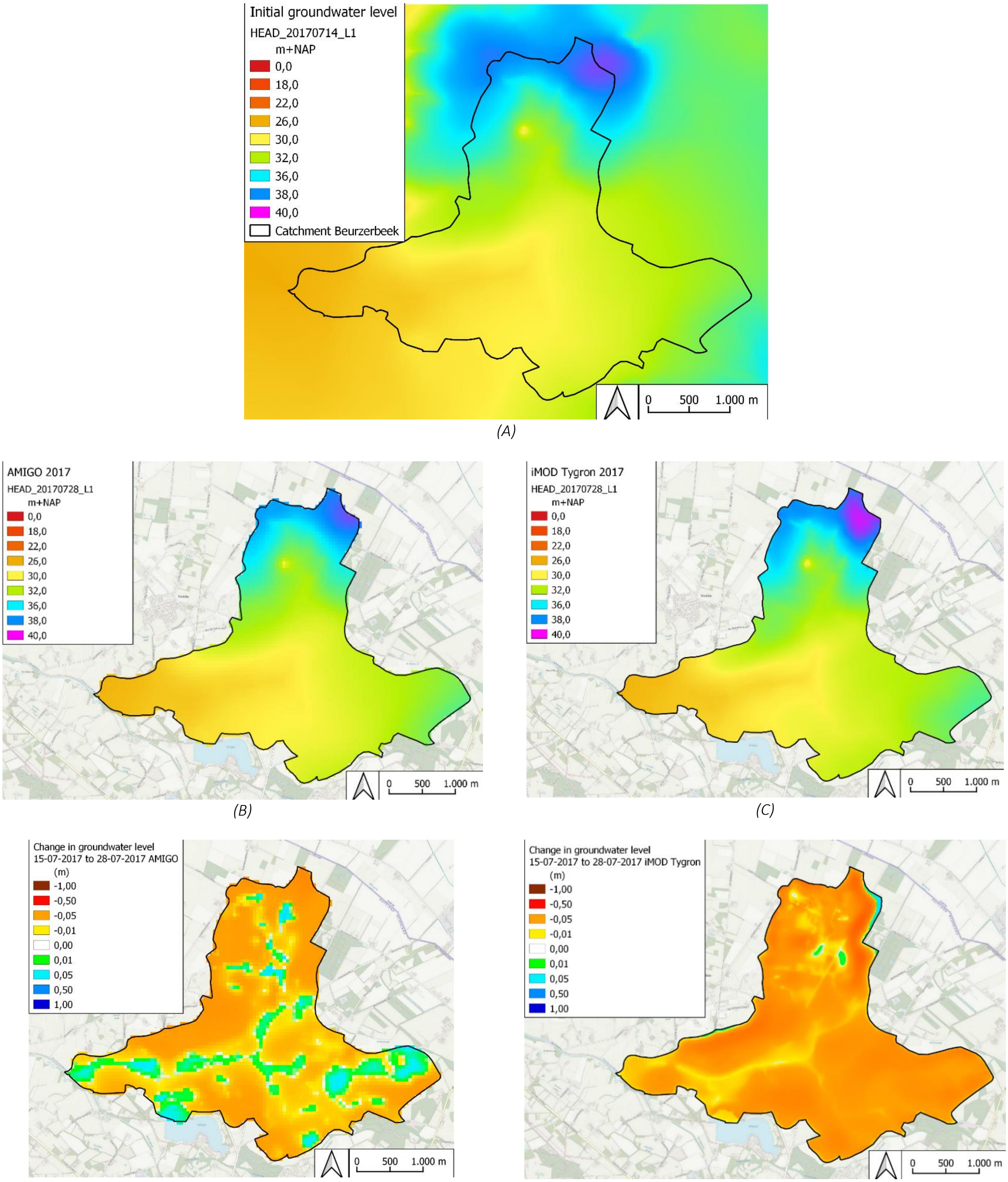
(B)

(C)

(D)

(E)

Figure 33: Maps of groundwater heads for the case study Beurzerbeek in 2016 (A) Starting heads for both AMIGO and coupled MODFLOW Tygron, (B) Final heads AMIGO, (C) Final heads MODFLOW TYGRON, (D) Change in heads AMIGO, (E) Change in heads coupled MODFLOW MODFLOW



(A)

(B)

(C)

(D)

(E)

Figure 34: Maps of groundwater heads for the case study Beurzerbeek in 2017 (A) Starting heads for both AMIGO and coupled MODFLOW Tygron, (B) Final heads AMIGO, (C) Final heads MODFLOW Tygron, (D) Change in heads AMIGO, (E) Change in heads coupled MODFLOW Tygron