Modelling the effects of the Maaswerken on the drinking water production near Roosteren, The Netherlands

Master's Thesis Research – Water Science and Management

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Preface

This master's thesis completes the final phase of my master study Water Science & Management at Utrecht University. The study is performed as an internship at drinking water company WML (Waterleiding Maatschappij Limburg).

First of all I would like to thank my supervisors Dr. Jaivime Evaristo (Utrecht University) and Falco van Driel MSc (WML) for sharing their inspiration and knowledge, and of course for all guidance during this research. Even during the Covid-19 situation they perfectly guided me by the use of online conferencing. I would like to thank Koen van der Hauw MSc (Sweco) and ir. Frans Roelofsen (Deltares) for helping me with some modelling issues. I thank Dr. Paul Schot for being the second reader of my research proposal and final thesis. Furthermore, I would like to thank the colleagues of the Research & Development department of WML for giving me a warm welcome during my internship. Lastly, I would like to thank my befriended students for always being there to discuss problems.

Summary

The provision of safe drinking water is of significant importance for a countries social and economic development (Cotruvo et al, 2019). As a constant monitoring of chemical components and microorganisms is not possible, adequate risk analyses, modelling and management are crucial (Ministry of Infrastructure and the Environment, 2014). This study presents the effects of lowering the riverbank of an inside bend of the Meuse river at the Roosteren drinking water production site of drinking water company WML (Waterleiding Maatschappij Limburg). This production site contains 5 shallow wells that partly abstract Meuse water through the riverbank (wells 9, 10, 11, 12 & 13). In the future, the inside riverbank in the study area will be lowered due to the Maaswerken project to provide the Meuse with more space during high discharges. As a result of this travel times of infiltrated river water towards the shallow wells can change, implying a change of microbiological and chemical risks for drinking water production. This study uses the regional groundwater model IBRAHYM to execute the initial model (present situation) and three modelling scenarios (low, median, high discharge after lowering riverbank). To examine the effects of the Maaswerken iMODFLOW is used to compute flow paths and travel times. The results show that during a median discharge minimal changes in travel time occur, as the Meuse wells are not abstracting Meuse water from the area where the Meuse moved inland after lowering of the riverbank. Furthermore, the high and low discharge scenarios after lowering the riverbank show largest and smallest spread in travel time distributions, due to changes in distance from Meuse to the wells. The high discharge scenario contains Meuse water with a travel time of <60 days for all Meuse wells, implying microbiological risks are at hand. Meuse wells 10 & 11 even contain Meuse water with a travel time of <60 days in all modelling scenarios, posing a microbiological risk. For the determination of the chemical risk, the ratio of abstracted Meuse water and phreatic water is required. It is advised to replace the Meuse wells further away from the Meuse, as these wells can be out of operation for 120 days or more per year due to the preservation of water quality after lowering of the riverbank. Additionally, wells 10 & 11 should be replaced as these are exposed to erosive processes due to inundation during high discharges, thereby affecting their physical stability.

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1. Introduction & Site Description

The provision of safe drinking water is fundamental to achieving a country's goals in social and economic development (Cotruvo et al, 2019). The fundamental social importance of safe drinking water can be inferred from the Drinking Water Law, as governing bodies have to take care of a sustainable security of the drinking water supply and this applies as "a compelling reason for public interest" in the exercise of their powers (Drinkwaterwet, 2015). Threats to safe drinking water, however, persist even in developed countries (Moreira & Bondelind, 2017). As constant monitoring of chemical components and microorganisms is not always possible, adequate risk analyses, modelling and management are crucial (Ministry of Infrastructure and the Environment, 2014).

In order to provide the inhabitants of Limburg with drinking water, the drinking water company WML (Waterleiding Maatschappij Limburg) produces drinking water from several water sources within the province. Both surface- and groundwater are used for the production of drinking water. Amongst the groundwater well sources is "Roosteren", which is located in the municipality of Echt-Susteren, about 1 km northwest of the village Roosteren and southeast of Belgian city Maaseik. The well field is located in the inside river bend of the Meuse near Roosteren (Figure 1). The Belgian side of the Meuse riverbank is mostly strengthened with a concrete wall. The Dutch riverbank is partly strengthened by a dike and partly made up of a soft "natural" riverbank. In 2006, at the upstream part of the riverbend in the western part of the area, Rijkswaterstaat (the Dutch Department of Waterways and Public Works) constructed a water retention area to accommodate high flow regimes of the Meuse (Rijkswaterstaat, 2020).

In the future (now planned before 2050), Rijkswaterstaat is planning to redevelop the inside riverbend area, including the water retention area and part of the WML well field. The planned work is part of the Maaswerken program, which aims to improve the flood protection river by executing several subprojects on different locations along the Meuse (Rijkswaterstaat, 2020). The subproject in the vicinity of the drinking water production site of Roosteren includes a lowering of the inside river bend, thereby creating more space for river water during high discharges. The area that is going to be lowered is shown in Figure 2. Wells 10 & 11 are located in the area to be lowered. Wells 9 & 12 are approximately on the border of the area to be lowered. The exact period of execution of the subproject is not confirmed yet, however it is now planned before the start of 2050. This study provides an initial exploration of the potential risks that may occur as a result of the Maaswerken in the vicinity of the Roosteren well field. Moreover, this study increases our understanding of the utility of a hydrogeologic model for surface water-groundwater interaction research.

The drinking water production site of Roosteren provides drinking water for parts of Middle- and South-Limburg (WML- Limburgs drinkwater, 2020). The well field consists of 12 wells which are located close to the river Meuse (Figure 1). Furthest from the Meuse (approximately 650 m) is a radial well, the well with the largest capacity in this well field. The remaining 11 wells are located closer to the Meuse within approximately 150 m. These 11 wells consist of 5 deep (>100 m below ground level) and 6 shallow (between 7 and 19 m below ground level) wells. The licensed abstractions for the deep and shallow wells are 2.5 million m^3/y and 6.5 million m^3/y respectively (Van Rijsselt et al, 2018). The deep wells are located on the east side of the well field and abstract groundwater from confined aquifers (Van Rijsselt et al, 2018). 5 of the 6 shallow wells partly abstract infiltrated Meuse water with a short residence time (<60 days) and are therefore called the Meuse wells (Dutch: Maasputten) (Kragt & Juhàsz-Holterman, 1992). These Meuse wells are located in pairs on mounds in the field. The distance between two wells in a pair is a few meters, while the distance between different pairs of wells is about 210-250 m. If only one well of a pair is active, it will mainly abstract groundwater. In the case of two active wells per pair, part of the abstracted water will be Meuse water (Van Rijsselt et al, 2018). As a result of the water travelling through the underground towards the wells, the water quality improves significantly (Stuyfzand & Juhàsz-Holterman, 2000).

In order to provide microbiologically and chemically safe drinking water, the travel times of Meuse water to the wells is of significant importance. With the infiltration of Meuse water into the riverbank, contaminants will infiltrate as well, including pathogenic microorganism (Medema et al, 2001). The phreatic groundwater abstracted by the wells does not originate from the Meuse, but originates from the infiltration of rainwater and from other surface waters east of the Meuse river. For the exact determination of the microbiological and chemical risks of the drinking water production it is important to know the ratio between abstracted Meuse water and phreatic water of the Meuse wells.

Adaptations as a result of the Maaswerken program will influence the water levels of the Meuse near the well field of Roosteren. The water levels will influence the flow paths and travel times of Meuse water to the wells (Hubeek, 2012; van der Hauw, 2019). This, combined with the fact that Meuse water is strongly contaminated with pathogenic microorganisms (Medema et al, 2001), makes it is important to understand how the travel times of Meuse water will change due to the Maaswerken. Therefore, the aim of this study is to understand how adaptations to the Meuse riverbank as a result of the Maaswerken will influence the groundwater flow paths and travel times. The corresponding research question is formulated as follows:

"What are the effects of the lowering of the riverbank as a result of the Maaswerken in the vicinity of the Roosteren well field on the riverbank groundwater flow paths and corresponding travel times, and what are the implications for the drinking water production in this area?"

In order to fulfil the aim of the study and answer the research question the regional groundwater model IBRAHYM v.21 is used. Particle tracking and flow path modelling is used to provide travel time data of water abstracted by the wells. The travel time data of each well and scenario is presented in cumulative distribution functions and compared to each other to obtain the effects of the lowering of the riverbank. Subsequently, implications for the drinking water production of the Roosteren well field are provided.

Previous research

Hubeek (2012) showed that two shallow wells (10 & 11) need to be displaced as a result of the Maaswerken. This report stated that it is possible to replace only some of the wells within the current well field, which can only produce a part of the current capacity of the production site. Yet, the outcomes of the IBRAHYM v.1.1 model in Hubeek (2012) are for indicative purposes only. The study points out that it is necessary to perform a detailed study containing a calibrated and small scale groundwater model to exactly determine which wells need to be replaced. Furthermore, the effects of the replacement of wells on the lowering and delimitation of the protection zones need to be studied using a more detailed model. This requires a detailed delimitation of the area affected by the Maaswerken at Roosteren (Hubeek, 2012).

Thesis outline

In the continuation of this study, first a background is given on the hydrogeology and hydrology of the study area, riverbank groundwater wells and the microbiological and chemical risks for drinking water production in chapter 2. Thereafter, the used methods and materials of this study are discussed in chapter 3. Subsequently, the obtained results are presented in chapter 4. In addition, the results are discussed and recommendations for future research are provided in chapter 5. Finally, the conclusions of the study are provided along with an advise for WML in chapter 6.

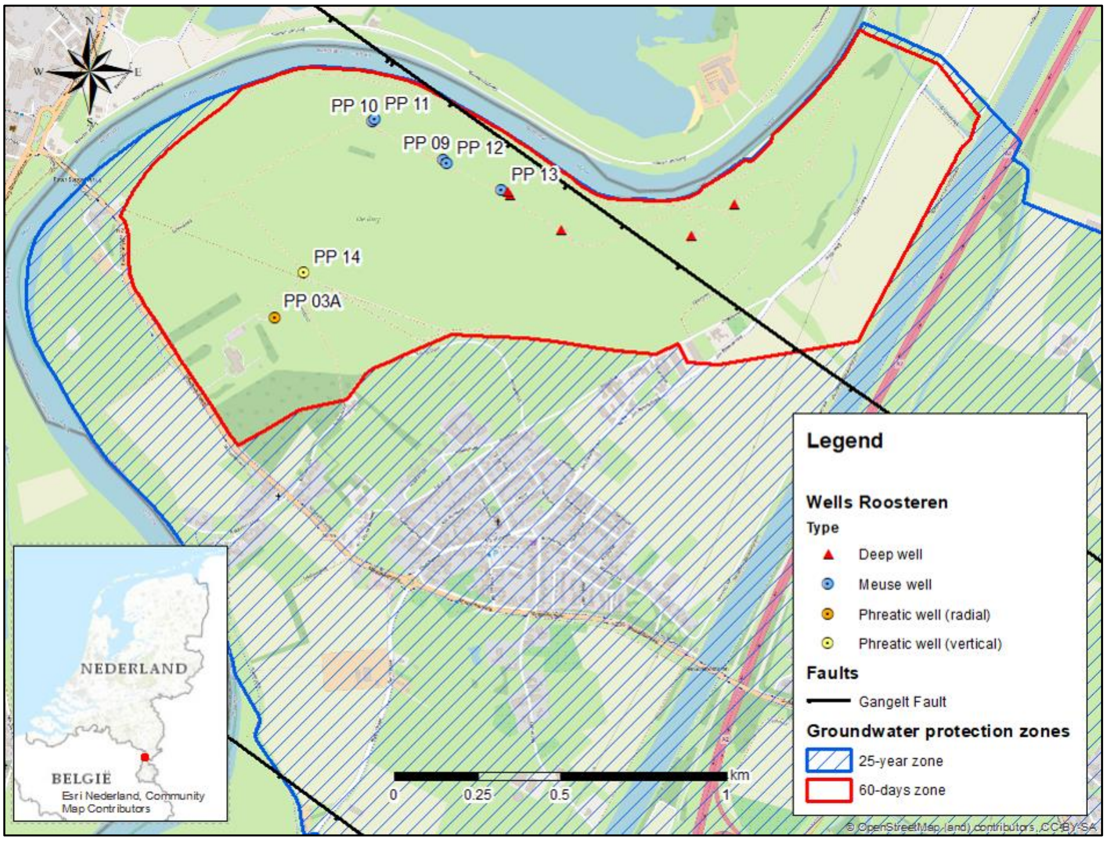


Figure 1 – *Overview of present situation with indication of the location of wells, the Gangelt fault and the groundwater protection zones. Note: the red dot on the map of the Netherlands indicates where the study site is located.*

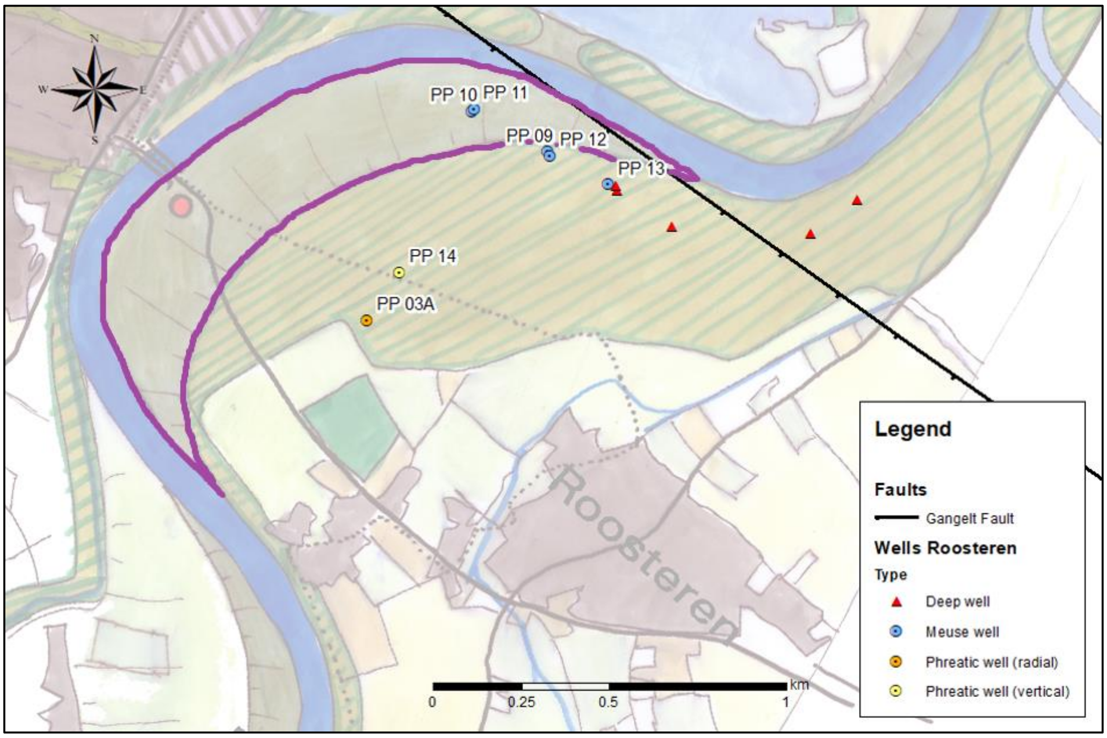


Figure 2 – *Indication of the zone to be lowered in the inside riverbend near Roosteren. The half moon shape in the inside of the riverbend indicates the area to be lowered (purple).*

2. Theory

Hydrogeology

The drinking water source in Roosteren is, from a geological point of view, situated in the Roer Valley Graben (Dutch: Roerdalslenk) between two faults, the Peelrand fault and the Feldbiss fault. Figure 3 & 4 show transects of the underground structure of the regional area near the well field at Roosteren. The hydrological basis of this area is formed by the Middle North Sea Group NM, which is mainly characterized by poorly permeable marine sediments (TNO REGIS II.2, 2020). On top of this group is the Formation of Breda which stretches from approximately -185 and -130 m NAP to approximately -600 and -500 m NAP southwest and northeast respectively of the Gangelt fault (Figure 3)(TNO REGIS II.2, 2020). On top of the Formation of Breda we can recognize the Formation of Inden (IE) and the Kiezeloöliet Formation (KI), which are alternations of sandy and clayey layers (TNO REGIS II.2, 2020). These formations contain the 2nd and 3rd aquifers that are addressed by the deep wells of the Roosteren well field (Van Rijsselt et al, 2018). The first aquifer is formed by the Formation of Stamproy (SY) and the Formation of Beegden (BE). These are mainly gravelly sediments deposited by the large rivers in the Netherlands (TNO REGIS II.2, 2020). These gravelly sediments have a porosity estimated to be around 20-25% (Stuyfzand & Juhàsz-Holterman, 2000). Clay layers can be found on a local scale in the Formation of Stamproy, which is of hydrological importance (Van Rijsselt et al, 2018). The top layer is formed by Holocene sediments which are mainly loams and sandy loams (TNO REGIS II.2, 2020).

The Gangelt fault is located in the northeast of the Roosteren well field (Figure 1 & 3). It has significantly influenced the hydrogeological situation in the study area. A displacement of the geological formations to approximately the top of the Formation of Stamproy (SYz2) can be recognized along the fault. The Gangelt fault is considered as almost impermeable (van der Hauw, 2019). However, the exact positioning, tilting and permeability of the fault are still unknown (Deckers et al, 2014).

Hydrology

The river Meuse originates in France and flows through Belgium and the Netherlands after which it drains into the North Sea. The river is supplied by a significant amount of tributaries draining water from a catchment of roughly 36.000 km^2. Near Maastricht the part of the Meuse splits into the Juliana Canal and the Zuid-Willems Canal. The Netherlands and Belgium agreed on the Meuse river always having a minimal discharge of 10 m^3/s downstream of the split (Maasafvoerverdrag, 1995). The average and median discharge of the Meuse river are approximately 200 and 155 m^3/s respectively, with a spread due to seasonal variation of 20-3500 m^3/s (Rijkswaterstaat, 2020). The Meuse river water levels occurring in the study area are indicated by Rijkswaterstaat as the "Reference Line Heights (Dutch: Betrekkingslijnen)". These indicate what water level height occurs at several measuring stations of the same river. The measuring station in the study area is that of Maaseik. The Reference Line Heights can be found in Appendix B. The study area is situated at the Meuse and the river forms the border with Belgium in this area. The Meuse regularly floods its riverbanks in the area, thereby entering the well field. On the southeast in the study area the Juliana Canal can be found. This canal is embanked by two dykes of 10 m above ground level and the canal bottom is equipped with a clay covering, excluding the canal from regional hydrology (De Kleine et al, 2015).

The regional groundwater flow in the study is mainly oriented southeast-northwest due to the presence of the Meuse, which forms the regional drainage basin. Height differences in the landscape and fault surfaces influence the regional groundwater flow as well. The flow direction in the vicinity of the well field varies with changing Meuse water levels, resulting in south-north to southeast-northwest oriented flow directions (Stuyfzand, 2000). The southeast-northwest flow direction is found to be dominant in 60% of the time (Juhàsz-Holterman, 1988).

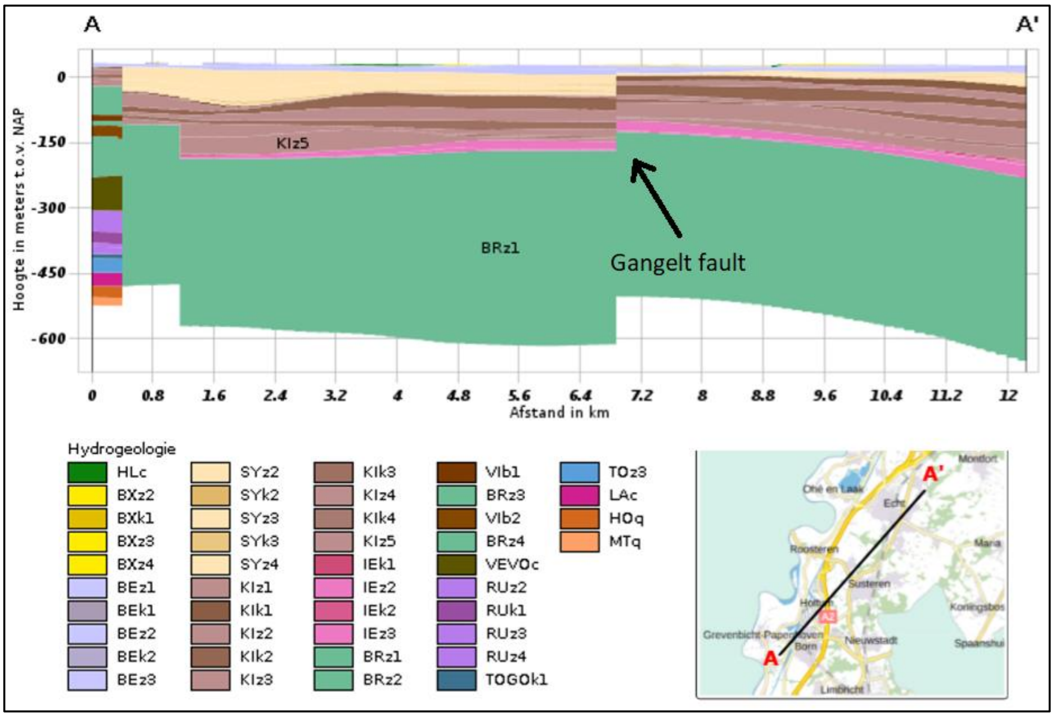


Figure 3 – *Southwest-northeast transect containing the underground structure of the regional area including the study site at Roosteren (TNO REGIS II.2, 2020). Note: the Gangelt fault is indicated in the transect. This fault is present in the well field of Roosteren.*

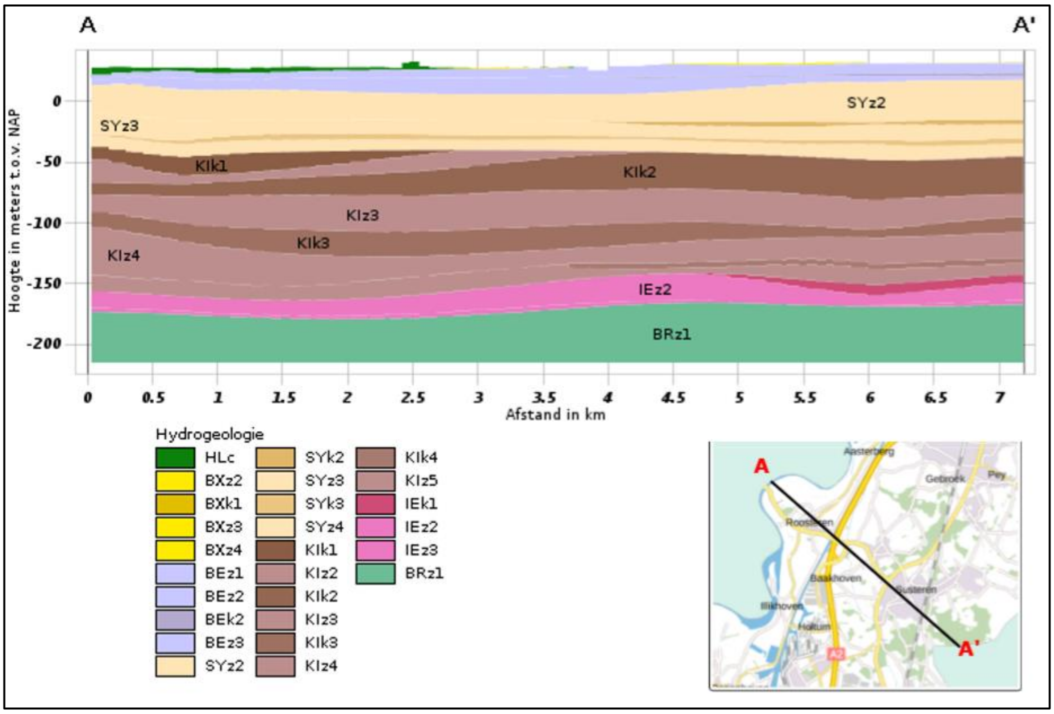


Figure 4 – *Northwest-southeast transect containing the underground structure of the regional area including the study site at Roosteren (TNO REGIS II.2, 2020).*

Riverbank groundwater well

The production of drinking water by the use of riverbank filtration is a method in which river water is abstracted through the riverbank by using abstraction wells close to the river. The heads in the vicinity of the wells need to be lower compared to the river water level. Also the infiltration capacity of the river bed must be sufficient and the river has to incise the aquifer. The filtering capacity of the soil in the riverbank reduces the amount of contaminants in the water being abstracted by the wells (Tufenkji et al, 2002). This can decrease the additional amount of treatment needed to produce drinking water. Figure 5 provides a schematic overview of the abstraction of river water by a riverbank groundwater well.

Different flow paths can occur at drinking water production sites that abstract riverbank filtrates. For the quantitative and qualitative management of bank filtration systems it is important to know the catchment zones, infiltration zones, mixing proportions in the pumped raw water, flow paths and flow velocities of the bank filtrate. Site specific conditions can have a significant influence on groundwater flow and transport processes at riverbank filtration sites (Hiscock & Grischek, 2002). In the beginning of 1998 the first wells that partly abstract Meuse riverbank water in Roosteren were taken into production. Since then, the Meuse in the vicinity of this well field changed from predominantly draining into predominantly infiltrating. During inactivity or reduced capacity of pumping of the Meuse wells and when the river water level is not rapidly rising, the groundwater flow is directed towards the river (Stuyfzand et al, 2006). Numerical modelling can bring more insights into flow paths when detailed hydraulic head and tracer tests data are available (Hiscock & Grischek, 2002). Stuyfzand & Juhàsz-Holterman (2000) studied the effects of riverbank filtration on the water filtrate for wells 10 and 11 in Roosteren by using natural chemical tracers, like chloride, iron and sulphate. This study contains research on travel times of Meuse riverbank water to the abstraction wells. Travel times are stated to be strongly dependent on river water levels and the rate of pumping by both wells of a well pair (Stuyfzand & Juhàsz-Holterman, 2000). The dependency of travel times on river water levels emphasizes the importance of this study, as the Maaswerken will directly influence the Meuse water levels. Besides the dependency on the river water levels, it should be taken into account that the changes in river water levels play an important role as well. Medema et al. (2001) showed that the dynamic character of the river Meuse has a large influence on the groundwater flow between the riverbank and the Meuse wells. This can be explained as the groundwater level responds delayed in respect to river water level. This will result in a difference in gradient between the groundwater level and the wells when comparing the measured heads with heads calculated in a groundwater model for different scenarios (Hubeek, 2012).

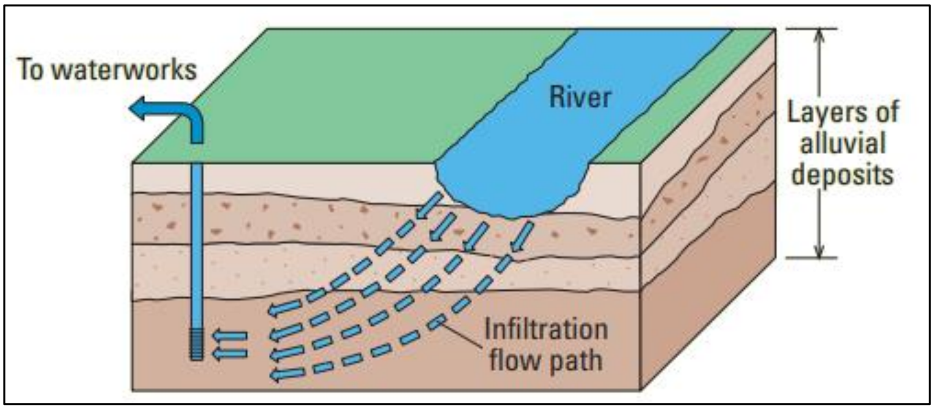


Figure 5 *– Schematic illustration of a riverbank groundwater well (Tufenkji et al, 2002).*

Microbiological and chemical risks

The abstraction of riverbank water originating from the Meuse, with a short residence time, brings microbiological risks for the drinking water production in Roosteren. The other types of groundwater abstracted in Roosteren are assumed not to be vulnerable for microbiological contaminations. The groups of microorganisms that pose risks to the drinking water production site of Roosteren include viruses, parasitic protozoa and bacteria (Van Driel, 2019). Besides the filtration of microorganisms by the riverbank, additional removal takes place in rapid sand filtration, active carbon filtration and UV-treatment. Moreover, operational measures are taking place at Meuse river water levels of >26.5 m +NAP to prevent microbiological pollutions in the abstracted water. This includes the decommissioning of wells 9 (or 12), 10 (or 11) and 13 (Prevoo & Juhàsz-Holterman, 2010).

Knowledge on the travel times of Meuse water towards the wells is of crucial importance to determine the microbiological risks for drinking water production. The widely used directive for the protection against microorganisms in the abstracted water is the 60-days-zone which indicates a zone around each well that includes a minimal travel time of 60 days for groundwater before it is abstracted (Van der Wielen et al, 2008). Travel times shorter than 60 days may pose risks to drinking water production (CBW, 1980). Previous research on microbiological contaminations for the drinking water production site of Roosteren showed that almost all observed microbiological contaminations took place during high Meuse discharges or inundations (Medema et al, 2001; Juhász-Holterman et al, 2002). High Meuse water levels may result in shorter travel times from riverbank to well, leading to a lower removal efficiency for microbiological and chemical components. Furthermore, due to rising water levels previously unsaturated zones can become saturated and transport river water towards the abstraction wells. These zones may however not display the same removal properties as the deeper saturated zone, which can lead to the abstraction of microbiologically unsafe water at the well (Schubert, 2000).

In addition to the microbiological contaminations, chemical contaminants pose a threat to the drinking water production as well, especially as organic micropollutants have a relatively high mobility in the soil (Puijker et al, 2008). As the Meuse river carries numerous chemical components the removal of these components is important for drinking water production. By using riverbank filtration the chemical components of the river water are attenuated through physical filtering, sorption and degradation (Ray et al, 2002). Same as for microbiological components, the removal of organic micropollutants depends on the travel time from Meuse to wells. Another important aspect regarding the chemical risks for drinking water production is the dilution of contaminated water with unpolluted water. Dilution takes place in the riverbank where Meuse water is mixed with phreatic groundwater, as well as after abstraction of the water, where water of the deep wells of the Roosteren well field is mixed with abstracted water from the Meuse wells (Van Driel, 2019). Both dilution steps can change the water quality of the abstracted water. In addition, the discharge of the Meuse river plays a role in the degree of chemical contamination of abstracted Meuse water. High and low discharges result in more and less dilution of pollutants respectively.

3. Materials and methods

The model names as referred to in this study are presented in Table 1. Both the Roosteren and Maaswerken model are based on the regional IBRAHYM v2.1 groundwater model.

***Table 1** – Model names as referred to in this study including a description and documentation source of the model.*

Model name referred to as:	***Base Model IBv2.1***	***Roosteren Model***	***Maaswerken Model***
Description	The regional groundwater model for Limburg; IBRAHYM version 2.1	Model used for the project of the recalculation of drinking water and groundwater protection zones of the Roosteren drinking water production site	Model used in this study to determine the effects of the Maaswerken on the drinking water production at Roosteren
Documentation source	Vermeulen et al, 2007 & Vermeulen et al, 2015	Van der Hauw, 2019 (technical report)	-

3.1 IBRAHYM model

Groundwater calculations are carried out using iMODFLOW v5.0. The Base Model IBv2.1 is set up for Waterboard Limburg (WL), the province of Limburg and Waterleiding Maatschappij Limburg (WML). The model is developed to function as an instrument for the analyses of the shallow and deep groundwater system and to determine the effects of changes in the water system in North- and Middle Limburg. The model has a resolution of 100 meter and stretches from the lignite quarry in Germany near Inden to the Meuse at 's Hertogenbosch (Vermeulen et al, 2007). The model contains 19 aquifer layers to represent the underground to a depth of approximately 2 kilometres. The layer construction of the model is based on REGIS II.1. In the model, the high-permeable gravel and sand deposits of the Formation of Beegden and Formation of Stamproy at the well field are present in model layers 4, 5 and 6 (Figure 6)(depending on the location relative to the faults)(Van der Hauw, 2019).

Model structure

In this section the main structure and functioning of the three models will be described and explained per aspect.

The aquifers of the model are represented by the 19 model layers. The first aquifer of the study area is formed by model layers 1-13 and stretches from about 30 m +NAP to −60 m +NAP in the model. The horizontal and vertical permeabilities are represented by the KHV and KVV maps respectively (Table 2). The KVV maps represent the resistance layers between each model layer. Important KHV and KVV input maps of the Maaswerken Model can be found in Appendix D & E.

The ground level functions as a reference for height-related data such as surface water and drainage levels. The ground level for the model is derived from the Algemeen Hoogtebestand Nederland (AHN)

(English: general height file Netherlands). The ground level input maps of the Maaswerken Model for the study area situation before and after lowering of the riverbank can be found in Appendix F.

The depth locations of the underground structure for well- and poor permeable layers for Limburg and adjacent Dutch provinces are largely based on REGIS v2.1. For the underground structure of adjacent German areas the following existing groundwater models were used: Zandmaasmodel (Royal Haskoning), Venloschollemodel en Rurschollemodel (Bachmann et al, 2005). The Belgium area was obtained from the Vlaams Grondwatermodel (Meyus et al, 2000). REGIS v2.1. also supplies the range of hydraulic conductivities (k-values) of the different layers (Vermeulen et al, 2015).

Groundwater replenishment in the models is based on measured precipitation values and the reference evapotranspiration of crops, in which interception and storage in the rootzone are taken into account (Vermeulen et al, 2007). In paved areas, replenishment is absent, due to the assumption that water directly runs off paved surfaces.

The upper boundary condition in the groundwater models are the surface waters. The difference between the surface- and groundwater levels determines the rate of infiltration or drainage. The locations of surface waters are taken from TOP10 vector files and mappings of waterboard Limburg. For the river Meuse, the locations of the river bed are taken from the height files of the Rijkswaterstaat Maaswerken (Vermeulen et al, 2007). Typical inputs for the Meuse river can be found in Appendix G.

Groundwater levels that exceed the ground level result in water being transported over the surface. The model accounts for this by using a Surface Overland Flow plane. This plane contains the height of the ground level plus 2 cm (Vermeulen et al, 2007).

Data for the abstractions in the Base Model IBv2.1 were obtained from WML, the province, the Waterdoelen model (for the province of Brabant), German and Belgium models. These abstraction data include the period of 1989-2004. The drinking water abstraction quantities from WML are taken per well field, and not per well, as well specific data was lacking. The abstraction quantities per well field are divided in percentages of the layers that are addressed (Vermeulen et al, 2007). At the large scale lignite quarry in Germany near Inden, groundwater is abstracted in order to excavate lignite. This quarry is simulated in the model by creating a fixed groundwater level at the height of the outcrop for the specific model layer. The abstractions of the wells in the Roosteren Model have been adjusted for this study as explained in the next section.

Faults are included in the model following the faults in REGIS v2.1. The iMODFLOW code for a fault contains a resistance for the fault in its total. In this way, the fault has an obstructing function, regardless of the layer it is situated in (Vermeulen et al, 2015). In the Roosteren and Maaswerken Models, the Gangelt fault contains a resistance of 2500 days up to the bottom of the Formation of Beegden. Above the bottom of this formation a resistance of 50 days is used (Van der Hauw, 2019).

The unsaturated zone is simulated using MetaSWAP 7.2.11 (Walsum et al, 2011). Groundwater recharge and discharge through the unsaturated zone are simulated using this module. The module is based on a simplification of ‘straight Richards’, which implies that processes like hysteresis, preferential flow and bypass flow are excluded from the model (iMOD user manual, 2017).

Simulation of flow paths

In order to simulate flow paths iMODFLOW is used to calculate budget terms for each grid cell in the model. The function iMODPATH is then used to compute the flow paths and the corresponding travel times. The groundwater flow equation used in iMODPATH is the partial-differential equation:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)+W = S_s\frac{\partial h}{\partial t}$$ (McDonald & Harbaugh, 1988),

where

- K is the hydraulic conductivity specified for all three dimensions by subscript;
- h is the groundwater head;
- W is the volumetric flux per unit volume and represents sources and/or sinks of water;
- S_s is the specific storage of the porous material;
- t is time.

This mathematical relationship is used to describe groundwater flow through an aquifer. The iMODPATH calculations provide outputs of the travelled flow path, coordinates of endpoint and travel time for each started particle (Langevin et al, 2017).

Sub-model and cut out

The Roosteren Model is created by making a cut out of the Base Model IBv2.1 around the drinking water production area near Roosteren. The Roosteren Model is improved locally and calibrated again compared to the Base Model IBv2.1. This sub-model is used for the recalculation of drinking water and groundwater protection zones (Van der Hauw, 2019). The advantage of using a sub-model is that the calibration is more accurate, meaning there is less deviation between measured and calculated groundwater heads. The resolution of the Roosteren Model in the vicinity of the drinking water production area is 5 meters, while the remaining area of the model uses a resolution of 25 meters (Van der Hauw, 2019). The Maaswerken Model is based on the Roosteren Model as this model contains the most recent and detailed calibration for the study site. In addition, it is suitable for the aim of this study as the distance of the model border to the area of interest is sufficient to prevent inaccuracies from the model border to influence the infiltration area. The area of interest of this study is part of the area of interest of the groundwater protection zone study.

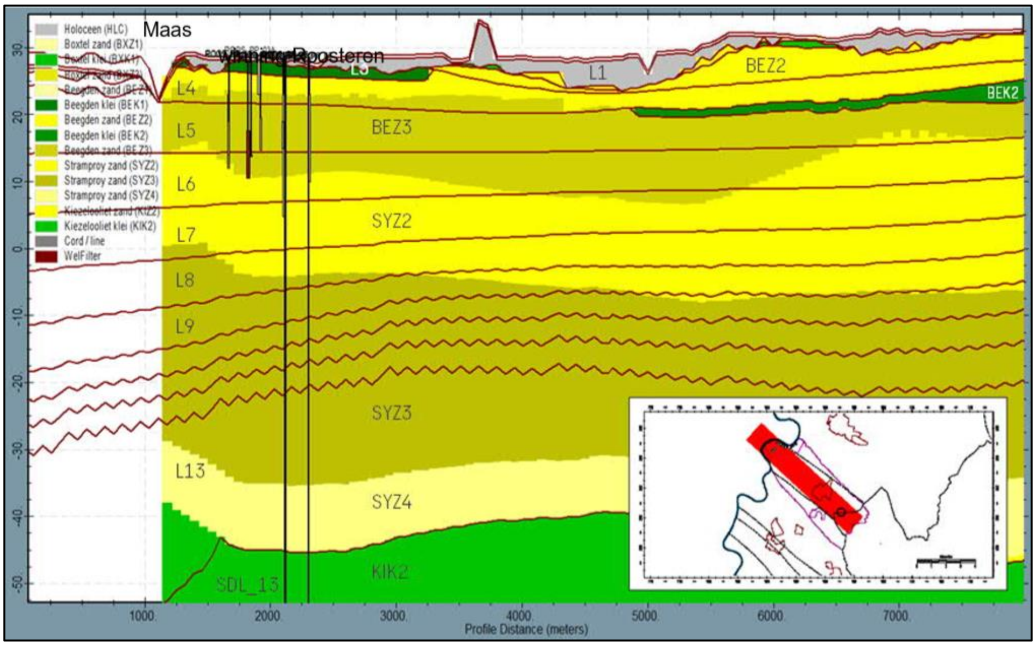


Figure 6 – Model (Base Model IBv2.1) cross section of the Meuse valley in the present groundwater protection zone with geological formations (planes), model layers (red lines), production wells (red) and computed phreatic groundwater level (blue)(Van der Hauw, 2019).

3.2 Preparations of Maaswerken model

The majority of the Maaswerken model input was adopted from the Base Model IBv2.1 and the Roosteren Model. An overview of the model input can be found in Table 2. An example of a model runfile as used in this study is provided in Appendix A. Adaptations that were made to the Maaswerken model are described below.

Model extent and resolution

The model resolution used in Maaswerken Model is 5x5 m. This resolution is chosen as the width of the Meuse river in the study area is only 25-50 m at its smallest point during low discharge and as the Meuse wells are located only ± 150 m from the Meuse. A 25x25 m resolution, as used in the Roosteren Model would be to coarse to determine local groundwater flow patterns. As computation times were taken into account and the accuracy of the model is chosen to be 5x5 m, the model extent is chosen to be 8000x8000 m. The model makes use of the following coordinates (Dutch coordinate system): 181500, 339500, 189500, 347500. The starting heads at the model boundary are obtained from the Roosteren Model.

Adaptation of riverbank

The IBRAHYM v2.1 model cut out for the Roosteren drinking water production site is adjusted and prepared prior to model runs. In order to simulate the situation after the lowering of the riverbank a half moon shape area in the inside of the river bend is lowered by adapting the IMOD model raster. The shape and quantity of this lowering is based on a factsheet on measures for the inside river bend area of Roosteren (Factsheet Roosteren – De Rug, 2019). The surface elevation is adjusted by defining a fixed elevation level at the boundary of the area that is to be lowered, and interpolating in between the boundaries. The border at the river side, has a fixed elevation value of 20 m +NAP. The elevation on the other border, on the side of the well field is equal to the present situation. In between the surface elevation is interpolated, thereby representing the future situation. The current riverbank is steep close to the Meuse river, resulting in largest lowering close to the Meuse. Unrealistic spikes in ground level heights have been adjusted manually afterwards to obtain a gradual surface elevation for the new riverbank. The difference between the original and new ground level for the riverbank can be found in Appendix F. In order to prevent errors from occurring and successfully complete flow path calculations using the iMODFLOW module, a minimal layer thickness should be preserved. In the largest part of the area, the top 5 layers would have disappeared after the lowering. Therefore a minimal layer thickness has been applied to these layers. The new top layers that are created are used in modelling scenarios SCE1, SCE2 & SCE3, as described in section 3.3 Modelling scenarios.

Adaptations to Meuse river

The median Meuse river water level in this study is the same as used in the Roosteren Model. This river water level is based on the Reference Line Heights for the Meuse over period 2016-2024 by Rijkswaterstaat. The river water levels in the high and low discharge modelling scenarios are obtained by adding and subtracting the differences with the median water level to this water level map. In this way the same river gradient has been preserved in each modelling scenario, which is realistic following the Reference Line Heights over the study area (Rijkswaterstaat Zuid-Nederland, 2019). In the modelling scenarios after the adaptations to the riverbank, the river contours have been expanded if the new ground level heights have become less than river level heights.

Pumping well discharges

For the discharges of the shallow wells in the study area the licensed abstraction per year for the first aquifer were used. The distribution of this abstraction over the active wells are based on the average abstraction data of the wells over the period of 2008-2018, as the current well set-up is used since 2008. For the radial well 03A this is 55.15% of the licensed abstraction of aquifer 1, corresponding with 9821 m^3/d. The remaining wells, 09 up to 14, are equally divided in terms of abstractions with 7.47% of the licensed abstraction of aquifer 1, corresponding with 1331 m^3/d. Subsequently, the assigned abstractions are divided over the present filters of each well following the ratios as determined in the Roosteren Model study. The abstractions of the deep wells in the study area are adopted from the Roosteren Model as well.

Model calibration

The calibration set used for minor additional calibration of the Maaswerken model is the same as used in the Roosteren Model. This set contains the averages of WML groundwater monitoring wells over period 2016-2017. The heads in the calibration data set in the vicinity of groundwater monitoring well WP45 (located near well 10) are too high for median discharges compared with the time series of WP45 over time period 2000-2018 (Figure 7). For groundwater monitoring well WP45 the head is 22.01 m, while the average and median of 2000-2018 are 21.6 m and 21.2 m +NAP respectively. Therefore, the model is calibrated so that heads in the well field of Roosteren are lower than in the calibration set. This is done by applying a multiplication factor of 0.5 to KHV maps of layers containing active shallow wells in the Roosteren well field. The calculated groundwater head near WP45 is 21.0 m +NAP after calibration. By applying the modifications to the model more realistic heads are obtained. Additionally, this led to flow paths patterns being more realistic.

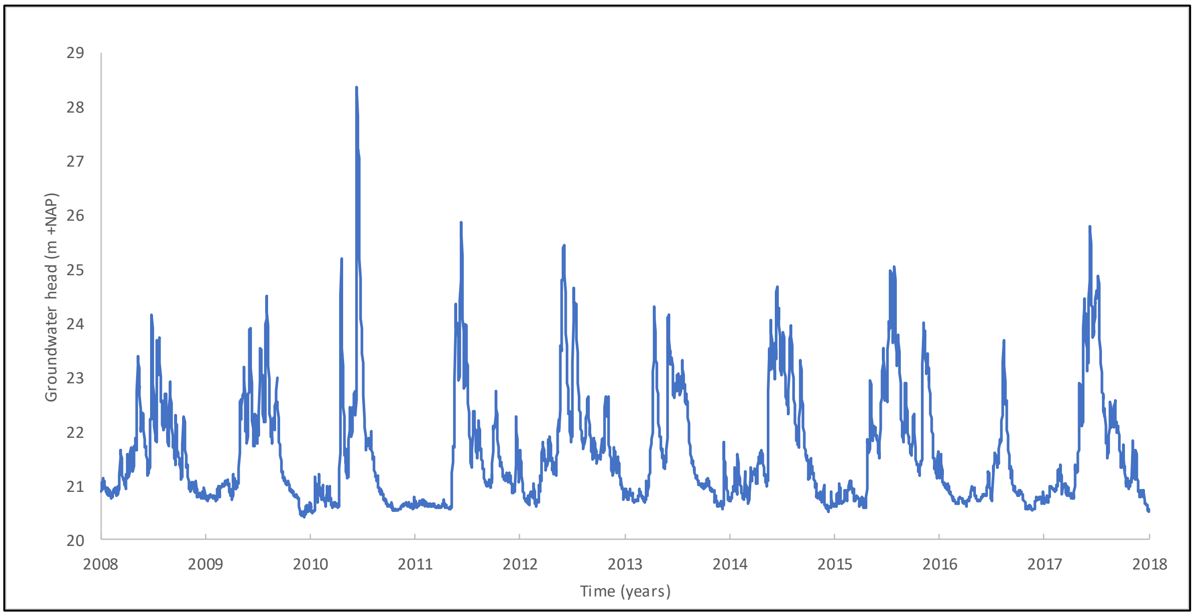


Figure 7 *– Groundwater head in groundwater monitoring well WP45 near Meuse wells 10 & 11 obtained from Dawaco (water monitoring system used by WML). Note: the average and median of the shown series are 21.6 and 21.2 respectively.*

Table 2 – Overview of input parameters and packages including a short description, units and sources. Note: descriptions are based on the descriptions as in the IMOD 5.0 User Manual (Vermeulen et al, 2019).

Parameter/Package	Input map	Description	Unit	Source
Starting heads	SHD	Specifies initial head to start the model simulation for each cell and model layer	m +NAP	*Van der Hauw, 2019*
Ground level heights	TOP/BOT	Defines the top and bottom level the permeable part of each model layer	m +NAP	*Vermeulen, 2007; Van der Hauw, 2019*
Horizontal permeabilities	KHV	Defines the horizontal permeabilities per model layer.	m/d	*Vermeulen, 2007; Van der Hauw, 2019*
Vertical permeabilities	KVV	Defines the vertical permeability of the resistance between two model layers.	m/d	*Vermeulen, 2007*
Vertical anisotropy for aquifers	KVA	Defines the vertical anisotropy for each model layer.	-	*Vermeulen, 2007*
Horizontal flow boundaries (faults)	HFB	Defines horizontal barriers that obstruct flow for instance due to semi- or impermeable fault zones.	days	*Vermeulen, 2007; Van der Hauw, 2019*
Wells	WEL	Defines the locations and quantities of abstractions for each model layers	m^3/d	*WML, 2008-2018; Van der Hauw, 2019*
Drainage	DRN	Defines the location, elevation and conductance of the drainage system (secondary streams and drainage pipes/ditches).	m +NAP (elevation) m^2/d (conductance)	*Vermeulen, 2007*
River	RIV	Defines the location, water level, bottom level, conductance and infiltration factor of primary river systems.	m +NAP (water & bottom level) m^2/d (conductance) - (infiltration factor)	*Vermeulen, 2007; Van der Hauw, 2019*
Recharge	RCH	Defines the quantity of water that recharges the groundwater as result of precipitation and sprinkling	mm/d	*Vermeulen, 2007*
Overland flow	OLF	Defines the elevation above which outflow of groundwater will occur when exceeded by the groundwater head	m +NAP	*Vermeulen, 2007*

3.3 Modelling scenarios

The initial modelling scenario (SCE0) of this study represents the current situation during the median river discharge in the study area. The Meuse water level corresponding with a median discharge of 155 m^3/s is adapted from the Roosteren model. In order to evaluate the effects of the Maaswerken three modelling scenarios are used for the system after adaptation of the riverbank (Table 3). These modelling scenarios contain discharges representing the seasonal variation in Meuse discharge. Firstly, a modelling scenario containing the median river discharge after lowering of the riverbank (SCE1) is simulated. This scenario is compared with the initial model SCE0 to investigate the changes in travel time. Secondly, a modelling scenario containing a high river discharge after lowering of the riverbank (SCE2) is simulated. This scenario represents a worst-case scenario and the river level used in this scenario forms the border on which certain wells are being taken out of operation to decrease risks for drinking water production. The third modelling scenario contains a low river discharge after the lowering of the riverbank (SCE3). This scenario represents a summer river discharge in which less dilution takes place implying a higher concentration of chemical compounds. The discharge scenarios are based on the Reference Line Heights, which can be found in Appendix B. The discharges and the corresponding river water levels are shown in Table 3. All scenarios assume steady-state conditions for the river Meuse, as running a transient model would require new river level data for each time step. The lack of data on Meuse water levels after the lowering of the riverbank for each time step and the time consuming process of obtaining this data make that running a transient simulation is beyond the scope of this research.

Table 3 *– Discharge scenarios and the corresponding river water levels near the Roosteren well field. Note: For the model input, the river water levels are decisive as river discharge is not an input parameter.*

	SCE0: Median discharge *before* adaptation of riverbank (**initial model**)	SCE1: Median discharge *after* adaptation of riverbank	SCE2: High discharge *after* adaptation of riverbank	SCE3: Low discharge *after* adaptation of riverbank
Discharge Q (m^3/s)	± 155	± 155	± 1300	20-50
River water level near well field (m)	21.46	21.46	26.50	20.80

3.4 Flow path modelling and travel times

The starting points where particles infiltrate are generated before each particle simulation. The particle simulation can be done using forward and backward tracing simulations. Forward simulations follow the infiltration path of a water particle in its natural way, while backward simulation follow the inverse pathway of a water particle, from the endpoint to the source. For the backwards runs that are performed during this study the particles are placed in circles with a radius of ± 2.6 m around each well. For each well 15 circles are placed over the depth of the filters of the well. From each circle ± 1600 particles are released, adding up to a total of 24000 released particles per well. More particles would result in unworkable computation times and data processing for the scope of this study. For the forward runs, particles are started within the contours of the Meuse river during the occurring discharge (Figure 8). Particles are started at every 10x10m at several depths in respect to the Meuse bottom level. As the contours of the Meuse river vary for each modelling scenario and IMOD lacks a function for entering the exact amount of particles to be started, the amount of started particles differ per scenario. The total released particles per scenario are as following: SCE0: ± 35500, SCE1: ± 30500, SCE2: ± 50500, SCE3: ± 21500. Particles are secluded for each well after the particle simulation of the forward runs are completed as they are still located in the same file after simulation. The seclusion is performed by using the IPF-Extract function within iMOD (Vermeulen et al, 2019). Subsequently, the travel times are processed into cumulative distribution curves by plotting the cumulative frequency of each travel time against the travel times for each well and scenario. Besides the analysis of travel times in cumulative distribution curves, the travel times <60 days are determined for each well and scenario as well. This provides an insight on the risks for the production of drinking water.

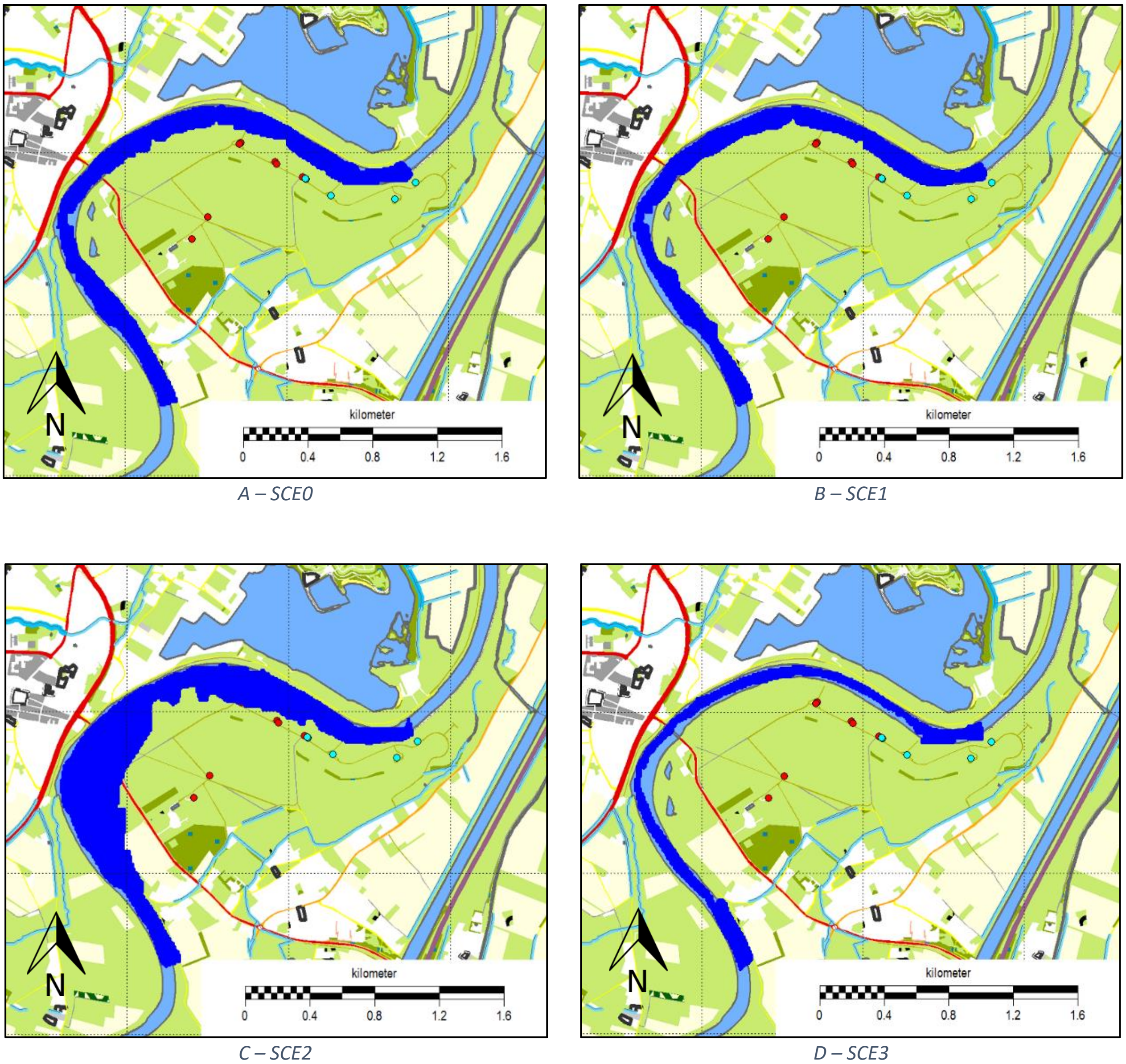


Figure 8a-d *– Schematic overview of the locations of Meuse contours in which particles are started for each modelling scenario in the forward calculations. Note: dark blue represents the locations of the started particles, red dots represent the shallow wells and green dots represent the deep wells.*

3.5 Sensitivity analysis & Model performance

In order to evaluate the sensitivity of the model used in this study, the effects of the river bed conductance parameter on the calculated groundwater heads are analysed manually. The river bed conductance parameter is chosen as this an important parameter for the infiltration of Meuse water into the riverbank. Model residuals are computed for the initial situation, +50% river bed conductance and -50% river bed conductance. For the calculations of the model residuals, the calibration set as used for the model calibration was used. The cumulative travel times distributions for the sensitivity analysis of the river bed conductance are plotted as well. This provides insights on the effects of the river bed conductance parameter in relation to the travel time distribution. The initial river bed conductance and +50% & -50% river bed conductance travel time distributions are plotted for the initial model (SCE0).

The performance of each modelling scenario in terms of computed groundwater heads is determined by computing model residuals. These model residuals display the difference between the used calibration set and the computed groundwater heads. The residuals are discussed in the discussion section.

4. Results

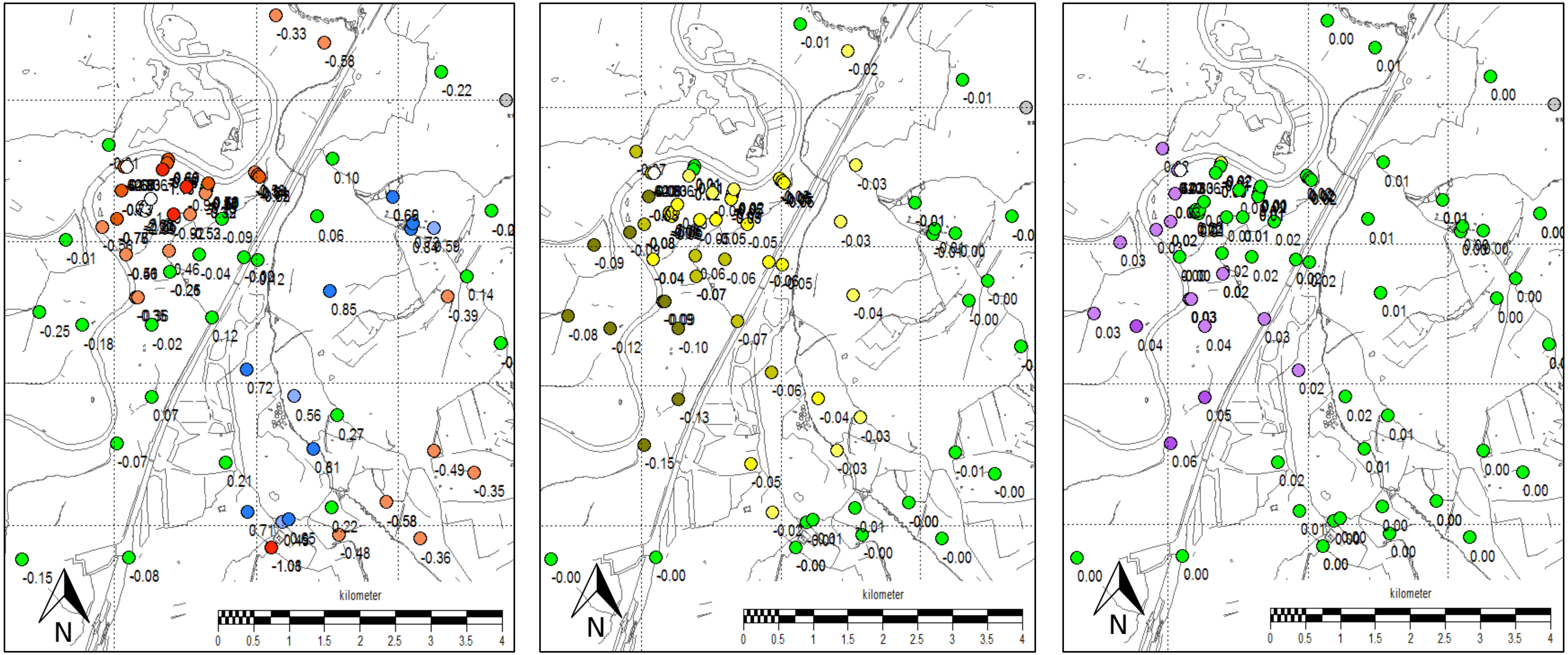
4.1 Sensitivity analysis & Model performance

Sensitivity analysis

The different scenarios for the evaluation of the riverbed conductance parameter showed minimal deviation (< 0.1 m) for most of the groundwater monitoring wells (Figure 9). The same applies for the cumulative time distribution curves of these different scenarios, which largely show comparable travel time distributions (Figure 11).

Model performance

The performance of each modelling scenario in terms of calculated groundwater is displayed in model residuals for the initial model and the three modelling scenarios (Figure 10). The computed groundwater heads in and around the well field in the initial modelling scenario (SCE0) display dry conditions compared to the calibration set (Figure 10a & b). A deviation of less than |0.3| m is considered to be accurate for the comparison with the calibration set as the initial modelling scenario SCE0 includes the median Meuse discharge whilst the calibration set is based on average values, which can result in the presence of small initial deviations. As averages of groundwater levels are used in the calibration set it can be recognized that the high and low discharge scenarios (SCE2 & SCE3) display wetter and drier conditions respectively compared to the initial modelling scenario (Figure 10d & e). The median discharge scenario after lowering of the riverbank (SCE1) shows negligible deviations with the initial modelling scenario (SCE0).

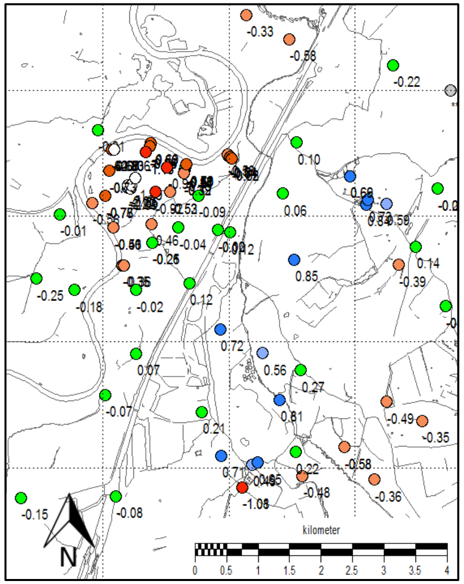


A – SCE0 initial riverbed conductance

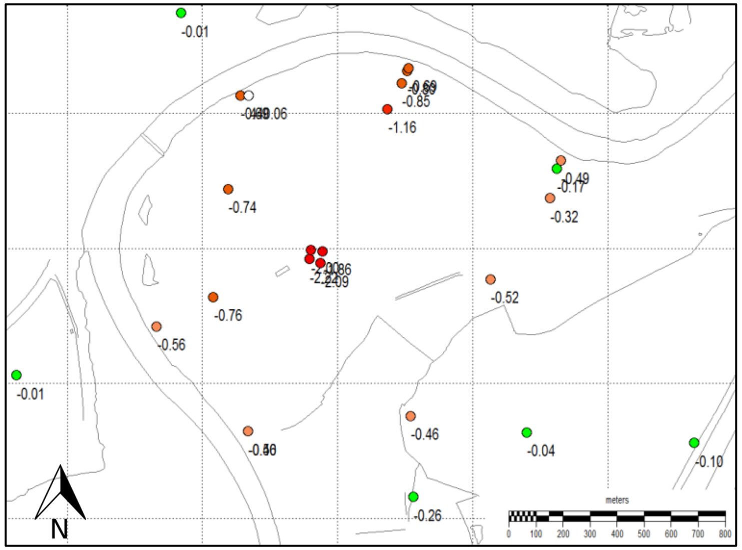
B – SCE0 riverbed conductance -50%

C – SCE0 riverbed conductance +50%

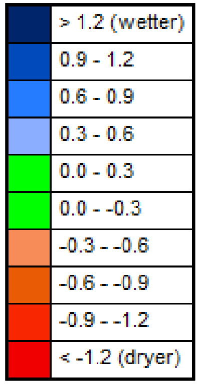
Figure 9a-c *– Model residuals (in meters) for the initial model SCE0 over model layers 1-7. Note: Figure A displays the deviations between the calibration set and calculated heads with initial riverbed conductance for SCE0. Figure B & C display the deviations between the modelling scenario SCE0 + and- 50% riverbed conductance and the initial modelling scenario SCE0.*

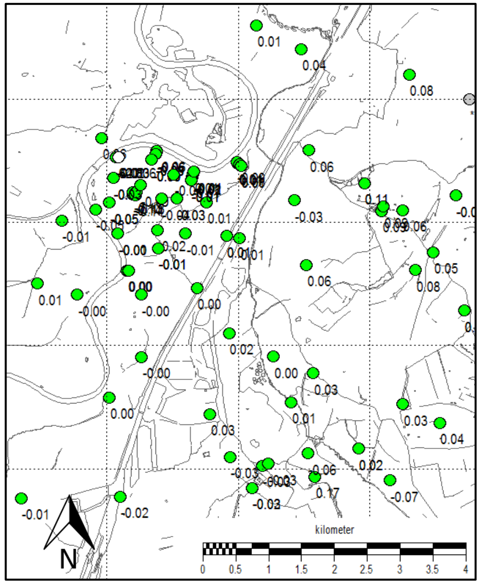


A – SCE0

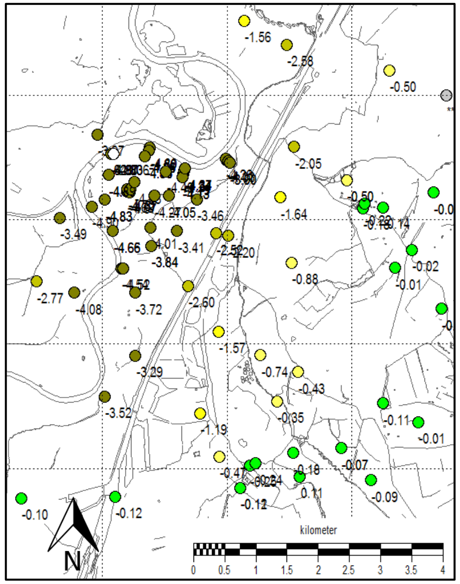


B – SCE0 zoom on well field

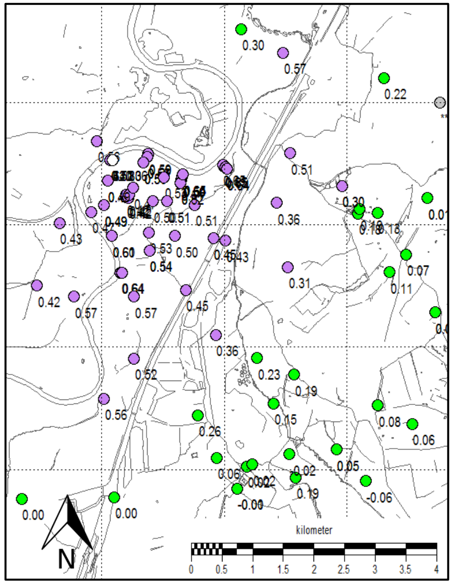




C – SCE1



D – SCE2



E – SCE3

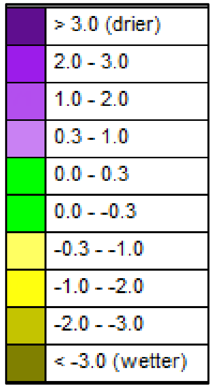


Figure 10a-d *– Model residuals (in meters) for the initial model and the three modelling scenarios over model layers 1-7. Note: Figures A & B display the deviations between the calibration set and calculated heads with for SCE0. Figures C, D & E display the deviations between the initial modelling scenario SCE0 and the modelling scenarios after lowering of the riverbank (SCE1, SCE2 & SCE3).*

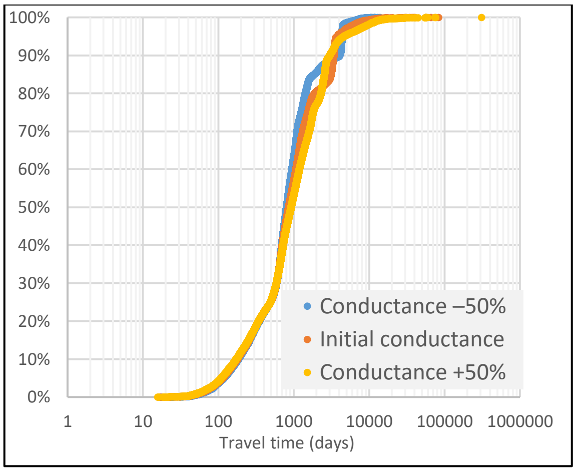


***Figure 11** – Travel time distribution curves for the abstracted Meuse water in SCE0 with the following riverbed conductance values: initial, -50% and +50%.*

4.2 Modelling results

Forward and backward flow path calculations

Both forward and backward flow path calculations have been performed during this study. The backward flow path calculation of this study provided flow paths that are inconsistent, as these flow paths significantly deviate from common knowledge on the geohydrological situation of the Roosteren well field. Besides, more than half of the studied wells does not abstract Meuse river water in three of the four model scenarios. In general, the forward flow path data seems logical and is therefore used for the travel time analysis.

The flow path modelling provided travel times which are divided both per drinking water production well and per scenario. An example of travel time data output can be found in Appendix C. Due to the regional character and corresponding coarse model schematisation of the IBRAHYM model, not all wells in the Roosteren well field abstract Meuse water in each modelling scenario. Table 4 provides an overview of the obtained forward calculated flow path data. Point estimates and corresponding confidence limits of wells and scenarios that fit a gamma distribution are provided in Appendix H. A typical flow path pattern of Meuse water towards the wells is shown in Figure 12.

***Table 4** – Overview of obtained forward calculated flow path data for all wells and model scenarios. (**x**: river water flow path data obtained; **–**:no river water flow path data obtained.*

Forward flow path calculations	SCE0	SCE1	SCE2	SCE3
Well 03A	x	x	x	x
Well 09	x	x	x	x
Well 10	x	x	x	x
Well 11	x	x	x	x
Well 12	–	–	x	–
Well 13	–	–	x	–
Well 14	x	x	x	–

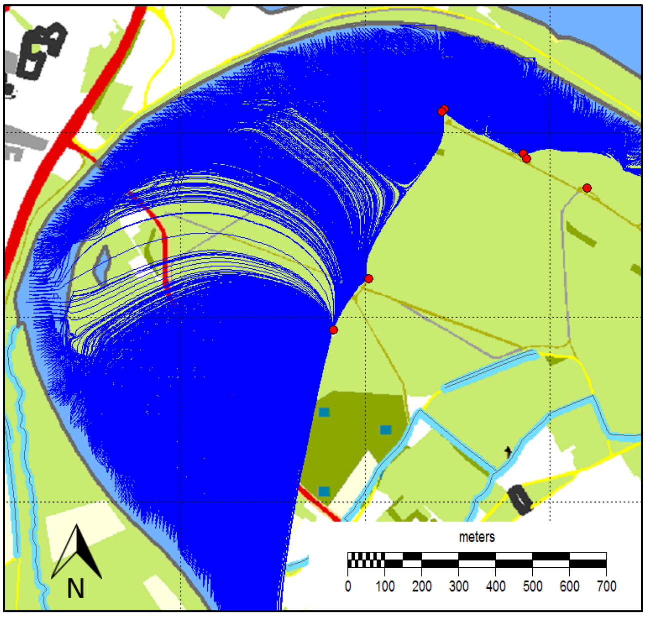


__Figure 12__ – Typical flow path pattern of Meuse water towards the wells displaying the prevailing flow paths in the initial model SCE0. Note: the shallow wells are indicated by the red dots, the flow paths are indicated by the blue lines.

Effects of Maaswerken on travel times

Obtained flow path and travel time data of wells 03A, 09, 10, 11 and 14 are used to explore the effects of the lowering of the riverbank. The cumulative distribution functions of the travel times are presented both per well (Figures 14 & 15) and per modelling scenario (Figure 15). In this section the modelling results are described per modelling scenario after lowering of the riverbank.

The travel times of the median discharge scenario (SCE1) are situated between the high and low discharge scenarios, especially for the smaller travel times (< 50% of all travel times). The spreading of travel times increased significantly after lowering of the riverbank as both smaller and larger travel times occur compared to the initial model before lowering. For the Meuse wells, no large differences in travel times are present between the initial model and the scenario after lowering of the riverbank. The travel time distributions before and after lowering of the riverbank are comparable. The travel time curves for Meuse wells 09, 10 and 11 mostly display the same patterns before and after the lowering of the riverbank. The travel time curves of the phreatic wells 03A and 14 show a slightly different pattern, as the scenario after lowering of the riverbank mainly contains smaller travel times compared to the initial model before lowering. For well 03A these differences are small. Also, the travel time curves for the before and after scenarios of the radial well 03A are mainly the same in shape, while the curves for well 14 slightly differ from one another.

The travel times during the high discharge scenario (SCE2) mainly decreased after lowering of the riverbank. The high discharge scenario contains flow paths with the smallest travel times for all wells (Figure 13 & 14) of all scenarios after lowering of the riverbank. The These include travel times of 0-20 days for Meuse wells (09, 10 & 11) and travel times of 200-500 days for the phreatic wells (03A & 14). The high discharge scenario is also recognized by the largest scatter in travel times (± 0-60000 days), as large travel times occur as well. Wells 12 and 13 only received flow paths from the Meuse in modelling scenario SCE2, the high discharge scenario.

The travel times of the low discharge scenario (SCE3) mainly increased after lowering of the riverbank. In contrast to the high discharge scenario, the smallest travel times (< ±50% of all flow paths) of the low discharge scenario (SCE3) are largest compared to the smallest travel times of other discharge scenarios, except for well 10 (Figures 14 & 15). The low discharge scenario is recognized by the steepest curves which imply the smallest scatter in travel times (± 30-42000 days). No particles started from the Meuse river reached the phreatic well 14 during the low discharge scenario, therefore no travel time distribution curve is obtained for this situation. Well 10 is recognized by several gaps in travel time distribution during the low discharge scenario (Figures 14b & 16d).

For all scenarios, the travel time distributions of the Meuse wells are mainly moving closer to each other for large travel times (Figure 13).

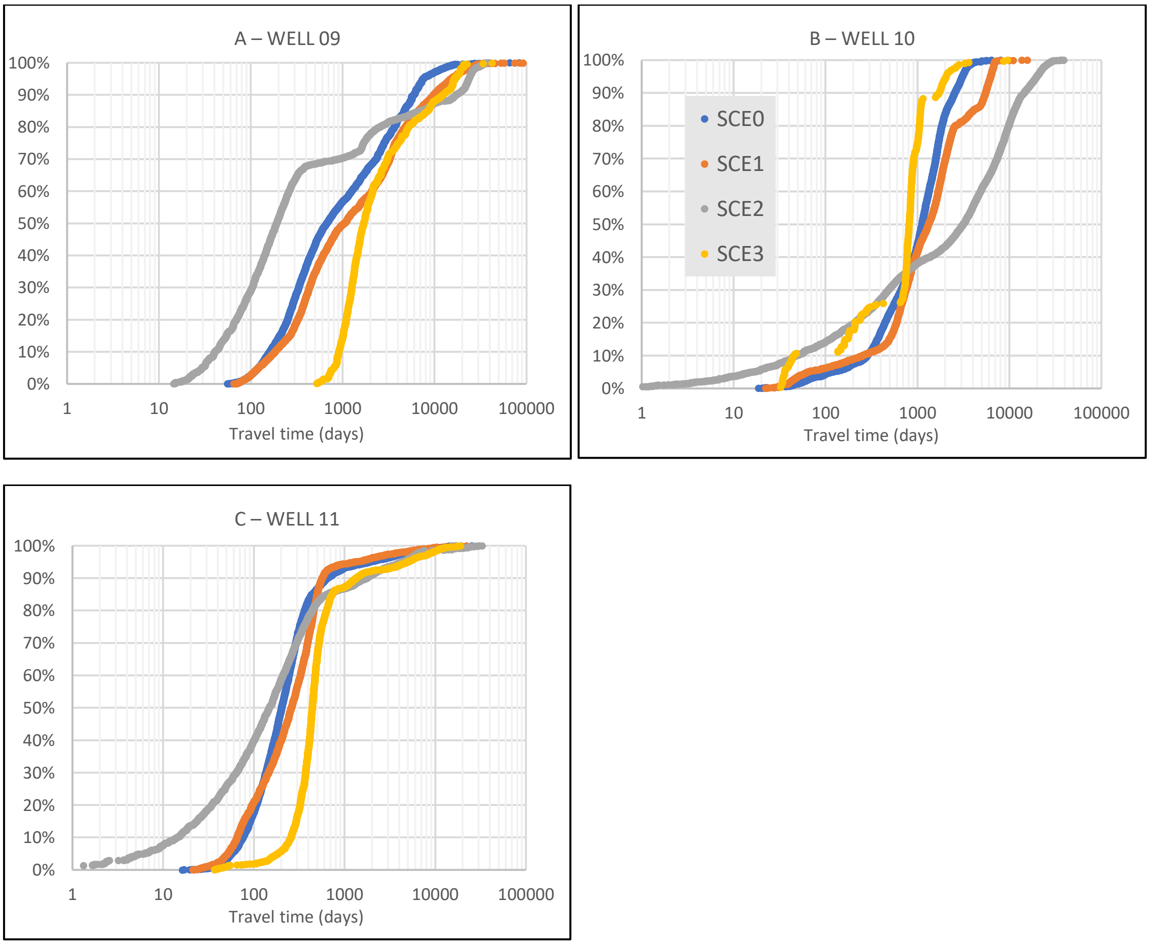


Figure 13a-c *– Cumulative distribution functions of groundwater travel times for Meuse wells 09, 10 & 11.*

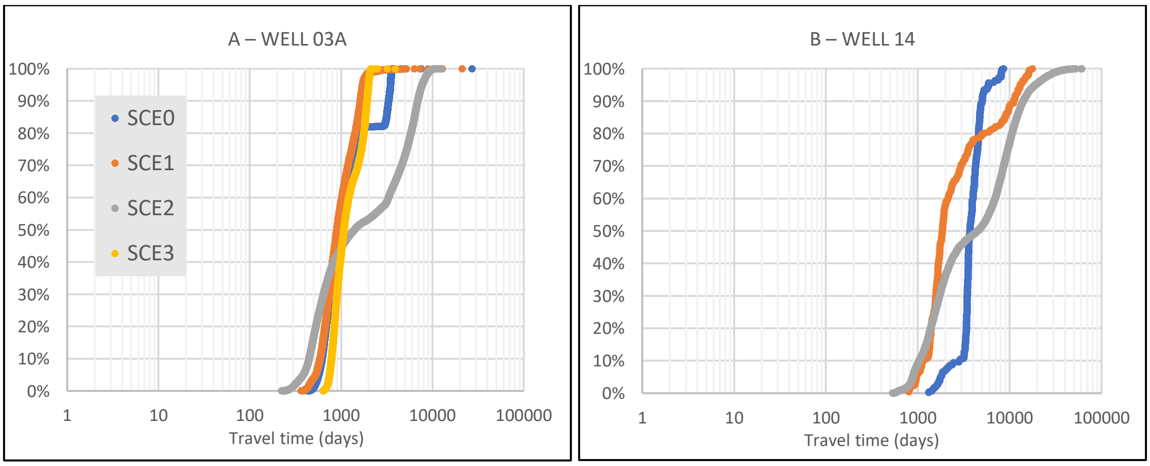


Figure 14a & b *– Cumulative distribution functions of groundwater travel times for phreatic wells 03A & 14.*

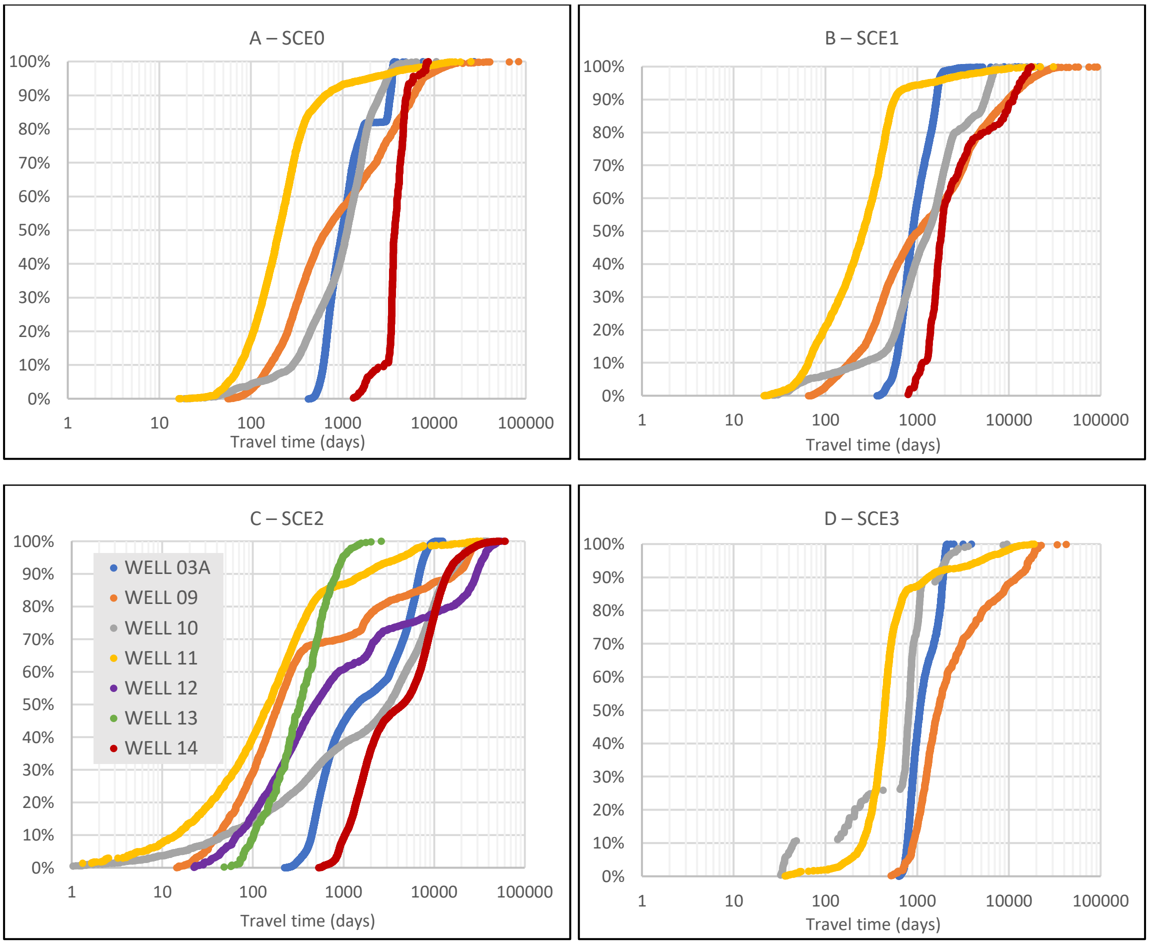


Figure 15a-d *– Cumulative distribution functions of groundwater travel times for the initial model and the three modelling scenarios.*

Travel time <60 days

In Table 5 the percentage of abstracted Meuse water with travel time of <60 days relative to the total abstracted Meuse water for each well and modelling scenario is presented. It can be recognized that wells 10 and 11 mostly contain the highest fraction of Meuse water (<60 days) for each scenario. In the median discharge scenarios (SCE0 & SCE1) these are the only wells to abstract Meuse water with a travel time <60 days. The fractions of Meuse water with a travel time <60 days increase after lowering of the riverbank for wells 10 & 11. During the high discharge scenario (SCE2), the abstracted Meuse water contains most Meuse water with a travel time <60 days of all scenarios for all wells. Furthermore it is notable that for well 10 during the low discharge scenario (SCE3) a relatively high fraction of Meuse water is obtained.

Table 5 *– Fractions of Meuse riverbank water with a travel time of <60 days compared to total abstracted Meuse water.*

	Phreatic wells		Meuse wells				
	03A	14	09	10	11	12	13
SCE0	0%	0%	0%	2%	6%	-	-
SCE1	0%	0%	0%	5%	8%	-	-
SCE2	0%	0%	17%	11%	29%	8%	1%
SCE3	0%	-	0%	11%	1%	-	-

Direct effects of Maaswerken

The adjustment of the riverbank as modelled in this study will influence the direct environment of the well field of Roosteren. Wells 09, 10, 11 & 12 are directly influenced as they are located in, or on the border of, the area to be lowered (Figure 16). As a result of the modelling of the adjustment to riverbank, the ground level is lowered about 2.8 m in the vicinity of wells 10 & 11 and about 1.0 m in the vicinity of wells 09 & 12. As a result of the lowering of the riverbank the Meuse river will expand only very little more inland with a median discharge. In the low discharge scenario the riverbed is smaller, which results in a bigger distance between river and well screens. The Meuse river will overflow its riverbanks in the high discharge scenario, thereby overflowing part of the inside of the river bend. This leads to a flooding of Meuse wells 10 & 11. The river water will come closer to wells 09, 12 & 13 too, however these wells will not be flooded in this situation.

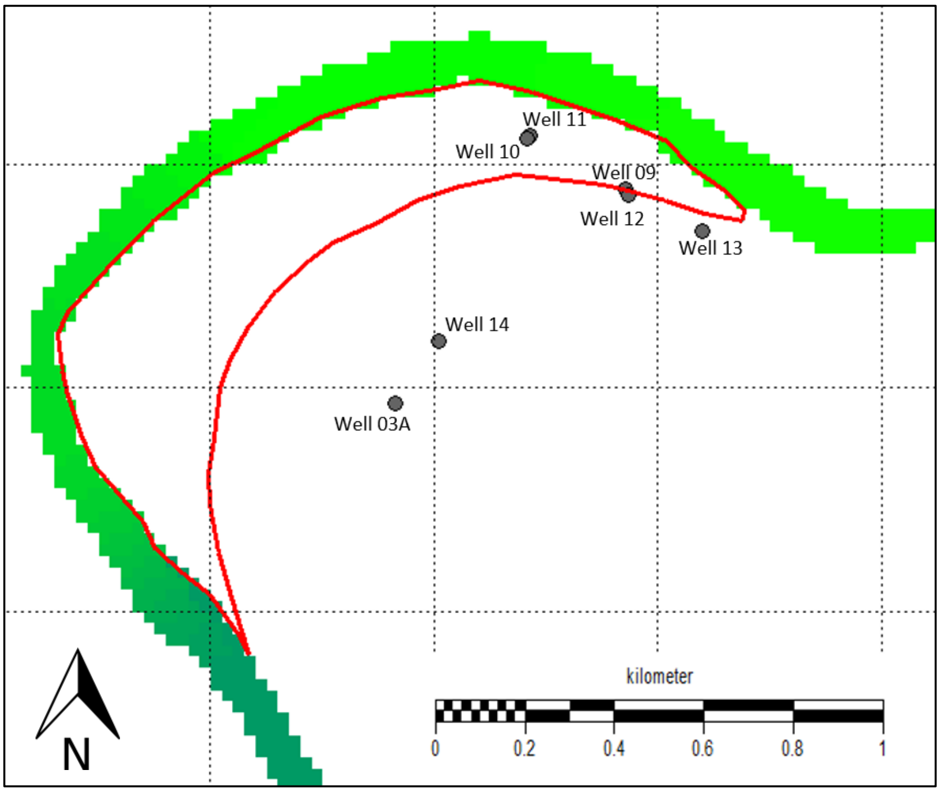


Figure 16 *– The lowered area as a result of the Maaswerken (outlined in red) in respect to the shallow wells of the Roosteren well field. Green represents the Meuse contours, the shadow indicates the gradient of the river. Note: Wells 10 & 11 and 09 & 12 are (partly) affected as they are located in or on the border of the lowered area respectively.*

5. Discussion

5.1 Sensitivity analysis & Model performance

Sensitivity analysis

The minimal differences in sensitivity analysis of the riverbed conductance parameter can be explained by the fact the riverbed conductance only influences the heads in the vicinity of the river, thereby hardly affecting the rest of the area. In contrast to the sensitivity of the Meuse water level, the riverbed conductance has shown to be less sensitive.

Model performance

The drier conditions in and around the well field in the initial modelling scenario compared with the calibration set are a result of the model calibration as a factor of 0,5 has been applied to the horizontal permeabilities maps as described in section 3.2. The wetter and drier conditions for SCE2 & SCE3 are the result of higher and lower Meuse river discharges respectively.

5.2 Limitations of the model

The model runs performed in this study assumed steady-state conditions. This assumption is made as running a transient analysis would require new river water level data for each time step. The lack of data on Meuse water levels after the adjustment of the riverbank for each time step and the time consuming process of obtaining this data make that running a transient simulation is beyond the scope of this research. However, it should be taken into account that true steady-state conditions do not exist in natural systems, as these systems fluctuate in response to climatic variations that can be seasonal, annual, decadal or longer (Reilly & Harbaugh, 2004). This strongly applies for the study area as well. Especially the high discharge scenario, SCE2, does not correspond with steady-state conditions, due to fast rising and descending river water levels. In reality, the groundwater level in the study area rises delayed compared to the river water level. The steady-state simulation of the high discharge scenario will therefore present a larger groundwater gradient between Meuse and production wells compared to the real situation. As a result of this, the shortest travel times of SCE2 are probably smaller than in reality (Hubeek, 2012).

The regional IBRAHYM groundwater model is developed to function as an instrument for the analyses of the shallow and deep groundwater system and to determine the effect of changes in the water system in North- and Middle Limburg. Due to the regional character of the model it has been set up elaborative to match all geohydrological aspects of the region. The regional character of the model does not benefit the local focus of the study as in some aspects the model schematization is too coarse to study local groundwater processes. Firstly, this can be attributed to basic input maps containing a coarse grid. The horizontal permeabilities of the model, modelled as KHV map per model layer, consist of a 100x100 m resolution. This does not coincide with the 25x25 m resolution of the river package in which the Meuse river is simulated. For the flow path line simulations this leads to flow paths being largely affected by the Meuse structure within the KHV map (Figure 17). The changes to the KHV maps of layers containing active shallow wells in the Roosteren well field as explained in the discussion of the sensitivity analysis help to undermine this effect. This weakens the effect of the KHV maps on the path line simulation. The discrepancy between realistic parameters and realistic outcomes may indicate that there is a conceptualization problem with the model (Reilly & Harbaugh, 2004). Secondly, the model schematisation of the Gangelt fault seems to have a significant influence on the flow paths as well. The fault is oriented Northwest-Southeast and located on the North-East side of the well field. As the fault is simulated in the HFB package, it represents a horizontal flow boundary where flow is (partly) obstructed. Although the river package, in which the Meuse river is simulated, overrules the HFB package, the surrounding model environment is still affected by the Gangelt fault. This affects the flow paths (Figure 18), however the determination of the exact effects of this model schematisation is beyond the scope of this study. Besides the uncertainties of the effects of the model schematisation, uncertainties regarding the positioning, tilting and permeability of the fault in reality still exist as well (Deckers et al, 2014).

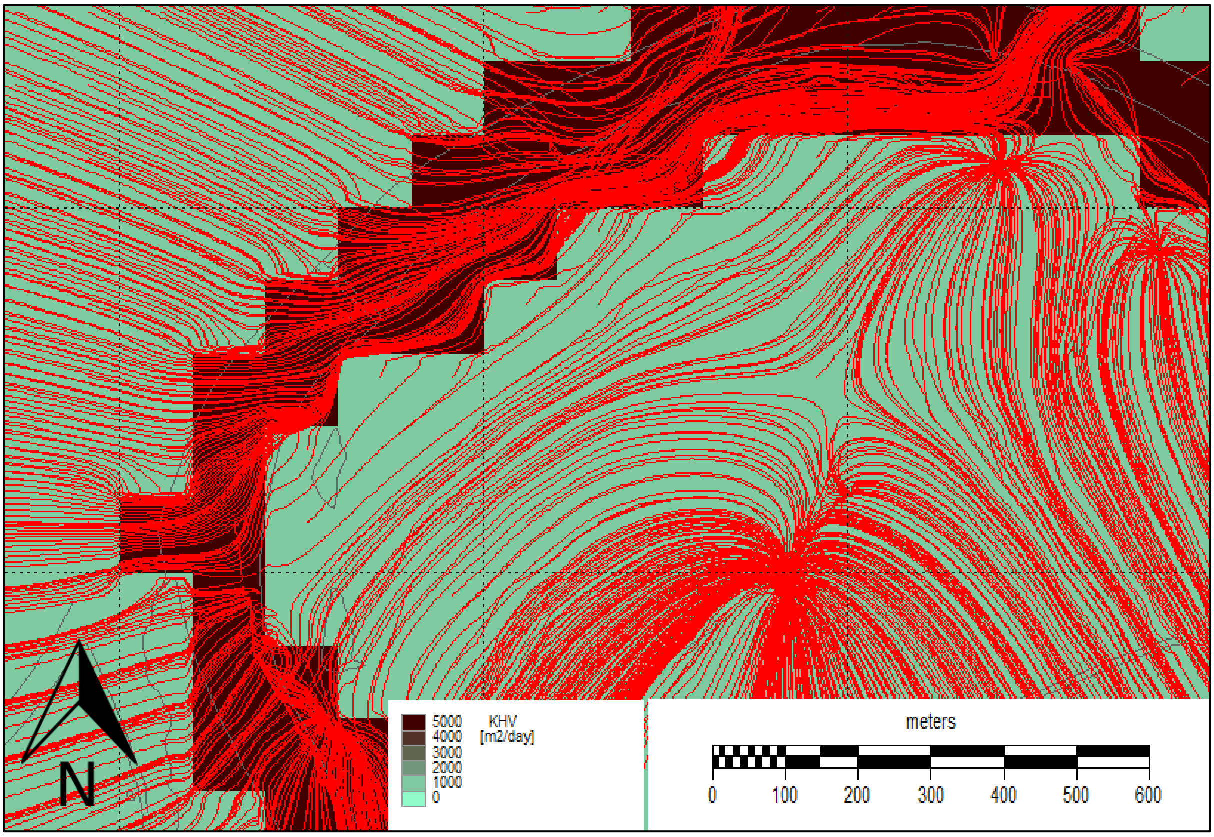


Figure 17 *– KHV map of model layer 1 and forwards simulated flow paths (red) before applying the multiplication factor of 0.5. Note: It can be recognized that the flow paths are largely influenced by the pattern of the KHV grid as these paths bend around the high value cells.*

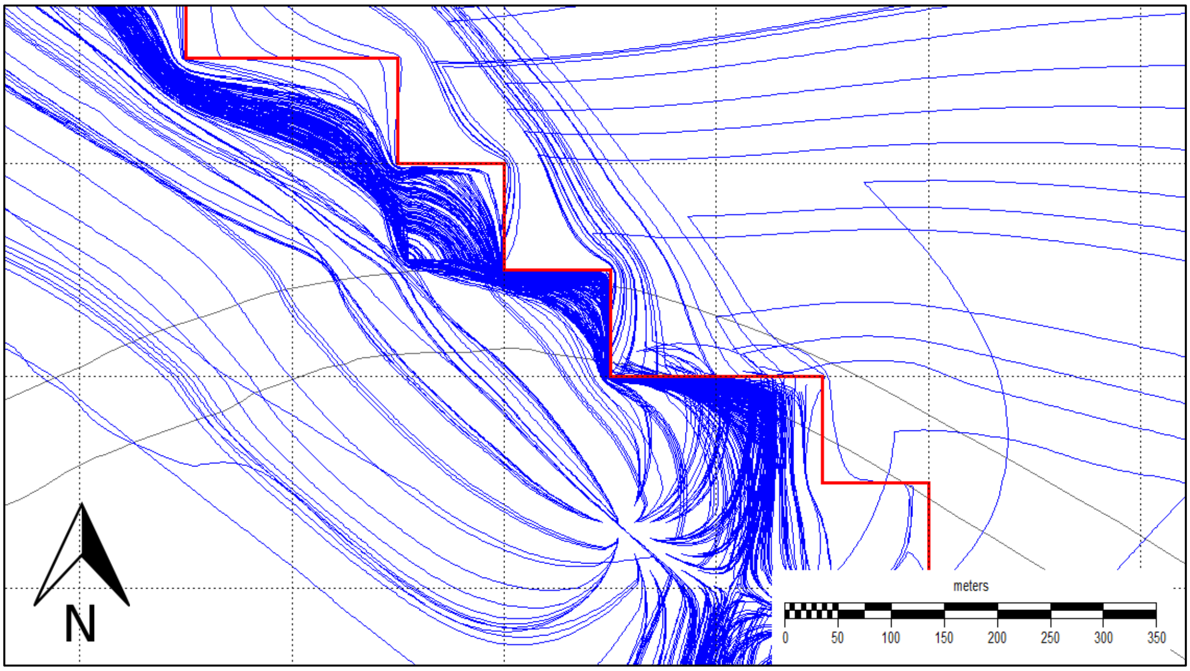


***Figure 18** – Flow paths affected by the model schematisation of the Gangelt fault. Note: Red line represents Gangelt fault, blue lines represent backwards calculated flow paths started from the Northeast side of the well field.*

The travel time analysis in this study is based on the calculated flow paths and their corresponding travel times. This method however is limited as it underlies the assumption that each flow path represents the same flux in terms of water quantity due the model not being able to calculate this groundwater flux. In reality the distribution of water volumes might not be equal over all flow paths, resulting in changes of the travel time distribution of water that is abstracted by the wells. The impacts on the travel time distributions are uncertain. A minimum of roughly 16.500 particles over the length of ± 3.5 km Meuse ends in either one of the wells for modelling scenarios SCE0, SCE1 & SCE2 and about 7900 particles for scenario SCE3. This can imply that large fluxes are represented by more flow paths as a result of the high particle density. One should bear in mind that the differences between the given particles per scenario are dependent on the quantity of started particles as described in the methods section.

5.3 Discussion of results

Forward and backward flow path calculations

The differences in obtained results for forward and backward flow path calculations showed to be significant. However, no evident cause has been determined for the inconsistent flow path patterns in the backward calculations. The inconsistency could be due to a limited quantity of Meuse water being abstracted by the wells, this however cannot be examined within IMOD. Additionally, the starting locations for particles can influence the flow paths patterns. The forward calculations with particles being started from the Meuse appear realistic and are therefore used in this study.

Effects of Maaswerken

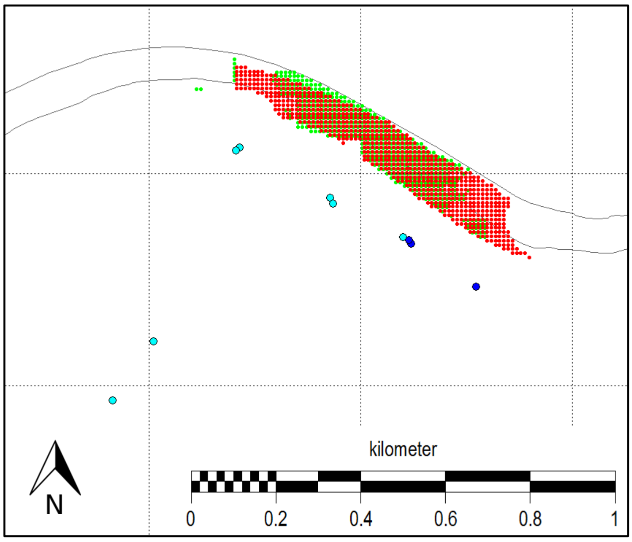
In this section the effects of the Maaswerken and possible explanations are discussed for each modelling scenario.

For the Meuse wells 09, 10 & 11 minimal differences in travel time curves were found between the initial model (SCE0) and the median discharge scenarios after lowering of the riverbank (SCE1). Largest parts of the travel time curve of the initial model SCE0 contain smaller travel times compared to SCE1. This would indicate that travel times from the Meuse riverbank towards the Meuse wells will slightly increase as a result of the lowering of the inside bend near Roosteren. However, changes are so minimal that this implication is not evident. The minimality of changes in travel times could be explained by the fact that the Meuse wells do not abstract water from areas where the Meuse moved inland as a result of the Maaswerken for SCE0 and SCE1. The reason that the two scenario are not completely similar can be the result of the changes in horizontal and vertical conductivity as a consequence of the changes in thickness of the model layers due to the adjustment of the riverbank. In scenario SCE1 well 09 abstracted Meuse water from a larger area compared to the initial model SCE0 (Figure 19a). This explains the larger travel times, as water further away from the well is abstracted (Hendrix & Meinardi, 2004). Well 10 showed another pattern, as the main infiltration area for the abstraction of Meuse water shifted away from the well. This can also explain the slightly larger travel times. One infiltration area furthest away from the well on the west side is no longer abstracted from in the median discharge scenario after adjustment of the riverbank (Figure 19b). This might explain that the smallest 10% of travel times are smaller in SCE1 compared to SCE0. However, in this case the large travel times are expected to be smaller as well, which is not the case. The infiltration area of abstracted Meuse water of well 11 has shifted slightly downstream, further away from the well. Though, changes are minimal, which corresponds with the minimal changes in travel time. The changes in travel time curves of radial well 03A after lowering of the riverbank during median discharge are small. This is likely to be the result of the relatively high abstraction (± 7 times larger compared to other wells) and central position of the radial well. Both result in abstraction of Meuse water being spread over a large area of the inside riverbend. As in general only small changes occur to the Meuse river in the study area during a median discharge as a results of the lowering of the riverbank, the changes in travel time curve are expected to be minimal as well. The travel times of the phreatic well 14 experienced an increase in spreading, as both smaller and larger travel times occur in the scenario after lowering of the riverbank compared to the initial model before lowering. This is the result of the larger infiltration area of abstracted Meuse water that occurs in the model scenario after adjustment of the riverbank (Figure 19d). The increase in infiltration area increases the chance of abstracting Meuse water with smaller and larger travel times.

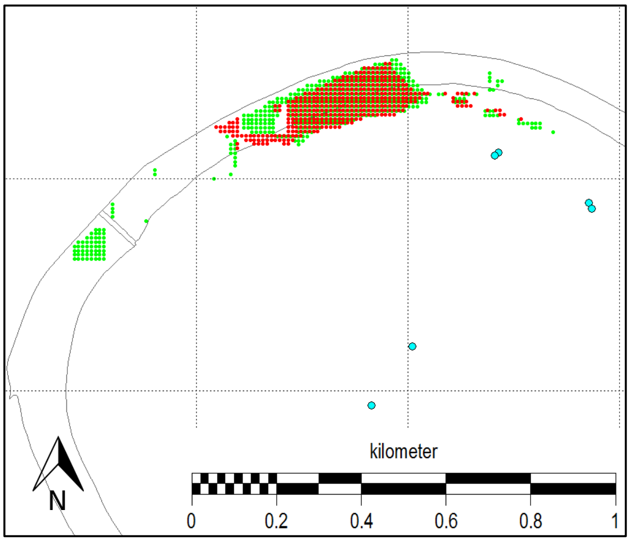
The high discharge scenario (SCE2) showed to contain the largest spread in travel times of all scenarios after the lowering of the riverbank, including both largest and smallest travel times for most wells. The small travel times can be attributed to two changes in this model scenario compared to the initial model (SCE0). Firstly, as a result of the high discharge the Meuse river expands inland compared to lower discharges. This leads to a significantly decreased horizontal distance between the river water and the wells, which also implies a decrease in the lengths of flow paths (Hendrix & Meinardi, 2004). The shortened flow paths could lead to a decrease in travel times, explaining the short travel times in SCE2. Secondly, as the Meuse expands more inland of the inside river bend in this scenario it covers a significant part of the area affected by lowering due to the Maaswerken (Figure 20). This can lead to smaller travel times as not only the horizontal, but also the vertical distance towards the wells will decrease, thereby decreasing the flow path length. SCE2 contains extreme small travel times of < 1 day for Meuse wells 10 & 11 (Figure 15c). This is the result of these wells being located in the riverbed, and thus being flooded during this discharge scenario. The large travel times in SCE2 are a result of the increased groundwater heads (up to + 4.9m compared to median discharge) in this model scenario as a result of the high river discharge. The ratio of river water/phreatic groundwater abstracted by the wells is likely to increase as a result of the increased heads in the vicinity of the wells. The abstraction of more river water can be associated with abstraction from larger areas within the inside river bend. This will lead to the presence of longer flow paths corresponding with larger travel times. It might be unrealistic that well 12 only abstracts Meuse water during the high discharge scenario, as this well is developed to partly abstract Meuse water (Witteveen+Bos, 2014). However, the actual ratio of phreatic groundwater and Meuse water that is abstracted has never been determined. Based on the model outcomes Meuse water is abstracted by wells 12 & 13 only during the high discharge scenario instead of other scenarios, as the prevailing groundwater head has largely increased and the distance from Meuse to wells has decreased.

The low discharge scenario, SCE3, showed smallest scatter in travel times of all scenarios. The small river bed of the Meuse in this low discharge scenario explains the small scatter, as Meuse water can only be abstracted from a limited area corresponding with flow paths containing roughly the same travel times. During a low Meuse discharge the riverbed is located further away from the wells, which results in longer flow paths and larger travel times. Well 10 showed several gaps in travel time distribution for the low discharge scenario, SCE3. This is a result of gaps in the infiltration area from where Meuse well 10 abstracts river water (Figure 21). It can be recognized that some flow paths in between the infiltration areas are stopped within or at the border of the river. This is probably due to an error in the model schematisation, however the exact cause has not been found.

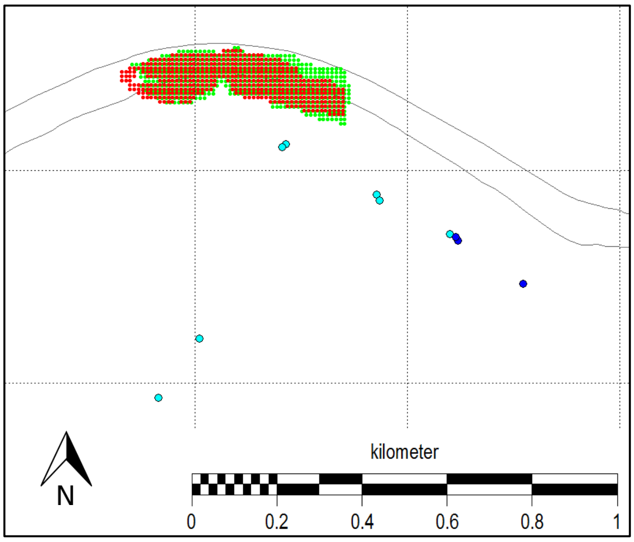
For all scenarios, the travel time distributions of the Meuse wells showed to move closer to each other with the increase of travel times, indicating that large travel times occur in most scenarios. The prevailing Meuse discharge scenario thus shows to rather influence the small travel times than the large travel times.



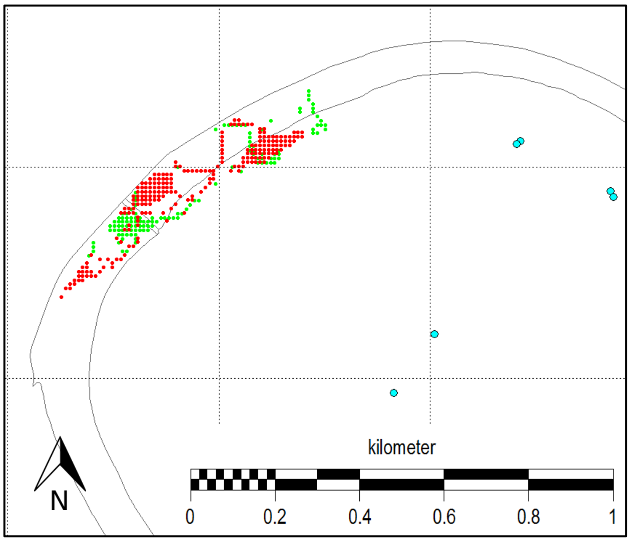
A – well 09



B – well 10



C – well 11



D – well 14

***Figure 19a-d** – Infiltration areas of abstracted Meuse water for wells 09 (a), 10 (b), 11 (c) & 14 (d). Note: Green dots represent SCE0 (before lowering of the riverbank); red dots represent SCE1 (after lowering of the riverbank), light blue dots represent the shallow wells and dark blue dots represent the deep wells.*

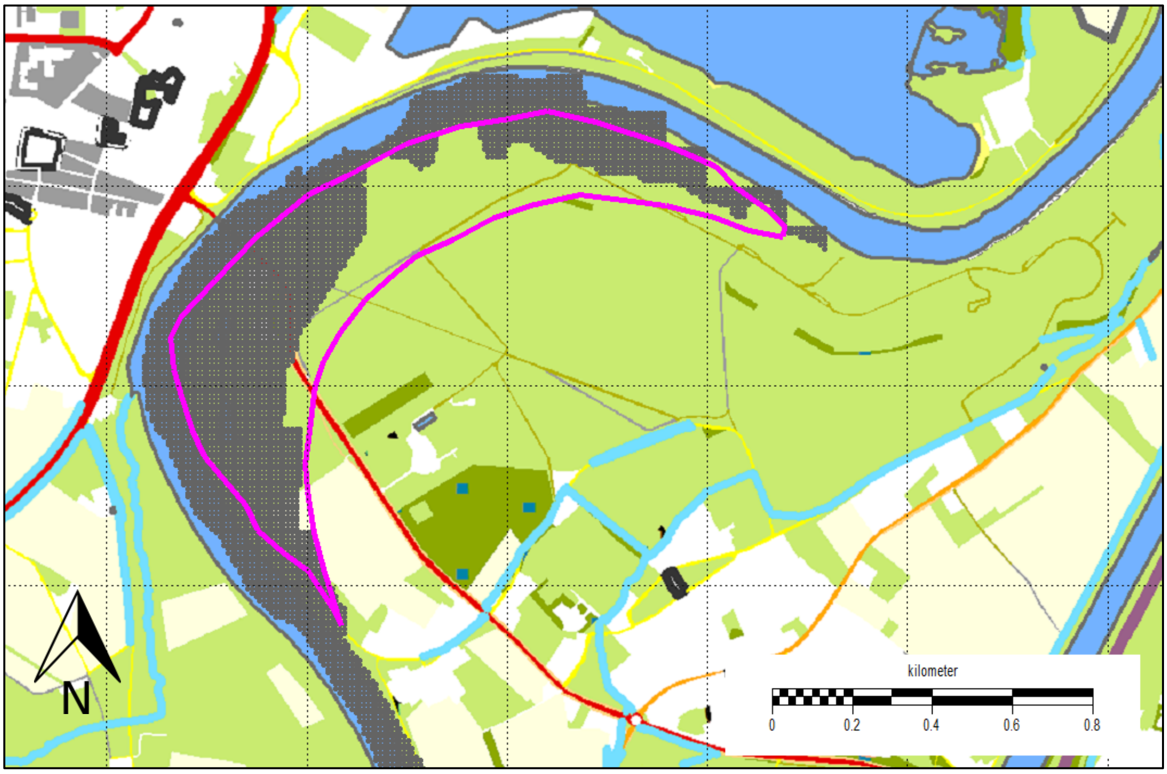


Figure 20 *– Infiltration area of abstracted Meuse water for shallow wells in the high discharge scenario, SCE2. Note: Grey dots represent the starting points of flow paths ending one of the shallow wells for this scenario; Purple line indicates the outline of the area lowered for the Maaswerken program.*

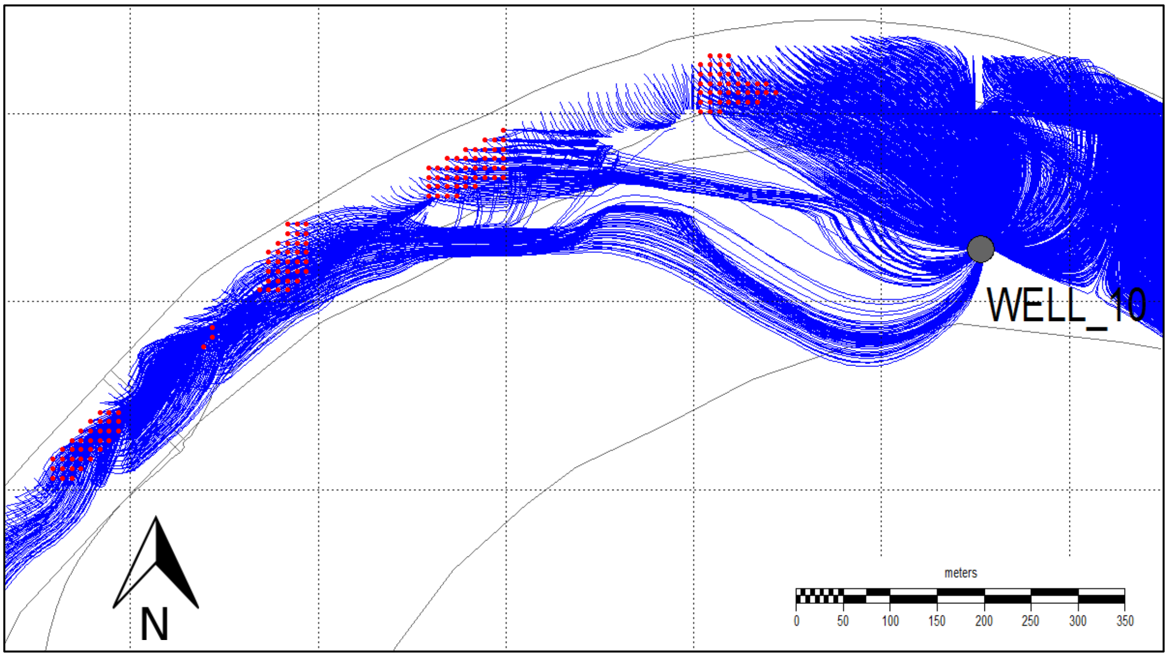


Figure 21 *– Flow paths starting (infiltration areas) points for well 10 (red dots) and flow paths for SCE3 (blue lines). Note: areas in between the infiltration areas seems to be missing flow paths that would travel towards well 10.*

5.4 Implications for drinking water production

Microbiological risks

The abstraction of Meuse water through the riverbanks leads to the water production being vulnerable for microbiological contaminations. The amount of microbial pollution in groundwater increases with shorter travel times. Therefore it is important to know the effects of the Maaswerken and changing discharges on the travel times. The 60-days-zone is a groundwater protection zone around the wells used for microbiological protection of the wells, as a residence time of 60 days or larger is needed for the removal of microorganism to provide safe drinking water (Schijven et al, 1995). The fractions displayed in Table 5 should be put into perspective as these only provide information on the ratio of Meuse water with <60 days travel time compared with total Meuse water, rather than information on the ratio of Meuse water/phreatic water. Though, the differences between the different modelling scenarios are useful as an indication for future changes.

Even in the median discharge scenarios (SCE0 & SCE1) wells 10 & 11 show to abstract Meuse water with a travel time <60 days, which forms a microbiological risk. The fractions of Meuse water with a travel time <60 days increase after lowering of the riverbank for wells 10 & 11, which implies that the risk on microbiological pollution increases as well. This should be taken into account when the Maaswerken will be realised in the future.

During the high discharge scenario, SCE2, the abstracted Meuse water contains most Meuse water with a travel time <60 days of all scenarios for all wells. This leads to an increased microbiological risk thereby emphasizing the necessity of the measures as included in the operational management plan (Prevoo & Juhàsz-Holterman, 2010). Wells 09 (or 12), 10 (or 11) and 13 are taken out of operation when Meuse water levels of > 26,5m +NAP occur, resulting in a decrease of Meuse water abstraction, thereby decreasing the risk. Additionally, an extra UV-treatment unit is put into operation to treat the abstracted water (Prevoo & Juhàsz-Holterman, 2010). Besides the effects of a high Meuse water level in this study one should bear in mind that a fast rising Meuse water level has a significant effect on the microbiological risks as well (Medema et al, 2001). These effects are not addressed in this study as a stationary model has been used.

No explanation has been found for the relatively high fraction of Meuse water for well 10 in SCE3. However in general the quantity of microorganisms is lower during summer, leading to a decreased microbiological risk.

Chemical risks

The changes in chemical risks for the drinking water production are hard to evaluate as the ratio of abstracted Meuse water, phreatic groundwater and deep groundwater is of significant importance to these risks. Though, decreases in travel time can indicate an increased chemical risk as the removal efficiency for chemical components in the soil becomes lower with shorter travel times.

Especially, the decrease in travel times as found in the high discharge scenario (SCE2) of this study can pose an increased risk. The shorter travel times combined with the higher levels of pharmaceuticals during winter, the period that high discharges are most likely to occur, explain these increased risks for drinking water production (Schmidt et al, 2007).

During low discharge conditions (SCE3) it should be taken into account that Meuse water is less diluted, leading to higher concentrations of chemical compounds in the infiltrated Meuse water. This leads to an increased chemical risk for drinking water production during low discharges as the fraction of Meuse water for well 10 is relatively high during these discharges.

Based on the travel time analysis and previous implications on microbiological and chemical risks it can be concluded that largest risks for safe drinking water production emerge during the high discharge scenario after the adjustment of the riverbank. In terms of microbiological risks this is accounted for by taking three Meuse wells out of operation and adding an extra UV-treatment unit during high discharges (Prevoo & Juhàsz-Holterman, 2010). Switching off Meuse wells during this scenario also decreases the chemical risk as no Meuse water is abstracted when only one well of each cluster (10 & 11 and 09 & 12) is active ((Van Rijsselt et al, 2018). To exclude any chemical or microbiological risks from the intake of Meuse water during the high discharge scenario, wells 09, 10, 11, 12 & 13 should be taken out of operation for at least 60 days during high discharges (>1300 m^3/s) as all Meuse wells abstract Meuse water with a travel time of <60 days. However, discharges of >1300 m^3/s occur ± 3 days a year (Rijkswaterstaat Zuid-Nederland, 2019). When these high discharges do not occur consecutive, but during different discharge peaks (as can be recognized in Figure 7), this implies that the Meuse wells will be out of operation for 120 days or more per year. This is not practical from a operational point of view. It is therefore advised to replace the wells further away from the Meuse river. In general, the differences between the median discharge scenario before and after the adjustment of the riverbank have showed to be minimal in this study as travel times do not change significantly. Single point of attention regarding safe drinking water production should be the increase of abstracted Meuse water with a travel time of <60% for Meuse wells 10 and 11. However, future research on the ratio of Meuse water/phreatic groundwater is required to determine the exact changes in risks for safe drinking water production.

Physical well management

Besides the quantitative and qualitive aspects for drinking water production by the Meuse wells, the physical preservation of the Meuse wells after the adjustment of the riverbank is important as well. Figure 16 shows the position of the wells in respect to the area lowered as a result of the Maaswerken. It can be recognized that wells 10 & 11 are located completely in this area and wells 09 & 12 are located on the border of the area. In terms of modelling, the physical conditions of the well have been disregarded as the wells are schematized as points that abstract water out of the layers with well filters. In reality however the stability of the mounds on which the wells are located is likely to be affected by the lowering of the area. In addition, during the high discharge scenario, wells 10 & 11 are exposed to erosive processes of the Meuse as a result of inundation, which is unwanted. As water levels corresponding with the high discharge scenario or higher occur ± 3 days a year (Rijkswaterstaat Zuid-Nederland, 2019), the preservation of wells 10 & 11 cannot be guaranteed. Therefore, it is advised to replace the wells so that these will not be inundated during high discharges.

5.5 Relation to previous research

The results of this study largely agree with previous research on this topic by Hubeek (2010). The uncertainty regarding the physical management of the Meuse wells, especially during high discharges, is emphasized in Hubeek (2012). Moreover, the travel times only decreased significantly during high discharges after lowering of the riverbank in both studies. Additionally, the largest risks regarding the removal of microbiological and chemical pollutants are found to occur in during high discharges after lowering of the riverbank. In addition to Hubeek (2012), travel times of <60 days for wells 10 & 11 in this study indicate that microbiological risks occur during median discharge scenarios both before and after lowering of the riverbank.

5.6 Recommendations for future research

The following is advised for future research on flow paths and travel time distributions regarding riverbank filtration wells and the Roosteren production site:

- Make use of a local groundwater model containing a more simple model layer construction, but a more detailed parameterization of river borders, river bed conductance, vertical and horizontal permeabilities and a more detailed schematization of occurring faults. It is useful to employ a model that includes the ability to determine fluxes of groundwater flows, like MicroFEM (Nienhuis & Hemker, 2010). Also, running transient state model instead of a steady state model would simulate a more realistic situation.
- Compare the same discharge scenarios before and after lowering of the riverbank to determine the exact effect of the Maaswerken during several discharges. This was out of scope for this study.
- Develop a method to validate modelling results based on chemical or microbiological tracers.

6. Conclusions

6.1 Conclusions of study

This study was performed as Rijkswaterstaat is planning to lower the inside bend of the riverbank at the Roosteren drinking water production site. This will pose effects to the production of drinking water. The main objective of this study was to determine the effects of the Maaswerken near Roosteren on the drinking water production. This is done by obtaining travel time data of three modelling scenarios using the regional groundwater model IBv2.1. The main outcomes of the study state that:

- The median discharge scenario (SCE1) showed that minimal differences occur in travel time distribution between the situation before and after lowering of the riverbank in the vicinity of the Roosteren well field. This can be explained as the Meuse wells do not abstract water from areas where the Meuse moved inland as a result of the Maaswerken in the model.
- The high discharge scenario (SCE2) results in the largest spread in travel times, as both smallest and largest travel times are found for most wells in this scenario. The smallest travel times in this scenario are a result of the decrease in horizontal and vertical distance of Meuse water to the wells as a result of the high discharge and the lowering of the riverbank. The largest travel times are a result of water that infiltrates at a bigger distance from the wells.
- The low discharge scenario (SCE3) contains smallest spread in travel times. This is a result of the small river bed area in this situation, as travel times from this area largely contain the same travel time. The relatively large travel times in this scenario are a result of the increased distance between river bed and wells.
- Large travel times occur in each scenario as travel time curves move closer to each other with the increase of travel times each scenario. The prevailing Meuse discharge scenario thus shows to rather influence the small travel times than the large travel times.
- Wells 10 & 11 abstract Meuse water with a travel time of <60 days during all modelled scenarios, implying microbiological risks are at hand. Additionally, the fractions of Meuse water with a travel time of <60 days increase after lowering of the riverbank for these wells, implying an increase in microbiological risk as well.
- The high discharge scenario (SCE2) results in most Meuse water with a travel time <60 days of all scenarios for all wells, implying an increased microbiological risk relative to other scenarios.
- The shorter travel times during the high discharge scenario lead to an increased chemical risk, as higher levels of pharmaceuticals occur during winter, coinciding with the high discharges. However, obtaining the ratios between abstracted Meuse water and phreatic water is required to evaluate the exact chemical risks.
- Wells 10 & 11 are located completely in the lowered area and wells 09 & 12 are located on the border of the area. In addition, wells 10 & 11 are partly inundated during the high discharge scenario. The stability of the mounds the wells are located on is affected as a result of lowering of the riverbank and high discharges.

Besides the effects of the Maaswerken on the drinking water production, the suitability of the model for the scope of the study has been discussed. It can be concluded that the regional character of the IBHRAHYM v2.1 model does not benefit the local focus of the study as in some aspects the model schematization is too coarse to precisely study local groundwater processes.

6.2 Advise

The ratio of abstracted Meuse water and phreatic groundwater should be determined for the Meuse wells to evaluate if the increase in travel time of <60 days for wells 10 & 11 after lowering of the riverbank poses too large risks for drinking water production. To minimize chemical and microbiological risks from the intake of Meuse water during the high discharge scenario, all Meuse wells should be taken out of operation for 60 days during this scenario as they abstract Meuse water with a travel time of <60 days. From an operational point of view all Meuse wells should be replaced further away from the Meuse, as Meuse wells can be out of operation for 120 days or more when a discharge of >1300 m^3/s occurs more than once a year. Additionally, Meuse wells 10 & 11 should be replaced as the erosive processes due to inundation during high discharges will affect the stability of the mounds these wells are located after lowering of the riverbank.

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Appendices

Appendix A – Example Runfile

This appendix shows an example of one of the runfiles used in this study (SCE0).

```
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500 50         0.001 100.0  0.98  1    5.0   50
181500.00  339500.00  189500.00 347500.00     5.00    0.0
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 1 1 0  (SHD)
 1 0 0  (TOP)
 1 0 0  (BOT)
 1 1 0  (KHV)
 1 0 0  (KVA)
 1 1 0  (KVV)
 0 0 0  (CPP)
 1 0 0  (ANI)
 1 1 0  (HFB)
 1 1 0  (WEL)
 1 1 0  (DRN)
 1 1 0          (RIV)
 1 1 0  (OLF)
 1 1 0  (RCH)
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 11,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L11.IDF
 12,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L12.IDF
 13,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L13.IDF
 14,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L14.IDF
 15,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L15.IDF
 16,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L16.IDF
 17,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L17.IDF
 18,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L18.IDF
 19,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\10KHVcorr4\KHV\25\KH_L19.IDF
19,(KVA)
 1,1.0,0.0,0.3
 2,1.0,0.0,0.3
 3,1.0,0.0,0.3
 4,1.0,0.0,0.3
 5,1.0,0.0,0.3
 6,1.0,0.0,0.3
 7,1.0,0.0,0.3
 8,1.0,0.0,0.3
 9,1.0,0.0,0.3
```

```
10,1.0,0.0,0.3
11,1.0,0.0,0.3
12,1.0,0.0,0.3
13,1.0,0.0,0.3
14,1.0,0.0,0.3
15,1.0,0.0,0.3
16,1.0,0.0,0.3
17,1.0,0.0,0.3
18,1.0,0.0,0.3
19,1.0,0.0,0.3
18,(KVV)
1,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L1.IDF
2,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L2.IDF
3,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L3.IDF
4,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L4.IDF
5,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L5.IDF
6,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L6.IDF
7,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L7.IDF
8,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L8.IDF
9,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L9.IDF
10,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L10.IDF
11,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L11.IDF
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13,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L13.IDF
14,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L14.IDF
15,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L15.IDF
16,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\KVV\VERSION_1\25\KVV_L16.IDF
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71,(HFB)
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0,2500.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\03HFB\100\GANGELT-HT-BOT_3D.GEN
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0,2500.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\BASIS0\03HFB\100\GANGELT-TO-BOT_3D.GEN
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BOT_3D.GEN
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L_3D.GEN
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N_3D.GEN
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D.GEN
4,(ANI)
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1,(CPP)
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PACKAGES FOR EACH LAYER AND STRESS-PERIOD
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126,(WEL)
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f

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12,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\WEL\VERSION_1\GLASTUINBOUW\imod_mkipf_wells_l12.ipf

13,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\WEL\VERSION_1\GLASTUINBOUW\imod_mkipf_wells_l13.ipf

14,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\WEL\VERSION_1\GLASTUINBOUW\imod_mkipf_wells_l14.ipf

15,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\WEL\VERSION_1\GLASTUINBOUW\imod_mkipf_wells_l15.ipf

17,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\WEL\VERSION_1\GLASTUINBOUW\imod_mkipf_wells_l17.ipf
2,(DRN)
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3,(RIV)
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0,1.0,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\RIV\VERSION_1\Maas_PLASUITIRIV\BOTTOM_MAAS19942011_MEDIAN.IDF
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1,0.66,0.0,E:\Projects\WML\Roosteren_Maaswerken\Model_Maaswerken\Model\DBASE\ORG\RCH\VERSION_1\PERCEELBEREGENING.IDF
1,(OLF)
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Appendix B – Reference Line Heights

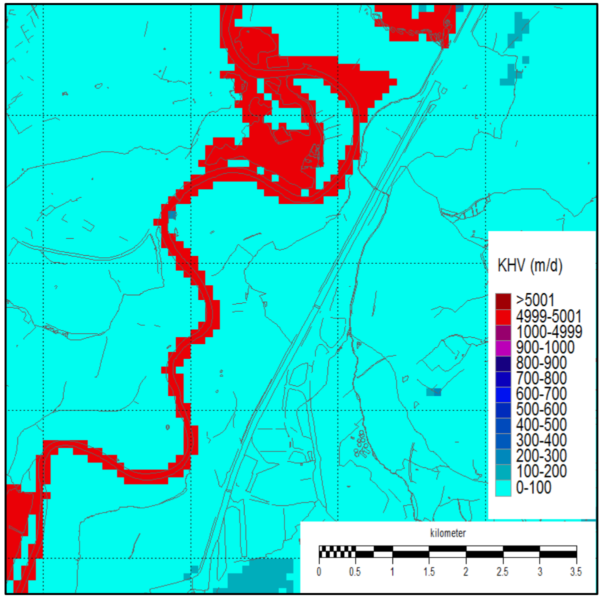
Table B1 *– Reference line heights near measuring station Maaseik (HIC) (Rijkswaterstaat Zuid-Nederland, 2019).*

Betrekkingslijnen Maas versie 2019_2020										**geldigheidsbereik 1 nov. 2019 - 31 okt. 2020**									
Informatiebron		**Gemeten waterstand 1.7.2018 - 30.6.2019**							**WAQUA in bereik recente hoogwaters**							**WAQUA**			
Waterstand Borgharen-dorp [m]		38.13	38.73	39.25	39.91	41.11	41.69	42.19	43.21	43.80	44.26	44.48	44.70	44.95	45.27	45.53	45.73	45.94
aantal dagen/jr dat ws hoger is		268	184	107	45	8	4	2										
Afvoer St. Pieter [m3/s]		80	155	280	530	1030	1280	1500	1982	2308	2609	2781	2969	3226	3578	3862	4113	4396
herh. tijd v/d topafvoer in jaren									5	10	20	30	50	100	300	1000	3000	10000
Afvoer Borgharen-dorp [m3/s]		(50)	(125)	(250)	(500)	(1000)	(1250)	(1470)	1971	2302	2603	2776	2965	3224	3573	3862	4118	4398
peilschaal op meetpunt	kmr	Waterstanden m + NAP																
	52	21.45	21.95	22.59	23.81	25.77	26.61	27.18	28.45	29.15	29.63	29.85	30.05	30.27	30.49	30.69	30.81	30.89
Maaseik (HIC)	52.80	21.08	21.46	22.21	23.46	25.40	26.23	26.92	28.23	28.91	29.40	29.62	29.82	30.02	30.23	30.41	30.51	30.58
	53	21.05	21.40	22.13	23.36	25.32	26.13	26.71	27.97	28.66	29.14	29.38	29.59	29.83	30.02	30.21	30.31	30.38
	54	21.01	21.24	21.85	22.99	24.86	25.62	26.14	27.25	27.97	28.54	28.81	29.05	29.30	29.50	29.68	29.80	29.90
	55	20.97	21.15	21.63	22.64	24.40	25.18	25.72	26.69	27.33	27.79	28.03	28.22	28.47	28.61	28.72	28.80	28.92
	56	20.95	21.05	21.41	22.29	23.98	24.79	25.34	26.24	26.79	27.17	27.34	27.49	27.73	27.98	28.16	28.32	28.48
	57	20.93	21.02	21.32	22.11	23.68	24.40	24.98	25.83	26.28	26.61	26.78	26.94	27.16	27.65	27.93	28.13	28.30
	58	20.93	20.99	21.23	21.94	23.44	24.12	24.67	25.61	26.08	26.41	26.57	26.71	26.85	27.03	27.26	27.44	27.59
	59	20.92	20.97	21.17	21.79	23.17	23.84	24.37	25.40	25.90	26.23	26.39	26.53	26.67	26.85	27.07	27.24	27.38
	60	20.92	20.96	21.12	21.66	22.96	23.61	24.13	24.93	25.30	25.57	25.69	25.80	25.92	26.06	26.24	26.38	26.50
	61	20.91	20.94	21.06	21.51	22.69	23.27	23.74	24.65	25.05	25.33	25.46	25.57	25.71	25.87	26.05	26.19	26.30
Stevensweert	61.57	20.91	20.94	21.06	21.51	22.69	23.27	23.71	24.46	24.83	25.09	25.21	25.32	25.45	25.61	25.79	25.94	26.06
	62	20.91	20.93	21.04	21.45	22.54	23.09	23.48	24.18	24.48	24.68	24.78	24.86	24.95	25.08	25.21	25.33	25.45
	63	20.89	20.91	20.99	21.30	22.23	22.78	23.24	24.05	24.35	24.56	24.64	24.72	24.82	24.95	25.08	25.19	25.31
	64	20.88	20.89	20.95	21.17	21.89	22.35	22.77	23.68	24.05	24.29	24.39	24.49	24.60	24.72	24.85	24.97	25.08
	65	20.87	20.88	20.91	21.04	21.50	21.80	22.21	23.30	23.57	23.78	23.90	24.01	24.14	24.29	24.45	24.59	24.73
	66	20.86	20.86	20.88	20.94	21.21	21.41	21.69	23.11	23.36	23.57	23.69	23.82	23.96	24.13	24.31	24.45	24.60
67.00z	66.50	20.85	20.86	20.86	20.90	21.06	21.18	21.38	22.35	22.81	23.11	23.25	23.38	23.52	23.69	23.88	24.02	24.19
68.00z	67	20.85	20.85	20.85	20.86	20.91	20.95	21.07	22.00	22.50	22.82	22.95	23.07	23.20	23.34	23.48	23.59	23.73
67.00n	67.50	20.85	20.85	20.85	20.85	20.84	20.84	20.91	21.81	22.23	22.53	22.67	22.80	22.95	23.11	23.25	23.36	23.50
Heel boven	67.34	20.85	20.85	20.85	20.85	20.85	20.85	20.93	21.83	22.25	22.53	22.66	22.78	22.92	23.09	23.23	23.35	23.49
68.00n	68	20.85	20.84	20.84	20.81	20.70	20.62	20.52	21.45	21.94	22.26	22.42	22.57	22.75	22.96	23.12	23.25	23.41
Stuw Linne	68.55																	
	69	16.89	16.94	17.12	17.67	18.89	19.48	19.99	20.99	21.63	22.00	22.18	22.33	22.53	22.77	22.94	23.08	23.25
	70	16.89	16.93	17.08	17.58	18.80	19.38	19.83	20.65	21.08	21.44	21.64	21.82	22.06	22.38	22.58	22.74	22.95
Linne beneden	70.40	16.89	16.93	17.07	17.56	18.75	19.33	19.78	20.60	21.04	21.39	21.58	21.76	22.00	22.32	22.53	22.69	22.90
	71	16.88	16.91	17.03	17.44	18.48	19.04	19.63	20.49	20.94	21.31	21.51	21.70	21.95	22.28	22.49	22.65	22.87
	72	16.88	16.91	17.01	17.38	18.35	18.88	19.47	20.36	20.86	21.25	21.46	21.66	21.92	22.25	22.47	22.63	22.85
	73	16.87	16.90	16.99	17.32	18.23	18.76	19.28	20.29	20.80	21.20	21.40	21.61	21.86	22.19	22.41	22.57	22.78
	74	16.87	16.89	16.96	17.22	17.96	18.47	18.74	19.72	20.29	20.76	20.99	21.24	21.53	21.88	22.11	22.29	22.55

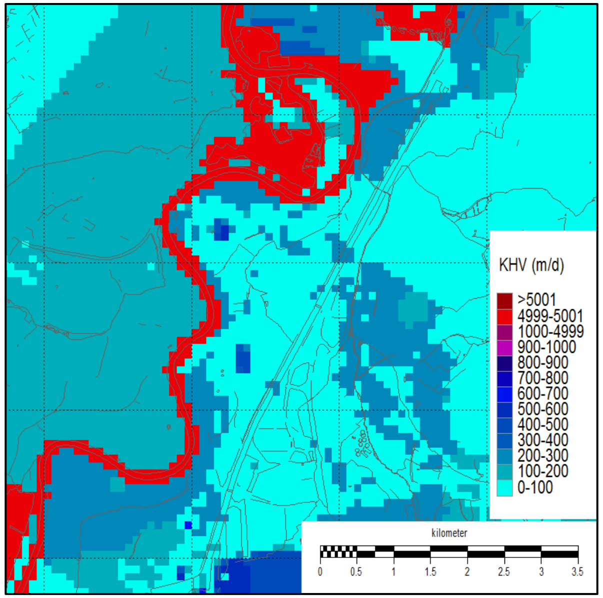
Appendix C – Example Flow Path Data

Table C1 *– An example of the first rows of a flow path data sheet as used in this study.*

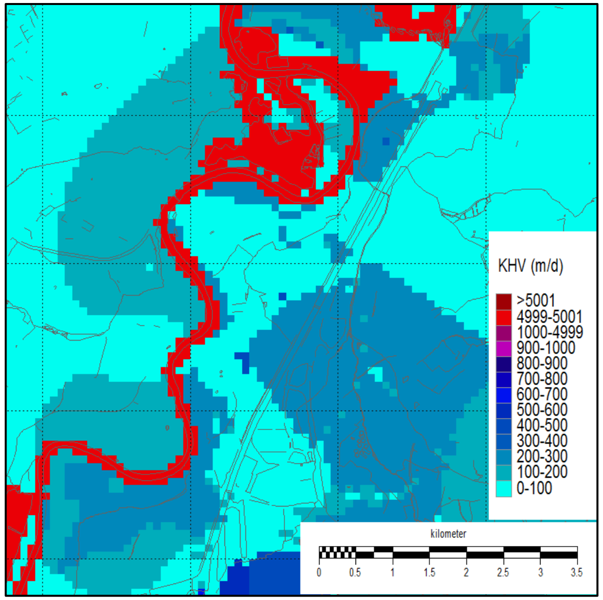
SP_XCRD.	SP_YCRD.	SP_ZCRD.	SP_ILAY	SP_IROW	SP_ICOL	EP_XCRD.	EP_YCRD.	EP_ZCRD.	EP_ILAY	EP_IROW	EP_ICOL	TIME(YEARS)	MAXLAYER	DISTANCE	IDENT.NO.	CAPTURED_BY	NUMBER	CUMULATIVE PERCENTAGE	TIME (DAYS)
184,682,420	345,150,719	24,000	2	470	637	184,709,627	345,060,000	22,157	4	489	642	0.05121	4	94,729	6660	3	1	0.03%	18.6917303
184,682,420	345,160,719	24,000	2	468	637	184,709,884	345,060,000	21,794	4	489	642	0.055488	4	104,420	6087	3	2	0.07%	20.2530178
184,692,420	345,160,719	24,000	2	468	639	184,710,000	345,059,867	21,723	4	489	642	0.058723	4	102,398	6097	3	3	0.10%	21.4339534
184,692,420	345,150,719	24,000	1	470	639	184,710,000	345,059,703	22,156	4	489	642	0.05875	4	92,717	6670	3	4	0.14%	21.4436296
184,702,420	345,160,719	24,000	2	468	641	184,710,000	345,059,829	21,208	4	489	642	0.061843	4	101,213	6107	3	5	0.17%	22.5725965
184,702,420	345,150,719	24,000	1	470	641	184,710,000	345,059,617	22,062	4	489	642	0.061956	4	91,437	6680	3	6	0.21%	22.6139291
184,712,420	345,150,719	24,000	1	470	643	184,710,000	345,059,455	21,959	4	489	642	0.062389	4	91,319	6690	3	7	0.24%	22.7718646
184,762,420	345,140,719	24,000	2	472	653	184,710,000	345,058,648	21,223	4	489	642	0.076404	4	97,423	7235	3	8	0.27%	27.8874162
184,612,420	345,180,719	24,000	2	464	623	184,709,337	345,060,000	21,435	4	489	642	0.084334	4	154,831	4809	3	9	0.31%	30.7819465
184,622,420	345,180,719	24,000	2	464	625	184,709,462	345,060,000	21,410	4	489	642	0.084786	4	148,849	4819	3	10	0.34%	30.9469229
184,522,420	345,200,719	24,000	1	460	605	184,709,297	345,060,000	22,494	4	489	642	0.086724	4	233,938	3316	3	11	0.38%	31.6541797
184,632,420	345,180,719	24,000	2	464	627	184,709,583	345,060,000	21,346	4	489	642	0.086968	4	143,298	4829	3	12	0.41%	31.7433237
184,512,420	345,200,719	24,000	1	460	603	184,708,497	345,059,496	22,498	4	489	642	0.08699	3	241,645	3306	3	13	0.45%	31.7514267
184,532,420	345,200,719	24,000	1	460	607	184,709,837	345,060,000	22,449	4	489	642	0.087351	4	226,453	3326	3	14	0.48%	31.8832647
184,542,420	345,200,719	24,000	1	460	609	184,710,000	345,059,867	22,394	4	489	642	0.088971	4	218,917	3336	3	15	0.52%	32.4743019
184,552,420	345,200,719	24,000	1	460	611	184,710,000	345,059,565	22,369	4	489	642	0.091855	4	211,562	3346	3	16	0.55%	33.5272028
184,572,420	345,200,719	24,000	1	460	615	184,710,000	345,059,127	22,272	4	489	642	0.100939	4	197,432	3356	3	17	0.58%	36.842735
184,582,420	345,200,719	24,000	1	460	617	184,710,000	345,058,902	22,232	4	489	642	0.106048	4	190,767	3366	3	18	0.62%	38.7074835
184,432,420	345,270,719	21,000	1	446	587	184,707,702	345,060,000	22,189	4	489	642	0.111563	4	346,676	122	3	19	0.65%	40.7205315
184,642,420	345,200,719	23,000	1	460	629	184,710,000	345,058,703	21,862	4	489	642	0.11158	4	157,280	3421	3	20	0.69%	40.7267
184,442,420	345,270,719	21,000	1	446	589	184,708,275	345,060,000	22,123	4	489	642	0.112549	4	339,238	129	3	21	0.72%	41.080385
184,782,420	345,130,719	24,000	1	474	657	184,710,000	345,057,794	21,633	4	489	642	0.113724	4	102,802	7755	3	22	0.76%	41.509406
184,422,420	345,270,719	21,000	1	446	585	184,707,190	345,060,000	22,242	4	489	642	0.115372	4	354,257	115	3	23	0.79%	42.110707



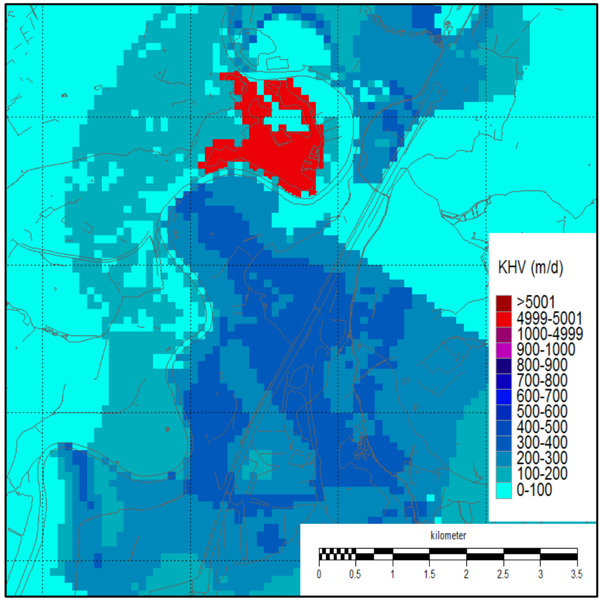
***D1** – KHV model layer 1.*



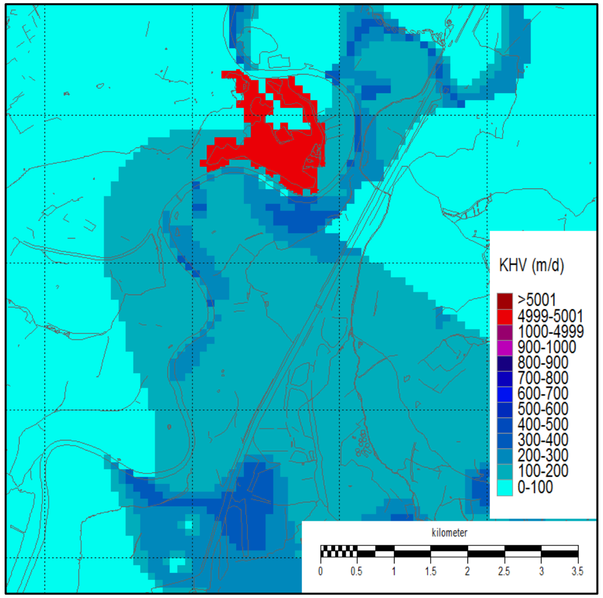
***D2** – KHV model layer 2.*



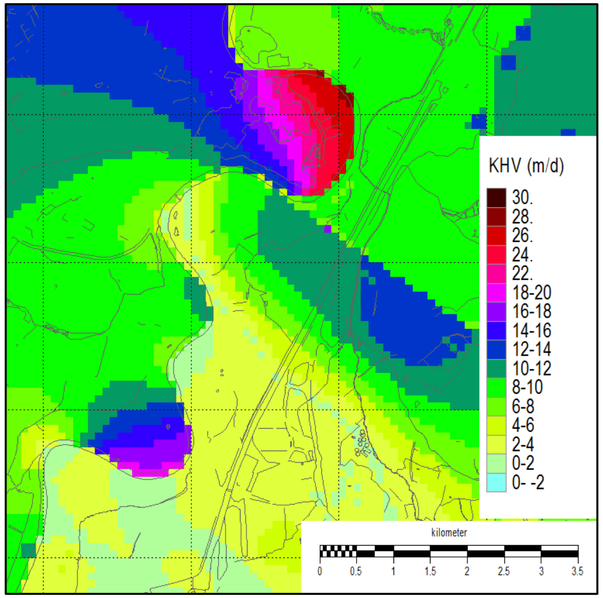
***D3** – KHV model layer 3.*



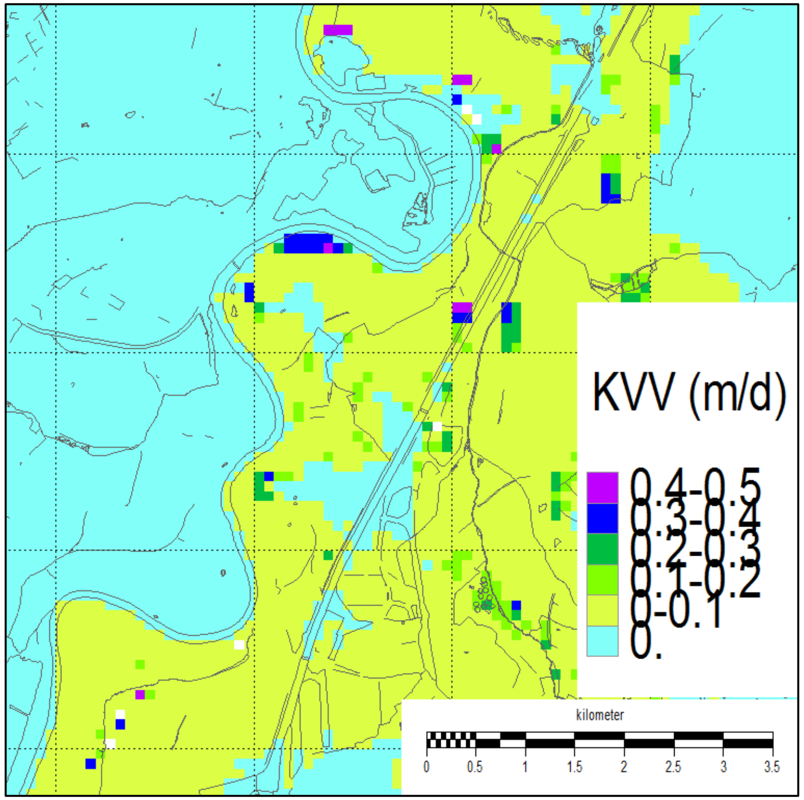
***D4** – KHV model layer 4.*



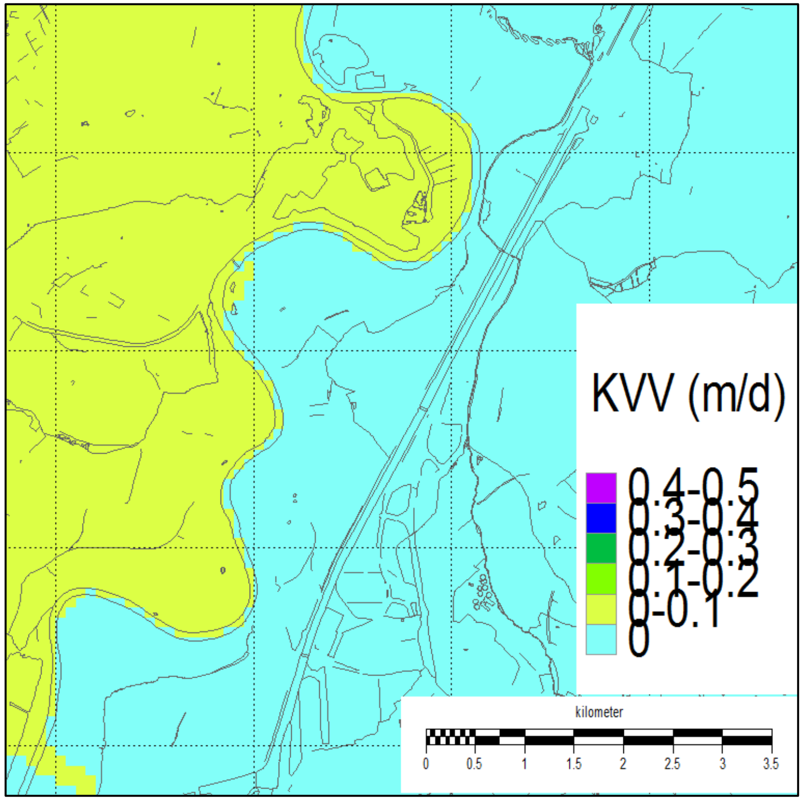
***D5** – KHV model layer 5.*



***D6** – KHV model layer 13.*

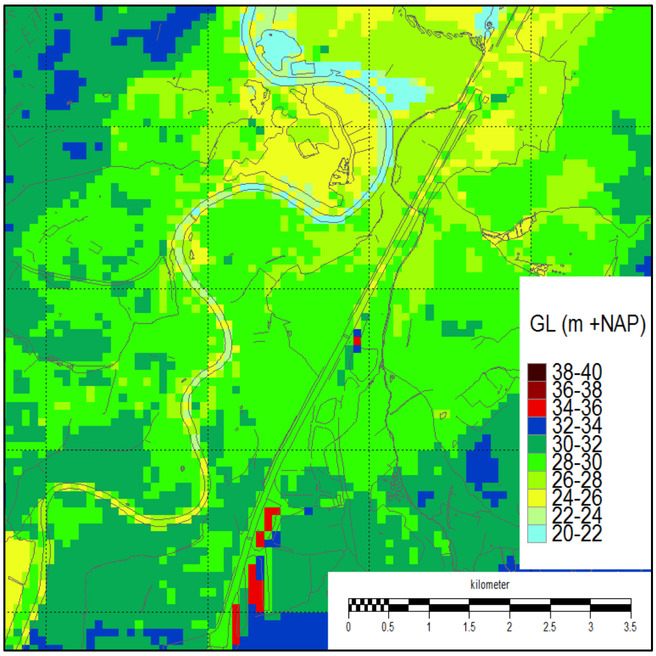


***E1** – KVV model layer 1.*

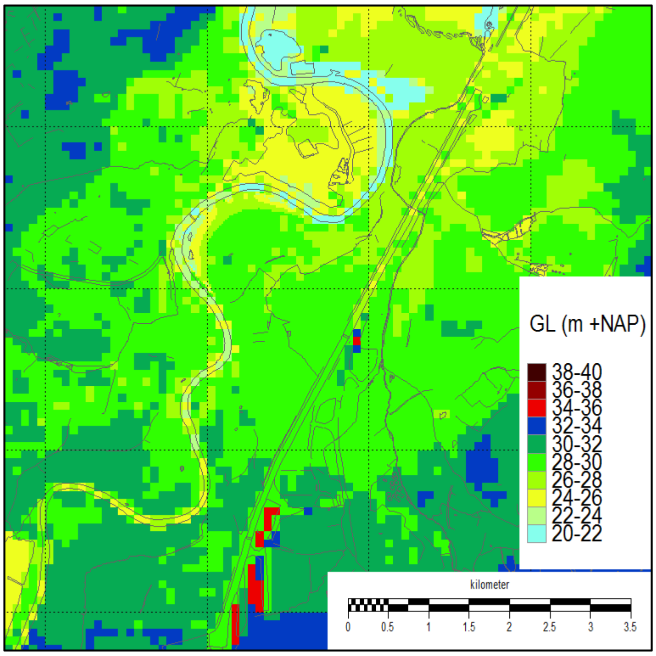


***E2** – KVV layer model 13.*

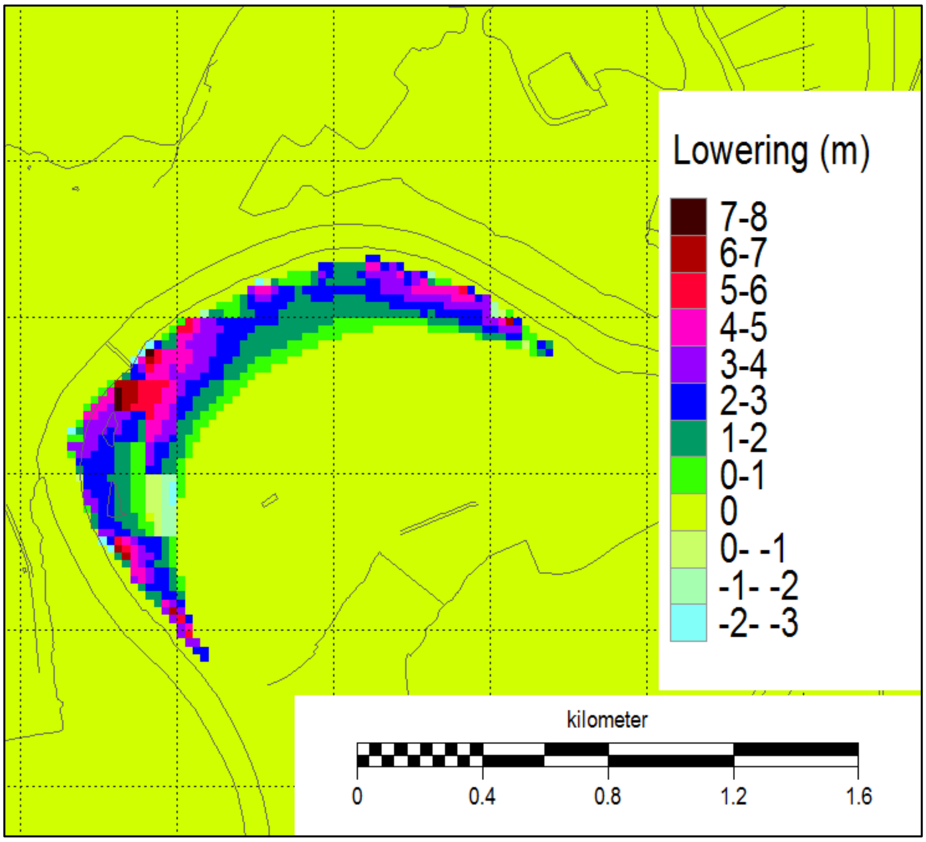
Appendix F – Ground Level Maps



F1 *– Ground level before lowering of riverbank (SCE0).*

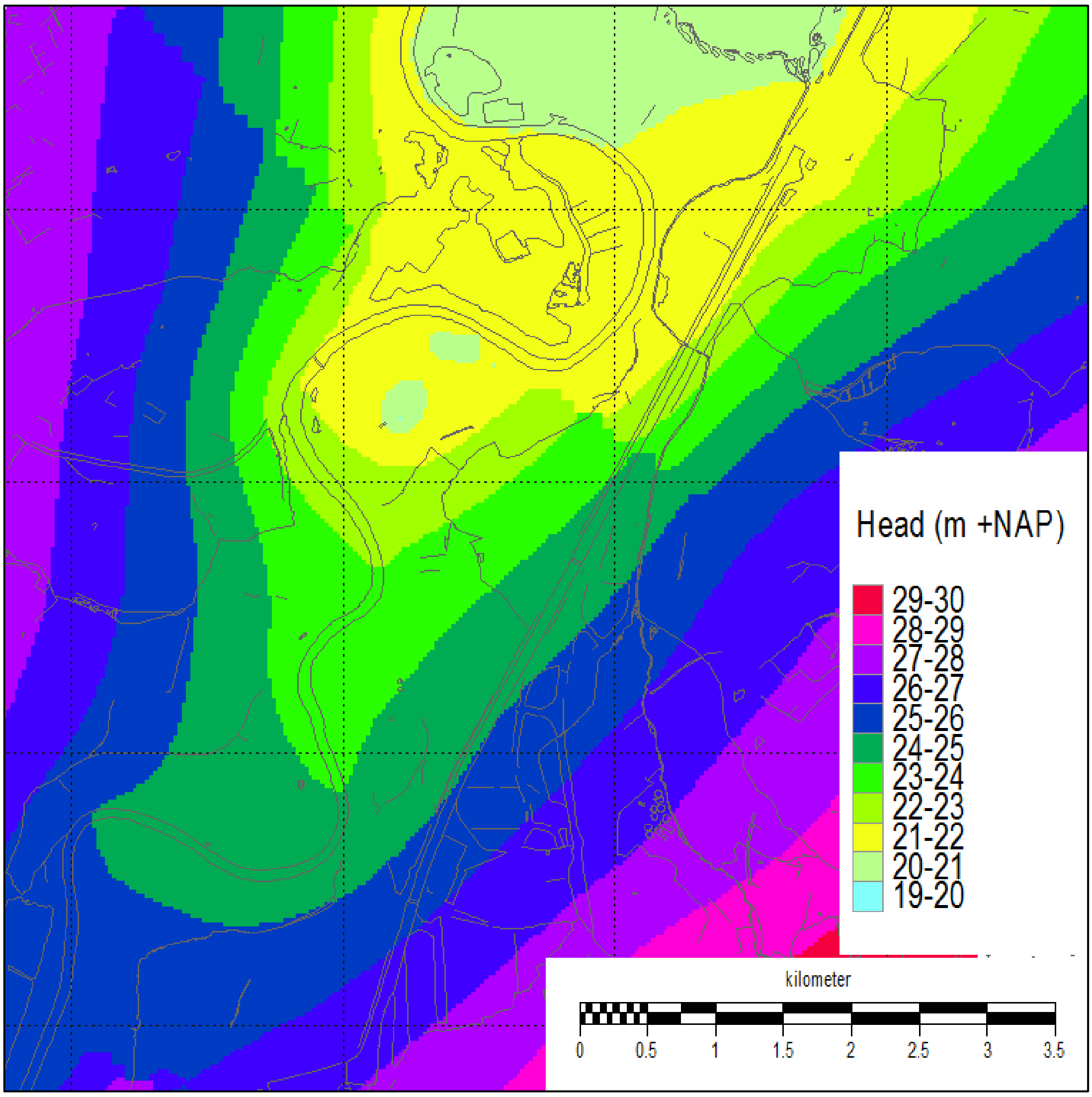


F2 *– Ground level after lowering of riverbank (SCE1, SCE2 & SCE3).*



F3 *– Difference map for lowering of inside riverbank. Note: positive values show the quantity as lowered, negative values show the quantity as heightened.*

Appendix G – Typical Model Values



G1 *– Groundwater head in model layer 5 for SCE0.*

Table G1 *– Typical input values for the Meuse river in the study area.*

	River bed conductance	Infiltration factor	Bottom river in study area
Typical value	312.5 (m^2/d)	0.3 (-)	17-20 (m +NAP)

Appendix H – Point Estimates & Confidence Limits

***Table H1** – Gamma distribution fit for some wells and scenarios including the distribution parameters, mean travel times, and lower & upper 95% confidence intervals. Note that these point estimates and corresponding confidence limits are indicative as the distributions do not contain an optimal fit for the travel time data.*

WELL	SCENARIO	ALPHA	SCALE	MEAN TT (DAYS)	LOWER 95% CONFIDENCE INTERVAL	UPPER 95% CONFIDENCE INTERVAL
09	**SCE3**	0.94	4596.50	**4343**	3500	5234
10	**SCE0**	0.88	1543.40	**1265**	986	1783
10	**SCE1**	1.07	1809.02	**1939**	1715	2169
10	**SCE2**	0.48	11425.00	**5430**	4908	5954
10	**SCE3**	1.24	702.31	**874**	607	1172
11	**SCE3**	1.72	636.08	**985**	939	1256
13	**SCE2**	1.96	211.13	**415**	318	521
14	**SCE0**	10.88	360.65	**3923**	2973	4998
14	**SCE1**	1.41	2675.70	**3782**	2544	5191
14	**SCE2**	1.14	5740.10	**6537**	6096	6985